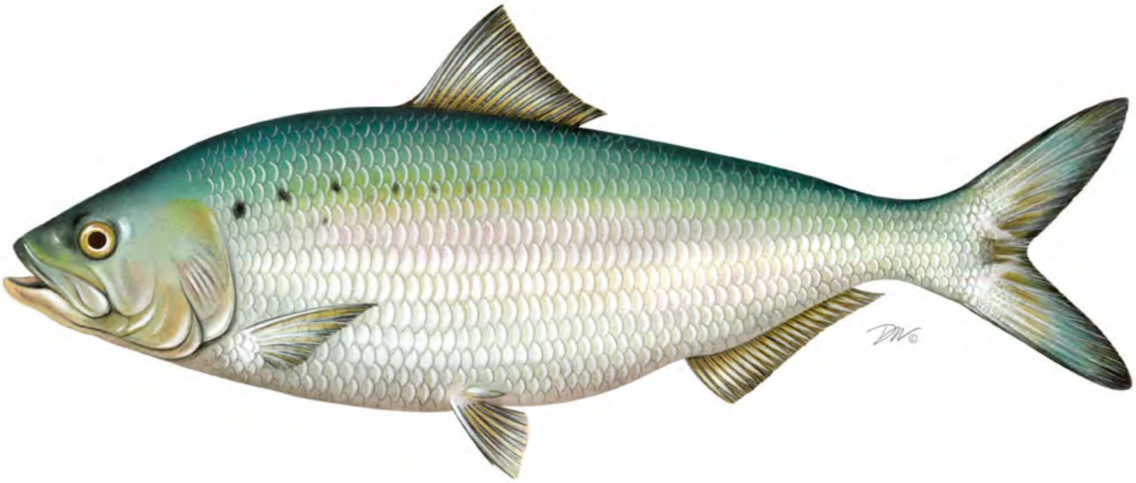
Atlantic States Marine Fisheries Commission

2020 American Shad Benchmark Stock Assessment and Peer Review Report



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Sustainable and Cooperative Management of Atlantic Coastal Fisheries

ACKNOWLEDGEMENTS

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The members of the SAS and TC follow on the next page.

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PREFACE

The 2020 American Shad Benchmark Stock Assessment and Peer Review Report is divided into two parts:

Part A – 2020 American Shad Benchmark Stock Assessment Peer Review
PDF pages 5-53

Part A provides a summary of the stock assessment results supported by a panel of independent experts through the ASMFC external peer review process. The Peer Review Terms of Reference provides a detailed evaluation of how each Stock Assessment Term of Reference was addressed by the SAS.

Part B – 2020 American Shad Benchmark Stock Assessment
PDF pages 54-1188

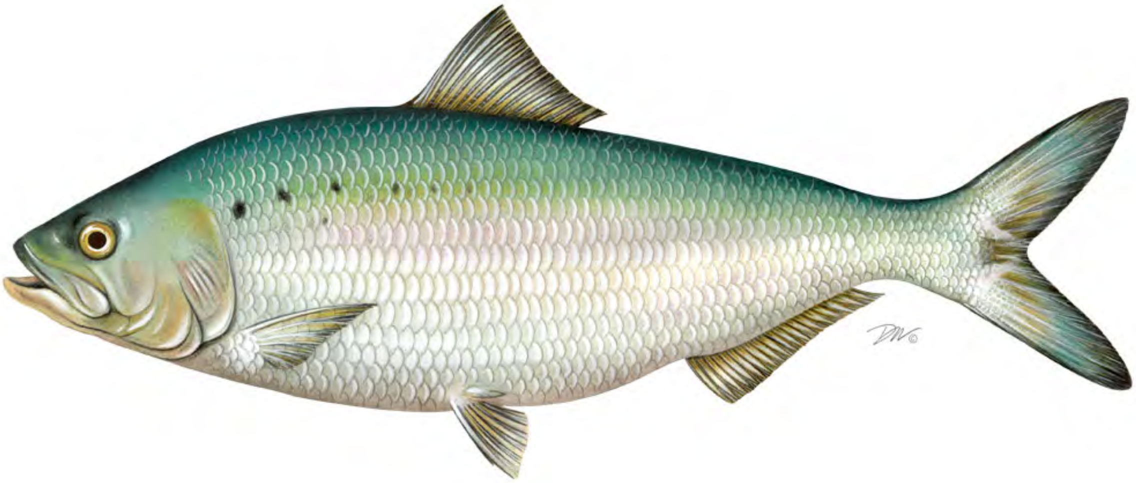
Part B includes the benchmark assessment of American shad (*Alosa sapidissima*) stocks of the U.S. Atlantic Coast from Maine through Florida. It was prepared by the American Shad SAS. The analyses and descriptions stem from data and summary reports provided by federal and state freshwater and marine resource management agencies, power generating companies, and universities to the ASMFC. The SAS routinely interacted with data collectors and managers to insure that application and interpretation of data were appropriate. Data collation and review occurred at a Data Workshop attended by memebrs of the American Shad TC and SAS (Baltimore, MD; March 5-8, 2018), methods to assess stocks were identified at a Methods Workshop attended by SAS members (Providence, RI; November 5-8 2018), and assessment results were reviewed at an Assessment Workshop attended by SAS members (Charleston, SC; November 18-22, 2019). Assessment results were subsequently reviewed by the TC and approved for peer review at a webinar on March 23, 2020.

Part B is further subdivided into nine Sections, with **Sections 1-8** providing the original benchmark stock assessment as presented to the Peer Review Panel. During the Peer Review Workshop, the Peer Review Panel and SAS discussed the analyses used to make stock status determinations. Additional analyses were conducted during the Peer Review Workshop and the Peer Review Panel asked that the SAS revisit stock status determinations for the systems affected by additional analyses and their recommendations to confirm final stock status determinations.

Section 9 presents the Addendum to the assessment report, which provides details on the additional analyses conducted during the Peer Review Workshop, recommendations by the Peer Review Panel, and final stock status determinations for stocks where determinations changed from the initial stock assessment report. These stocks include: the Connecticut (Section 3.4), Potomac (Section 3.10), Neuse (Section 3.16), Cape Fear (Section 3.17), Winyah Bay (Section 3.18), Santee Cooper (Section 3.19), ACE Basin (Section 3.20), and Savannah (Section 3.21) stocks. The stock status determinations that changed are described in the Addendum with heading numbers that correspond to their heading numbers in the main stock assessment report.

Atlantic States Marine Fisheries Commission

2020 American Shad
Benchmark Stock Assessment Peer Review



Conducted on
June 2-5, 2020

Prepared by the
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INTRODUCTION

The American shad was, historically, one of the most important exploited fish species in North America (Stevenson 1899; Limburg et al. 2003). Indicative of this fish's high desirability, American shad artificial propagation was the first article in the first proceedings (1871) of the American Fish Culturists' Association, later to be renamed the American Fisheries Society.

In the late 19th century, annual harvests reached over 50 million pounds (22.7 x 10^3 MT). The stocks declined due to a combination of overfishing, pollution, and habitat loss due to dam construction; over 4,000 km of spawning habitat have been lost (Limburg et al. 2003). In the years between the previous two benchmark stock assessments (in 1998 and 2007), coast-wide harvests averaged 555 MT – an order of magnitude lower than in the late 19th century. Since that assessment, coastwide commercial harvests have plummeted even further, to an average of 224 MT between 2007-2018 (NOAA Fisheries Statistics) – one hundred-fold lower than in the late 19th century. From 1950-2018, four stanzas of decline are discernable in the commercial catches, with the most recent decline approximately coinciding with the period since the last benchmark assessment:

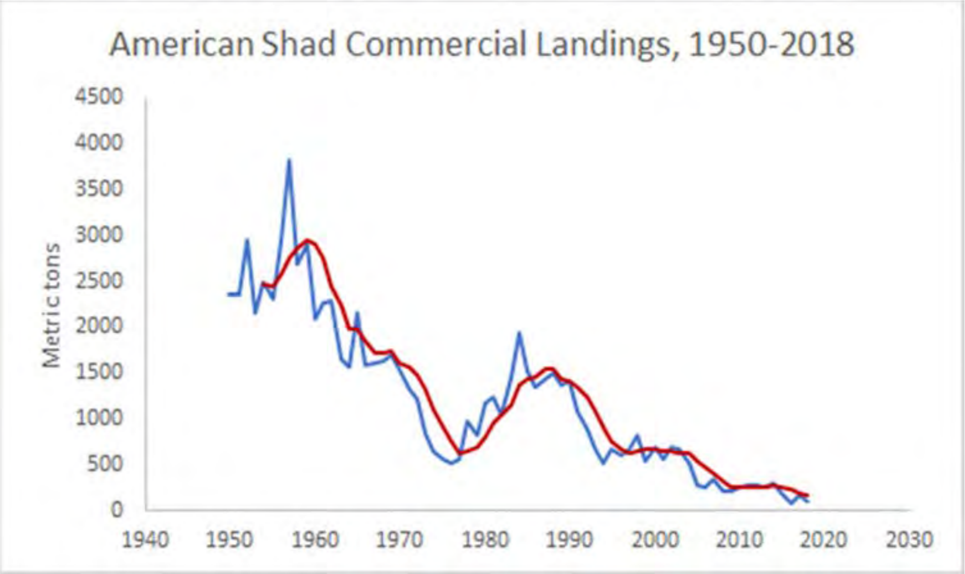

Figure 1. Trend in U.S. commercial catches, 1950-2018. Red line is a 5-point moving average smooth. Data source: NOAA Fisheries Statistics.

The stocks of American shad in their native range along the North American east coast are likely currently at all-time lows. The Shad and River Herring Technical Committee of the Atlantic States Marine Fisheries Commission (ASMFC) undertook the fifth assessment of American shad in 2020, through the Stock Assessment Subcommittee (SAS). Earlier assessments were conducted in 1984, 1988, 1998, and 2007 (ASMFC 1985, 1988, 1998, 2007).

The current assessment contains an extensive compilation of data from many sources and examines status at the river-stock level from some 46 different river systems, aggregated into 23 groupings, since some rivers feed into fairly discrete embayments or basins, and are easier to account for this way.

Eleven Terms of Reference (ToRs), i.e., information and analytical goals, were developed to guide the SAS when undertaking the assessment of the status American shad. The peer review report contains a careful examination of the findings summarized in the draft Stock Assessment Report, organized under eight ToRs specific to the review. An Advisory Report follows the review under the ToRs.

It is noteworthy that the amount of new data, particularly following recommendations of the last benchmark assessment, and the level of new analyses takes the assessment up a significant level from prior benchmarks, and reflects a culmination of understanding of the species and attempts to manage it. Of particular note are the facts that (a) two systems (Potomac and Albemarle Sound) had sufficient data to attempt the use of statistical catch at age (SCA) models, and (b) for the first time, a coastwide habitat assessment of continental waters was undertaken, with specific reference to dams and passage as impediments to sustainable stocks. Additionally, sufficient time and CO2 emissions have accumulated such that climate change projections could be assessed in terms of impact on somatic growth. Finally, there is growing recognition that the suite of in-river predators on juvenile shad is shifting, due to introductions/invasions of non-native species such as various catfishes, pike, black bass, snakeheads, etc. As pointed out by the SAS, predators can have a disproportionately large impact on year class success when fish populations are at such low levels, as is currently the case, threatening resilience (Waldman et al. 2016).

The Review Panel (RP) appreciates the hard work put in by the SAS to create a comprehensive assessment. A Review Workshop was conducted via webinar during the week of June 4, 2020. Workshop discussion was valuable to clarify various points, and overall the benchmark assessment passes review, with a few suggestions going forward. The remainder of this document presents our peer review and advisory report.

TERMS OF REFERENCE

1. Evaluate choice of stock structure.

The American Shad Stock Assessment Subcommittee (SAS) provided a thorough review of the information pertaining to stock (population) structure for American Shad in the Assessment Report, and made practical decisions when applying this information. Like most anadromous fish species, American Shad show a high degree of fidelity to specific watersheds, although some straying and mixing occurs among populations. For American Shad, evidence of population structuring comes from both tagging studies (e.g. Melvin et al. 1986) and genetic analyses (e.g., Hasselman et al. 2013; Cushman et al. 2019). Population structuring at the watershed scale is also evident in other Alosa species such as Alewife and Blueback Herring (McBride et al. 2014; Palkovacs et al. 2014). Based on a review of the literature, the SAS concluded for American Shad that stray rates to non-natal river systems are about 3%. As noted by the SAS, the degree of population differentiation among river systems is greater in the north than in the south, adding to the complexity of stock structure decisions.

As was the case in the 2007 assessment (ASMFC 2007a), the SAS chose a stock structure for American Shad that treats each main stem river and its identified tributaries as an individual stock unit. The choice was applied to the extent practical, although not applicable in all situations. In some instances, there was a need for a broader system definition (e.g., Merrymeeting Bay, Albemarle Sound, Upper Chesapeake Bay, Winyah Bay, ACE Basin). Due to the mixed-stock composition of many data sets available for the assessment and the lack of data to define stock composition, analyses of mixed-stock data sets were also provided in the assessment to inform the condition of the coastwide metapopulation. Three regional metapopulations were also identified, based on reproductive strategy and genetic studies, and used for data sharing where life history information was limited. These were: the semelparous metapopulation (Florida to the Cape Fear River, NC), the southern iteroparous metapopulation (stocks north of the Cape Fear River to the Hudson River, NY), and the northern iteroparous metapopulation (stocks north of the Hudson River).

Selection of stock structure depends in part on the purpose of the analysis. For fishery assessment purposes, where the goals are mainly to determine whether overfishing is occurring and whether the stock is in an overfished state, ideally stocks are defined such that the abundance is determined by intrinsic factors like reproductive rates and mortality rates, and extrinsic factors such as immigration and emigration can be ignored. The decision by the SAS to carry out the assessment at the watershed scale aligns with this criterion. The criterion cannot always be applied, particularly in the case of mixed stock fisheries. The RP supports the decision to model the mixed-stock fisheries the way they were done because landings could not be assigned to specific populations. For other purposes, such as sharing life history parameters in data limited situations, grouping populations with similar life history characteristics makes sense. The RP believes the SAS's decision to define three geographically-based metapopulations is a practical choice that captures the major life history variability exhibited by American Shad populations as one moves north to south. The larger groupings may also become important for recovery planning purposes, where straying and meta-population structure become important determinants of overall productivity and abundance (e.g. Hanski 1999; Hanski 2004).

Overall, the RP found the information on American Shad population structuring very thorough and clearly presented. Stock structure decisions made by the SAS based on this information were sound.

2. Evaluate the thoroughness of data collection and the presentation and treatment of fishery-dependent and fishery-independent data in the assessment, including the following but not limited to items a-e below.

The RP commends the SAS for providing very thorough descriptions of data available for the assessment. For each of the 23 stocks delineated in the assessment, the SAS provided a narrative describing (as applicable): the habitat available for each stock; the rivers included in aggregated stocks; the presence of dams and barriers to fish passage; water quality; presence of invasive species; human-induced mortality from sources other than fishing; stocking history; fisheries management plans; and the fishery and management history. The RP found the information valuable for evaluating the assessment and believes it will be of value to others using the assessment results. The SAS also provided thorough descriptions of the many datasets available for assessing American Shad stocks, including information about life history parameter values (e.g., growth coefficients, natural mortality rates, maturity schedules), commercial and recreational fisheries data, adult abundance indices (both fishery-dependent and-independent), fish counts at dams, young-of-the-year abundance indices, and tagging data. The major data types evaluated for use in the assessment for each stock are summarized in Table 1. The table does not do justice to the amount of work that is put into monitoring the populations. For many stocks, there is more than one data source available under each heading. For example, more than one fishery-independent survey exists for several stocks. The Review Panel noted there were data pertaining to adult abundance and biological characteristics for all stocks.

In addition to the stock-specific data collections described above, the SAS also provided excellent summaries of data available for the coastwide metapopulation and mixed stock analyses. These include fishery-dependent data sources: U.S. Coastwide Commercial Landings, New Jersey Ocean Commercial Logbook Index, Atlantic Ocean Commercial CPUE Index, Delaware Mixed-Stock Fishery Landings, New Jersey Delaware Bay Commercial Logbook Index, Delaware State Delaware Bay Catch Rates, and Canadian Commercial Landings; and fishery-independent data sources: Maine-New Hampshire Trawl Survey, Rhode Island Coastal Trawl Survey, Connecticut Long Island Sound Trawl Survey, New Jersey Ocean Trawl Survey, Delaware Bay 30’ and 16’ Trawl Surveys, and the Northeast Area Monitoring and Assessment Program (NEAMAP) Mid-Atlantic Trawl Survey.

Overall, the RP was very impressed (and a little overwhelmed) by the amount of data available for assessing American Shad stocks. Descriptions of datasets in the Assessment Report are both comprehensive and thorough.

Table 1. Major data types available for the 23 American shad stocks included in the assessment.

		Fishery Dependent				Fish Independent				
System	Aging w/scales (S) or otoliths (O)	Biological Samples	Commercial Fishery Landings	Recreational Fishery Information	Catch Rates	Fishery Independent Adult Surveys	Adult Counts at Fish Passage Facilites	YOY indices	Adult Biological Samples	Tagging
Merrymeeting Bay			Historical				Y	Y		
Merrimack	S & O						Y			
Pawcatuck							Y			
Connecticut	O	Y	Y	Y	Y		Y	Y	Y	
Hudson	S	Y	Y	Y	Y	Y		Y	Y	Y
Delaware	S & O	Y	Y		Y	Y	Y	Y	Y	
Nanticoke	S & O	Y	Historical		Y	Y		Y	Y	
Susq & Upper Ches	S & O	Historical	Historical	Y	Historical	Y	Y	Y	Y	Y
Patuxent	S & O					Y			Y	
Potomac	O	Y	Y		Y	Y		Y	Y	
Rappahannock	S	Y	Y (bycatch)			Y		Y	Y	
York	S	Y	Y (bycatch)			Y		Y	Y	
James	S	Y	Y (bycatch)			Y	Y	Y	Y	
Albemarle Sound	S		Y	Y	Y	Y		Y	Y	
Tar-Pamlico	S		Y	Y	Y	Y			Y	
Neuse	S		Y	Y	Y	Y			Y	
Cape Fear	S		Y	Y	Y	Y			Y	
Winyah Bay	S	Y	Y		Y	Y			Y	
Santee-Cooper	S		Y	Y	Y	Y	Y	Y	Y	Y
ACE Basin	S		Y		Y	Y				
Savannah	S & O	Y	Y	Y	Y					
Altamaha	S & O		Y		Y	Y			Y	Y
St Johns	O			Y		Y		Y	Y	

2a. Presentation of data source variance (e.g., standard errors)

The assessment team used multiple methods to quantify the uncertainty of their analyses, including calculating coefficient of variations, parameter standard deviations, 95% confidence or credible intervals, bootstrapping, the delta method, likelihood profiling, and one analysis that partitioned the variance into both measurement and process error. The assessment team generally provided measurements of uncertainty (i.e., results, tables, and figures), which provided sufficient evidence to support their conclusions. The RP commends the SAS for presenting uncertainty of nearly all their analyses in a much more comprehensive way than was done in the 2007 assessment.

The coefficient of variation (CV), calculated as the ratio of the standard deviation to the mean, was one of the main methods the assessment team used to quantify uncertainty throughout the report. As described in Assessment Report Section 2.3.4.2, the CV was used to assess uncertainty for all abundance indices developed from fishery-dependent and fishery-independent surveys with sufficient uncertainty data. In certain cases (e.g., Potomac River Commercial Pound Net CPUE, Albemarle Sound CPUE index), the empirical data were unavailable to calculate the CVs. Besides using the CV to measure the uncertainty of the abundance indices, the assessment team also used CVs to measure uncertainty in ageing methods. One of the themes throughout the assessment report was to determine the accuracy of shad ageing methods. The assessment team compiled data from multiple sources to examine the accuracy of shad ageing based on different methods. To summarize the methods, they compared percent agreement between multiple readers, compared the difference between age estimates from scales and otoliths collected from the same fish, and compared estimates of scale age estimates to known age fish (ages were known based on tag data). In all cases, the precision of the various readers' accuracy was estimated using the CV of the percent agreement.

The next most common method used to report uncertainty in model parameter estimates was reporting of standard errors, or 95% confidence intervals (CIs) for the output from generalized linear models (GLMs). The assessment team used a variety of GLMs throughout the assessment to estimate total mortality from catch curves, evaluate survey data as a function of environmental covariates, develop new catch indices, and to standardize catch indices (area under the curve of daily catch rate versus time of year). In most cases, when multiple covariates could potentially be included, the most parsimonious model was selected using Akaike’s Information Criterion (AIC). The Review Panel appreciated this approach for reducing model complexity. The uncertainties for generalized linear models were presumably calculated from the variance-covariance matrix. Uncertainties were often displayed in figures but the captions often did not differentiate whether they represented standard errors or 95% CIs; however, the uncertainties from GLM output were rarely provided in tables. Nevertheless, the Review Panel felt the assessment team did an admirable job quantifying uncertainty throughout the assessment.

The estimates of uncertainty provided from the various population models were calculated in different ways depending on the different programs used (i.e., delay difference, ASAP, and stock synthesis). The delay difference model was implemented using the DLMtool library in R, and presumably uncertainty estimates were calculated using the variance-covariance matrix from the inverted Hessian. The Age Structured Assessment Program (ASAP) was the statistical catch-at-age-model used for the Albemarle Sound population. ASAP uses the Markov Chain Monte Carlo (MCMC) approach to estimate Bayesian posterior distributions of total biomass, spawning stock biomass, and fishing mortality. Posterior distributions were used to estimate the 95% Bayesian credible intervals (CRI) for these parameters. Perhaps the most thorough quantification of uncertainty was in the evaluation of the Potomac statistical catch-at-age model that was fit using the Stock Synthesis 3 (SS3) program. Asymptotic standard errors were calculated for parameters and derived values with the delta method. The assessment team then took the uncertainty analysis a step further by sampling from input data distributions to generate new sets of input data. The base model was then run with each of the bootstrap data files to generate uncertainty about model parameter estimates and derived values (see Assessment Report Section 3.10.8.5.4). Another method used with the stock synthesis model was likelihood profiling for the mean recruitment parameter. The model was run over a range of values to determine how well defined the parameter space is by the available data. Results indicate the lower end of the parameter space was well defined. Data appeared less informative at the upper end of the parameter space.

The assessment also used Bayesian credible intervals (CRI) to assess parameter uncertainty for two analyses. The first analysis was to estimate system specific von Bertalanffy growth model parameters. The posterior distributions for growth model parameters were estimated using Hamiltonian Monte Carlo methods and statistical significance was determined by evaluating 95% credible intervals (CRI) for overlap with zero. Similarly, the assessment subcommittee used a Bayesian hierarchical spatial analysis to explore possible underlying metapopulation trends in abundance. The analysis divides the variance into measurement error, which are input as CVs, and process error, which are estimated. Process error is due to interannual variation in catchability, which is often assumed to not occur (i.e., time-invariant catchability) when interpreting indices of abundance. Process error is assumed to be time-invariant. The Bayesian analysis was applied via MCMC to approximate the posterior distributions of parameters, including survey-specific process error, survey-specific catchability, and annual means of the hierarchical index.

The Review Panel also commended the assessment subcommittee's choice to use the power analysis to determine their confidence in being able to detect a trend in abundance depending on the observed levels of uncertainty in various surveys. Power analysis was a good approach and demonstrated how different surveys may need to improve their levels of certainty to detect the desired abundance trends. Improvements could be done either by increasing sample size, or decreasing the uncertainty by correlating the abundance with environmental covariates, and/or lengthening the survey(s) by continued observation.

One weakness regarding the presentation of uncertainty is that the best available data for estimating natural mortality in the assessment models was a maximum age estimator from Then et al. (2014). Unfortunately, the approach only provides a point estimate of total mortality and unrealistic levels of certainty for the model results. To account for this, the assessment subcommittee performed sensitivity analyses to determine how different estimates of mortality might affect results and found the model was generally sensitive to mortality estimates. However, the sensitivity analysis still did not propagate the uncertainty for the total mortality estimate into the abundance estimates.

2b. Justification for inclusion or exclusion of available data sources.

The SAS provided thorough reviews of the available data sources and strong rationales for the inclusion or exclusion of individual data sources. Both trend analyses and catch curve analyses played large roles in the assessment, and the selection criteria for the analyses were well described in the assessment report.

For the abundance trend analyses, the SAS identified four criteria for accepting candidate data sets: the TC members' recommendation that the data set accurately represents interannual abundance changes; a minimum time series length of 10 years for adult indices and 5 years for young-of-year (YOY) indices; an average of at least 5% positive annual observations over the time series being considered; and an average of at least 2 annual positive observations over the time series being considered. The RP agreed with the SAS that the selection criteria were appropriate given the data limitations, the short time frame many monitoring programs encounter American shad (e.g., spring spawning runs), and the understanding that many stocks have experienced very low abundance levels during the time series. The RP notes the use of power and sensitivity analyses in support of the trend analyses helps to address concerns that may arise from the stringency of the criteria. The use of the TC members' recommendations takes advantage of the detailed knowledge and experience individuals have with specific monitoring programs. For the trends in mean length analyses, the RP believes the decision to only use data sets for analysis that contained sex information and a minimum time series of 10 years with at least thirty fish sampled per year to be reasonable and well supported in the assessment report.

For catch curve analyses, two criteria were used to filter data sets for the analysis: a minimum of three age classes greater than or equal to age of full recruitment (see below) and at least 30 individuals across these age classes had to be observed for age. The RP agrees with the concern noted by the SAS that the criterion of at least three age classes may systematically filter out data sets with periods of higher mortality. The RP considers the threshold for number of observed fish to be a practical decision given the sample sizes available for certain populations, but notes the negative bias in the mortality rate that can occur when using age-based catch curves for *Alosa* increases at low sample size (Section 3.3). The RP also supports the decision that any monitoring programs with fewer than three consecutive years of data for a given sex and age structure were also dropped from the analysis, particularly given the precision of estimates from a single catch curve.

In addition to the wide-scale decision criteria, the SAS also had to make decisions about which data to include in models for each individual population, at times choosing to make decisions about whether or not to include a data set in a model based on whether it produced satisfactory results. This is also a reasonable approach because it provides a qualitative assessment of the consistency among various data sources available for the population. The basis for such decisions was also well described in the assessment report.

In summary, the RP commends the thorough review of both the available data sources provided by the SAS, as well as their justifications for decisions about whether or not to include data in the assessment.

2c. Consideration of data strengths and weaknesses (e.g., temporal and spatial scale, gear selectivities, ageing accuracy, sample size).

There were common strengths and weaknesses in the data gathered from fishery-dependent catch and fishery-independent surveys included in the stock assessment for the 23 river stocks and the ocean mixed stock fishery. The most common strength was that many of datasets had relatively long time-series to observe trends in abundance and mortality. Some of the fishery landings records extend back through the mid to late 1800s. Unfortunately, the effort data associated with landings records is much more recent, generally extending back only a few decades. Another strength of the data is that a wealth of biological and environmental covariate data has generally been collected with the fishery-independent data, as well as some of the fishery-dependent data. Biological data include information on fish length, weight, sex, and collection of ageing structures (scales or otoliths). Environmental data varied depending on the survey, though generally included water temperature, river flow, salinity, weather conditions, and tidal stage. These covariate data allowed the SAS to fit GLMs to standardize the catch indices and control for covariates throughout the time series. Another common strength of many of the datasets is they include information on both adult and juvenile populations. Where fisheries still exist, there is generally both fishery-dependent and fishery-independent survey data on the adult spawning population. Most of the surveys occur throughout the majority of the spawning season. Furthermore, for many stocks there are also surveys that include data on juvenile abundance (Table 1).

The two weaknesses of the datasets included in the stock assessment were: 1) most survey and catch data are indices and, alone, cannot be used to estimate true abundances, and 2) many of the surveys were designed to collect data on other species (i.e., striped bass or herring). The majority of the fishery-independent surveys used in the stock assessment annually sampled the same fixed index sites rather than using a stratified random sampling design. This poses a problem because it is probable that American shad will change their spatial distribution inter-annually depending on environmental conditions (Lee and Rock 2017). As a result, sampling the same fixed stations only allows the stock assessment the ability to estimate an index and to observe the trend in abundance, and mortality, through the time series. In contrast, if the surveys were to use a stratified random sampling design, perhaps with a subset of fixed index sites, they could use an occupancy model to determine which sites were reasonable habitat for adults and juveniles. Related to the inability to estimate abundance, there is relatively little tagging data available for the surveys. Mark-recapture data provides a valuable piece of information necessary to estimate population abundances, especially over relatively short time periods when the population can be considered closed. However, the Review Panel acknowledges the challenges in tagging delicate juvenile American shad. A discussion about ways to incorporate tagging data into the stock assessment is provided in the research recommendations.

With the dam passage datasets, another weakness is that neither the dam passage efficiencies or the percentage of the population that spawns downstream of the dams has generally been estimated, which can bias population estimates. Dam passage efficiency rates likely vary relative to dam discharge and river flow rates. Efficiency rate is often unknown. Furthermore, it is likely a proportion of the American shad population spawns downstream of many dams. For example, a population of American shad persisted and produced sustainable runs in the Connecticut River from the time the Holyoke Dam was built until fish passage was provided in 1975. This suggests spawning may occur downstream of the dam, in which case the fish lift count would not provide estimates of the true population size.

One final common weakness of the data in the stock assessment was very little data pertaining to the recreational fishery catch. In general, it is thought the recreational fishery for American shad has declined considerably in recent decades. However, for the most part, the potential impact of recreational fisheries on the population is not quantified, with the exception of a few creel surveys. Even the creel surveys were generally relatively limited in scope and often occur at a single access point.

Age determinations were based mostly on scales, a traditional method (Cating 1953). Scale ageing is known to underestimate true ages of older fish, and for this reason otoliths have become increasingly accepted as a more reliable chronometric structure in fishes. A disadvantage of otoliths is that lethal sampling is necessary, which can be problematic in systems with depleted populations. However, the Technical Committee has committed to acquiring otoliths for ageing. A comparison of ageing known-age fish using scales vs. otoliths found that uncertainty from scale reading is about twice that of otoliths (Figure 2). With more training, better otolith reading is likely, and workshops have been suggested as part of future work.

The SAS provided a thorough evaluation of the age determination methods for both scales and otoliths, ultimately concluding otoliths currently provide the better age determinations. The RP accepted the conclusion, while noting an important use of age composition data is for estimating mortality rates. Information about the age-at-maturity (available from both scales and possibly from otoliths) and number of previous spawnings (currently difficult to obtain from otoliths) can aid in mortality rate estimation by allowing an age class to be subdivided based on the age-at-maturity and the number of times a fish has previously spawned. These are key determinants of the survivorship to a given age because mature fish are subjected to increased mortality through exposure to in-river fisheries, passage and dams, and the energetics associated with migration and spawning. This topic is discussed more fully in the research recommendations.

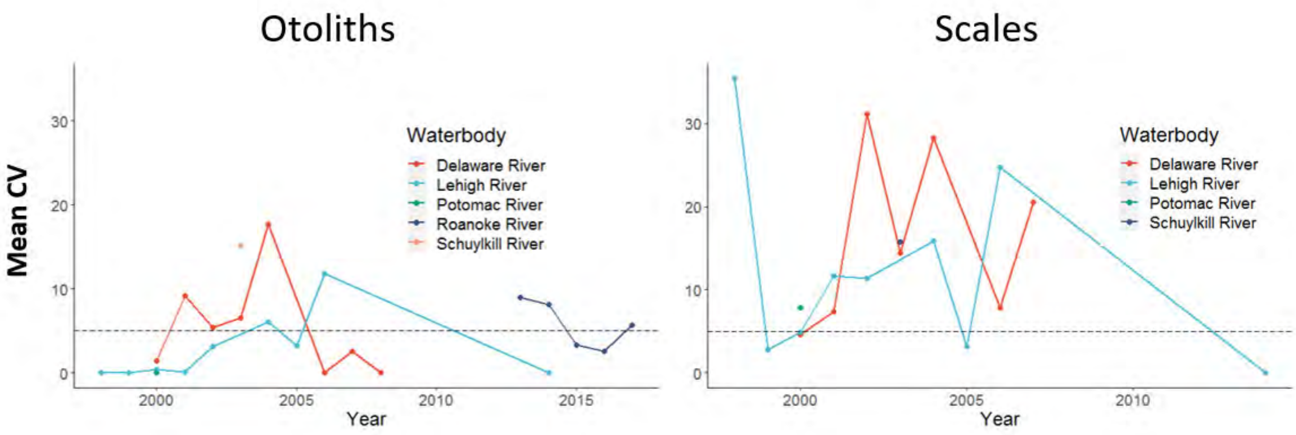

Figure 2. Accuracy and precision of otolith vs. scale age determinations from known-age fish, measured with CVs. Acceptable CV is within 5% (dashed lines). Scale uncertainty is double that of otoliths. Re-drawn from the assessment report.

A few other weaknesses regarding juvenile data were identified and also recognized by the SAS. Weaknesses included the fact that overall, juvenile (YOY) data were lacking for most of the southern semelparous stocks, and trends in juvenile abundances were unknown for most systems/stocks. Certain data sets, notably in the Hudson and Delaware, proved quite useful. However, no juvenile index was felt to be adequate to aid in estimating juvenile mortality at sea, i.e., between the time of first egress from natal habitats and first return as spawners. Note evidence exists showing subadults accompanying adults to the spawning grounds (Limburg 1998). Estimating juvenile mortality at sea was a research recommendation by the SAS and the RP agreed it is important.

Maturity data are only available currently from in-river surveys. No information currently exists at sea to evaluate maturity at age, or within individual stocks or regions. The RP recommends the SAS consider taking advantage of the Northeast Area Monitoring and Assessment Program (NEAMAP) Mid-Atlantic Trawl Survey, and other nearshore trawl surveys where shad occur, to sample adult maturity as well as genetic composition in mixed assemblages at sea.

Additionally, the data on semelparous runs were somewhat more limited than for iteroparous runs, particularly how many individuals actually reach the spawning grounds and successfully reproduce. Improving semelparous run size estimates was suggested as a research recommendation. If such data existed, methods of analyses used on semelparous Pacific salmonids could be applied.

2d. Calculation and/or standardization of abundance indices.

The RP commends the thorough process by which abundance indices were compiled for the assessment. The TC presented a total of 175 series, which included YOY and adult surveys using various gears such as gillnets, seines, and electrofishing. Surveys that encountered shad were reported, although not all were designed to target the species. Recreational and commercial fishery CPUE datasets that encountered shad were also considered. The RP believes the SAS and TC are the best qualified groups to determine the validity of the indices for shad. In many situations, regression models were used to standardize series to account for environmental covariates, when available, that may affect catchability. The RP believes these are best practice for standardizing suitable indices of abundance and standardizing to control for catchability.

As a future research recommendation, the RP suggests indices could be standardized using a hierarchical approach. For example, conditions in the Chesapeake Bay main stem, e.g., water flow and temperature, can affect catchability in individual river systems. Standardization approaches that include Bay-wide effects may be able to inform individual river systems that do not have environmental covariates data.

2e. Estimation of bycatch.

Bycatch of shad in the assessment was primarily quantified for the mixed stock ocean fishery because bycatch in the rivers is rarely recorded. The NMFS Northeast Fisheries Observer Program (NEFOP) began in 1989 and provided incidental catch estimates in the mixed stock ocean fishery by fleet from 1989-2017. Fleets included in the analyses were those sampled by NEFOP and stratified by region fished (Mid-Atlantic versus New England), time (year and quarter), gear group, and mesh size. Using the combined ratio method (Wigley et al. 2007), the assessment subcommittee estimated the total incidental catch across all fleets during the time period. They found both the total annual incidental catch and the corresponding estimates of precision (CV) varied substantially among years (Assessment Report Table 272, Figures 354 and 355). Unfortunately, because sufficient genetic information is not currently available, it was not possible to attribute incidental catch to individual stocks. Using single nucleotide polymorphisms (SNPs) rather than microsatellites may provide increased ability to differentiate stocks (see research recommendations). Furthermore, because coastwide estimates of absolute abundance were not available, it was not possible to estimate the discard mortality that incidental catches represented.

Bycatch in state waters was largely unquantified. Known bycatch fisheries occur in New York and to a lesser degree, in the New England states (Maine to Massachusetts). In 2014, river herring and shad catch caps were implemented in both the Atlantic mackerel and herring fisheries to reduce river herring and shad bycatch. A mixed-stock bycatch fishery that includes American shad occurs in Chesapeake Bay. This bycatch is likely discarded and not quantified. The Delaware DFW discontinued monitoring of American shad bycatch during the commercial striped bass season because no bycatch had been reported over a 10-year period from the striped bass fishery. The recent absence of shad bycatch is due to a voluntary change to larger gill net mesh sizes used in the striped bass fishery in order to target larger fish. Virginia allows a bycatch only fishery for American shad. Virginia bycatch data were reported and included in coastwide totals. Because discards in state waters were unquantified or undocumented, the assessment team generally could not include them in models. However, in models that required discard mortality rates, the assessment subcommittee did a good job of documenting these methods. Since there are no studies on American shad discard mortality rates in commercial fisheries, the assessment assumed values based on generally observed fishing practices. A mortality rate of 100% was applied to commercial gill net discards while a rate of 20% was applied to commercial discards from pound nets. The lower pound net rate was selected because fish captured in pound nets are held in the water column while trapped and then can be released following minimal interaction with the gear.

In general, the RP finds the analytical approaches, analyses, and estimates were the best possible, given the data. The RP noted an improvement in bycatch data availability since the previous assessment. Bycatch estimation methods were well documented, and target fisheries where American shad bycatch occurred were correctly selected.

3. **Evaluate the methods and models used to estimate population parameters (e.g., Z, biomass, abundance) and biological reference points, including but not limited to:**

    a. **Evaluate the choice and justification of the preferred model(s). Was the most appropriate model (or model averaging approach) chosen given available data and life history of the species?**

    b. **If multiple models were considered, evaluate the analysts' explanation of any differences in results.**

c. **Evaluate model parameterization and specification (e.g., choice of CVs, effective sample sizes, likelihood weighting schemes, calculation/specification of M, stock-recruitment relationship, choice of time-varying parameters, plus group treatment).**

d. **Evaluate the diagnostic analyses performed, including but not limited to:**

   - **Sensitivity analyses to determine model stability and potential consequences of major model assumptions.**

e. **Evaluate the methods used to characterize uncertainty in estimated parameters. Ensure the implications of uncertainty in technical conclusions are clearly stated.**

The SAS used a wide variety of analytical tools to estimate population parameters and reference points, including: trend analyses (power analyses, ARIMA models, and Mann-Kendall models); catch curve models to estimate total mortality rates; habitat assessment and simulation modelling; Thompson-Bell spawner biomass per recruit models; delay-difference models; and age structured assessment models (ASAP and SS3). The rationale for each approach was well described by the SAS. Each analysis provided different information to aid in the management of each shad stock depending on their unique characteristics, management situation, and data availability.

The trend analyses provide information about whether survey abundance, mean length, and/or mean length-at-age are increasing or decreasing. The analyses provided information regarding whether populations are responding to management actions (e.g., fishery closures) since 2005. The Thompson-Bell spawning biomass per recruit model was used to develop instantaneous total mortality biological reference points for American shad, against which the estimates of the total mortality rates could be compared. The instantaneous total mortality rate was estimated using catch curve models. The models use age composition data from individual years. Ages are one of the most widely available data types for American shad and provided a standard method that could be applied to many of the stocks. The habitat assessment and simulation modeling provided a mechanism to evaluate how dams, so prevalent in the catchments used by American shad (and generally across eastern North America), may have reduced the potential size of individual populations throughout their range. Finally, for stocks with open fisheries, three stock assessment models were used: delay-difference models (appropriate in the absence of age composition data); ASAP (a well-vetted, age-structured stock assessment package), and Stock Synthesis 3 (also a well-vetted, age-structured assessment model with a greater variety of options than ASAP). The models were designed to provide estimates of abundance, biomass, and fishing mortality rates; and to provide estimates of stock status.

In-river American shad fisheries harvest almost entirely mature fish as they are returning to the rivers to spawn. In certain analyses, the SAS chose to define selectivity based on maturity, analogously to gear selectivity. While the RP accepted this approximation for the assessment, they noted size at maturity and size at gear selection are not the same. Gear selectivity is typically modeled using the separability assumption, $F_a = s_a F$, where the instantaneous fishing mortality rate for a given age class, F_a, is a function of the instantaneous fishing mortality rate for a fully-selected age class, F, and the age-specific selectivity, s_a. In this situation, when F increases or decreases, the fishing mortality rate for the partially selected age classes also increases or decreases. However, this is not the situation when only mature fish are harvested; in this case the immature component of the age class remains unfished. It is not available to the fishery. The implications of this approximation are discussed further in the Sections 3.2, 3.3, and 3.6.

The RP was impressed by the number of analytical methods undertaken by the SAS. The RP found that all the analyses are complementary, while addressing different questions. Comments pertaining to each specific model are provided below.

3.1 Trend Analyses

Using the fishery-dependent catch data, and fishery-independent survey data, the trends in American shad abundance for each of the stocks along the Atlantic coast were analyzed with Mann-Kendall trend analysis. The purpose of the Mann-Kendall trend analysis (Mann 1945, Kendall 1975) is to assess whether there is a monotonic upward or downward trend in abundances over time. This is similar to the more familiar linear regression model, generally used to test if the slope is different from zero. The difference between the Mann-Kendall and a linear regression is that the Mann-Kendall test is non-parametric, and therefore not restricted to the assumption of normality like the linear regression. This makes the Mann-Kendall more flexible for estimating these kinds of data. However, it does not mean the Mann-Kendall test is assumption free. The following assumptions underlie the Mann-Kendall test:

- When no trend is present, the measurements are independent and identically distributed
- The measurement observations are unbiased and provide representative samples of the underlying population over time

The RP noted that because there is potential for violation of both assumptions, the Mann-Kendall tests conducted in the assessment should be viewed as exploratory analyses. The first assumption is likely violated because fish are experiencing similar conditions within the same river through time. Thus, even though there may not be a trend, they are not completely independent from each other. For example, climate change can result in regional changes in temperature and precipitation patterns through time that could affect shad spawning and rearing habitat. Furthermore, as noted in the stock assessment report, some of the sampling methods have the potential to be biased. The fish passage observations, in particular, are known to be biased because shad do not generally migrate through fish passages effectively and are therefore not representative samples of the underlying population. Furthermore, as previously noted, an unknown proportion of the population may spawn downstream of dams and it is possible the proportion may change inter-annually. Such changes would greatly bias the time series. These uncertainties in the trend analysis were acknowledged in the assessment.

The RP recommends future assessments take advantage of more advanced time-series analysis methods to account for potential non-stationarity in the data and the potential regional autocorrelation. The RP recommends future assessments use the Box-Jenkins method (Box and Jenkins 1976) to analyze time-series. The Box-Jenkins method is a systematic method of identifying, fitting, checking, and using an autoregressive, moving average (ARIMA) time-series model. The first step in the process is to determine if the time-series is a stationary stochastic process, implying the mean and variance are constant throughout the time-series. Stationarity can be tested using the Augmented Dickey-Fuller test and the KPSS test. If the time-series exhibits non-stationarity, this can be corrected using a lagged time-series differencing or fitting a least squares regression and then fitting the Box-Jenkins model to the residuals of the regression. Once we have a stationary time series, the final step is to fit the ARIMA model with the most appropriate auto-regressive and moving average parameters.

Another alternative suggested by the RP for future assessments was to consider using a multivariate time-series analysis, such as Dynamic Factor Analysis (DFA). DFA provides the ability to look for a set of common underlying processes among a large set of times series (Zuur et al. 2003). The DFA approach was recently used to separate the effects of smaller-scale local drivers of salmonid population dynamics from regional and global drivers that are shared among populations (Jorgensen et al. 2016, Ohlberger et al. 2016). Since adult shad all migrate to the continental shelf during the winter months, intuitively there will be common factors (e.g., North Atlantic Oscillation) that drive population dynamics of each of the river stocks. The DFA will provide a means to parse regional and local sources of variability, and potentially identify the scales of spatial autocorrelation between different stocks. A function to conduct DFA is available within the Multivariate Autoregressive State-Space (MARSS) modeling package in R (Holmes et al. 2012).

3.2 Thompson-Bell Spawner Biomass Per Recruit Model

The SAS chose to use a modified Thompson-Bell SBPR model to calculate per-recruit reference points. The model inputs include estimates of natural mortality rates, fishery selectivity, maturity schedules, weight-at-age, and knowledge of the timing of fishing mortality, natural mortality, and spawning relative to each other. SBPR values estimated for each of the three metapopulations (northern iteroparous, southern iteroparous, and southern semelparous) were used for all stocks within each metapopulation. The RP considered this a practical decision given the data limitations for many stocks.

The SAS undertook many sensitivity analyses to evaluate model assumptions and data inputs, including an egg-per-recruit analysis (fecundity-at-age is substituted for weight-at-age), as well as alternate assumptions about natural mortality rates and the relative timing of fishing mortality, natural mortality, and spawning. They found the Z40% reference values were sensitive to the assumptions about life history parameters (e.g., natural mortality rates), though not to the relative timing. The RP considered the analyses to be very thorough.

The RP questioned whether the Thompson-Bell model fully matched anadromous *Alosa* life history and fisheries. Within the model, for a given fishing mortality rate, *F*, the number of fish at age *a* is given by:

$$N_a = N_a e^{-(cp_a F + dM)},$$

where *c* is the fraction of fishing mortality within a year before spawning, *p* is the fraction recruited to the gear at age *a* and *d* is the fraction of natural mortality within a year before spawning. The SBPR for a given level of F, $SBPR_F$, is then calculated as:

$$SBPR_F = \sum_a N_a m_a w_a$$

where N_a is the number at age *a*, m_a, is the age-specific maturity probability and w_a is the mean weight at age *a*. Because the fisheries target mature fish, the SAS set p_a equal to the proportion mature. The RP questioned this assumption and its effect on survivorship to a given age because, for partially mature age classes, the immature component is not subjected to fishing pressure. For this reason, survivorship would better be calculated by tracking the mature and immature components separately, with the numbers-at-age calculated as the sum of the mature component of the previous age class (decremented by both fishing and natural mortality) and the immature component of the previous age class (decremented only by natural mortality). The RP noted that this issue was addressed in an SBPR model specific to *Alosa* life history (Gibson and Myers 2003a, 2004), that has been used in assessments for river herring (ASMFC 2012a,b; Gibson et al. 2017). Notwithstanding this issue, the RP accepted the Thompson-Bell model as a reasonable approximation for estimating BPR and accepted its use for the Northern and Southern iteroparous metapopulations.

The RP questioned the application of the Thompson-Bell model for the semelparous metapopulation, as well as the use of a Z-based reference point. Because all fish die after spawning, the natural mortality rate on mature fish after spawning is infinite, whereas the total mortality rate on immature fish is simply the natural mortality rate. This can be modeled using the *Alosa*-specific SPR model. The RP expressed a preference for a reference fishing mortality rate over a reference total mortality rate because of the difference in natural mortality rates in the immature and mature components of each age class. An equivalent F-based reference point corresponding to Z40%, would be the fishing mortality rate that harvests 60% of the female spawner biomass annually. Exploratory analyses undertaken at the workshop showed the Thompson-Bell model as applied did not return this value. For the reasons above, the RP did not accept the use of this model or the use of a Z-based reference point for semelparous stocks.

For the delay-difference and SCAA models, the reference points used for status determination were calculated internally in the model. This ensures the assumptions (e.g., selectivity) used in the reference point calculation are consistent with those in the estimation model. The RP believes this is the best approach. For SCAA, the F40% reference point was the fishing mortality reference point, analogous to the Thompson-Bell model. The biomass proxy reference point was calculated from fishing at F40% and recruitment equal to the estimated mean recruitment. For the delay-difference model, only the exploitation rate was used for status determination. The exploitation rate at maximum sustainable yield (U_{MSY}) was used as the reference point, since density-dependence is built in and estimated in the model.

3.3 Total Mortality Estimators (catch curves)

The SAS used catch curve models to estimate the instantaneous total mortality (*Z*) from the available age composition data, with the objective of having a standardized approach for generating total mortality estimates to compare against per-recruit reference points. Catch curves are likely the simplest age-structured model in that they use a single year of age composition data to estimate a single parameter, *Z*. They typically require the assumptions of constant, non-selective mortality rates for a closed population with constant recruitment (Ricker 1975), conditions that are not typically met for most species and assessments. It is also assumed the sampling of the age structure and methods for ageing are unbiased. Catch curves are well-studied: several methods have been developed for fitting the models, and there has been extensive testing of the methods via simulation (e.g., Dunn et al. 2002; Smith et al. 2012; Millar 2014). Because of their restrictive assumptions, Quinn and Deriso (1999) recommended against the use of catch curves if alternative models are available. However, the RP considered the use of catch curves appropriate in the assessment because the method could be applied to all of the stocks for which age composition data are available, does not require estimates of abundance or landings, does not require a continuous time series, and can be applied in situations where fisheries are closed. Additionally, the SAS did use more complex models where appropriate in the assessment, and compared results to the catch curve results.

The SAS used three methods to analyze catch curves: Chapman-Robson estimators (Chapman and Robson 1960), weighted linear regressions (Maceina and Bettoli 1998), and generalized linear mixed models with random intercepts (Millar 2015). The last method relaxes the assumption of constant recruitment. As discussed by the SAS, the Chapman-Robson estimator has proven reasonably robust to assumption violations, while weighted linear regression has been shown to perform about as well as the Chapman-Robson estimator under some configurations. The SAS presented the results from all methods, but chose to use the weighted linear regression results for their final status determinations. The RP accepted this as a practical decision.

The SAS chose not to develop estimates using repeat spawning data given concerns with the reliability of these data expressed by peer reviewers of the most recent river herring assessment (ASMFC 2012a,b) and through analyses within the assessment (see Section 2.c). The RP accepted this decision, particularly given many of the age composition datasets were developed by reading otoliths from which information about repeat spawning cannot be obtained. However, they noted for datasets developed by reading scales, the uncertainties associated with interpreting spawning marks are not completely avoided by using only age data because age determinations from scales involves counting spawning marks on the scales.

As described by the SAS, because most sampling occurs in-river during spawning runs and therefore only samples mature fish, the resulting mortality estimates contain no information on the mortality levels of juvenile fish which could be unsustainable even if mortality of spawning adults is sustainable. This is an important limitation to consider when applying results and is well described by the SAS.

The RP agreed with the SAS decision not to split total mortality into fishing and natural mortality components due to uncertainty in other non-riverine fishing components of mortality (i.e., bycatch mortality, barrier mortality, water quality mortality). The SAS also correctly chose not to develop estimates for semelparous stocks because the age composition data would be highly reflective of the maturity schedule rather than mortality. Fish in semelparous stocks spawn once and then die.

While catch curves are a well-studied assessment model, simulation testing has been based on general marine fish data and life history. As discussed, age composition data collected for American shad are almost entirely representative of mature fish. Immature fish that remain in the ocean are not subjected to the effects of in-river fisheries, dams or other stressors in fresh water. When fish mature over several age classes, the in-river abundance in a partially mature age class (x) is the sum of the number of fish that have matured at an earlier age that survived to age-x (the survivorship of which depends on when they matured) and the number of fish that are maturing at age-x (again with a different survivorship). During the review, the RP brought to the attention of the SAS a very recent simulation analysis about the use of catch curves with *Alosa* life histories using alewife as the model species (Billard 2020). The analysis used a life cycle model to project numbers by age and previous spawning history forward through time. Variability was included in the stock-recruitment relationship and maturity schedules; and simulations were done with different fishing mortality rates and sample sizes. The simulations show both the high variability in catch curve estimates of Z given this life history, as well as a bias that exists because immature fish entering the spawning population at later ages are not subjected to the same mortality rate as mature fish (Figure 3). This bias becomes more prevalent as the mortality rate for mature fish increases and as sample size decreases. An alternative method of fitting the catch curve that partitions the data based on age-at-maturity and fits a separate intercept for each age-at-maturity and a common slope across each of sub-group (Billard 2020) reduces the variability in the estimates and nearly eliminates the bias. This second model can only be fit if there is information about the previous spawning history.

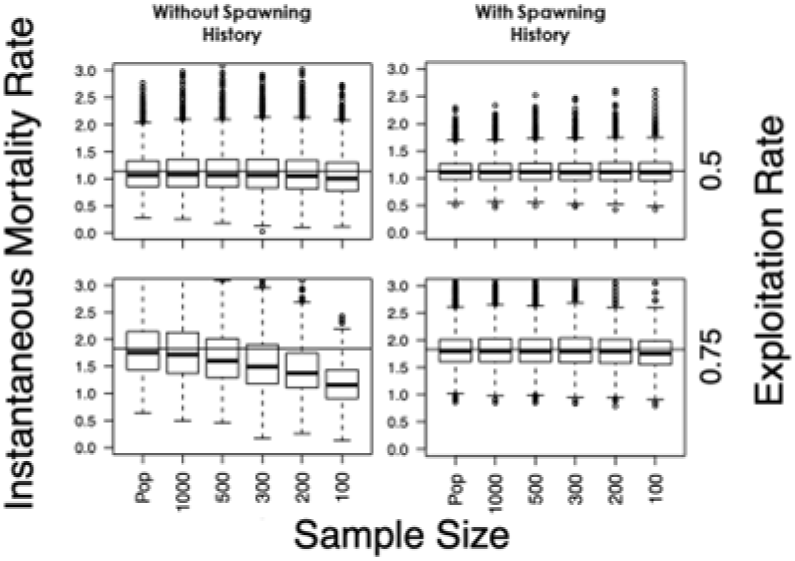

Figure 3. Boxplots comparing instantaneous total mortality rate (Z) estimates obtained using two methods of fitting catch curves using Poisson generalized linear models: using age as the independent variable (left column), and using the number-of-previous-spawnings and age-at-maturity as the independent variables (right column). The two rows show results using two simulated exploitation rates: 0.5 and 0.75. Catch curve regressions were fit to simulated data using sample sizes of all fish (Pop), 1,000, 500, 300, 200 and 100 fish, depicted on the X-axis of each panel. Each individual boxplot shows the results of 3,750 attempted estimates of Z for each sample size and exploitation rate combination. The horizontal solid line represents the true instantaneous total mortality rate in each panel. Adapted from Billard (2020).

The results of the Billard (2020) analyses are not immediately applicable to the American shad catch curve analyses due to differences in the maturity schedules, longevity, and life history variability, however, given the process generating the numbers-at-age in the samples is very similar, a similar pattern would be expected. The RP did not recommend the second catch curve model be used in the assessment because scale-based ages are not available for many of the stocks, and because of uncertainty in determining the previous spawning history (see Section 2.c). The analyses do illustrate how resolution of the age determination issues with scales could improve stock assessments for American shad as well as a bias to consider when interpreting the presented results.

The SAS provided 95% confidence intervals associated with each total mortality rate estimate, a method of characterizing uncertainty the RP considered appropriate for this parameter. The RP noted the confidence intervals were quite wide for most estimates. This uncertainty was not carried forward in the final status determinations, but should be considered when applying the results.

Overall, the RP found the catch curves methods used in the assessment were thoroughly explored by the SAS, limitations of the methods were well described in the Assessment Report, and the decisions made by the SAS were practical given the available data and the issues with age determinations. The RP accepts the use of catch curve models in the assessment for these reasons, while recommending caution when determinations indicate mortality rates are below a threshold, due to the potential bias and deviations from the true rates demonstrated via simulation.

3.4 Habitat Assessment and Simulation Modelling

Dams have been recognized as a persistent threat to American shad migratory range and spawning potential since the 1830s (Walburg and Nichols 1967; Limburg and Waldman 2009). In many river systems, dams are the greatest contributor to reduced spawning habitat and population declines (Beasley and Hightower 2000; Kocovsky et al. 2009). Because American shad are iteroparous through the northern portion of their range, they are subject to increased mortality at dams before and after spawning that can limit abundance and age structure. Although many dams have been retrofitted with fish passage improvements, their resulting passage efficiency has mostly been poor (Haro and Kynard 1997; Moser et al. 2000; Sprankle 2005; Haro and Castro-Santos 2012).

To address the role dams play in limiting American shad stocks, the SAS used a habitat assessment and population simulation model (Stich et al. 2019). Historical spawning habitat was quantified for individual rivers by characterizing 21,113 dams and 485,618 river reaches based on river width, distance from seawater intrusion, and slope as a proxy to natural migration barriers. The determination of habitat was limited to reaches with channel widths greater than 15 m. The amount of habitat was also validated with input from local experts to determine where natural barriers, environmental conditions, or water quality limit spawning habitat. Within each habitat reach, horizontal area was estimated using the equation:

$$A = 0.8 * wl,$$

Where *l* = mean segment length, *w* = mean reach segment width and the area estimate, *A*, is limited by a 20 % fluctuation in river level unavailable as habitat along the margins of rivers. Mean channel width, *w*, is estimated as a function of the mean annual discharge, where,

$$w = k * Q * b$$

Here, *Q* = discharge, *k* and the exponent *b* are region specific coefficients. Ponds and lakes were not included in the analysis because American shad do not use this type of habitat, although a landlocked shad population has existed in Millerton Lake, California in the upper San Joaquin drainage since 1955 (Hasselman et al. 2012). The model was used for 125 Atlantic Coast rivers ranging from the St. Johns River, Florida to the St. Lawrence River, Quebec.

The SAS simulated the population of American shad from each river using a model, *anadrofish* (Stich et al. 2020), developed with the software package R. The model was developed in response to the 2007 American Shad Stock Assessment Review to characterize dam-driven factors of *M* with the expectation that *M* currently exceeds *F* and is limiting population recovery. The model allows testing of population sensitivity to fishing, dam passage, and life-history parameters. Using the *anadrofish* model, American shad spawning populations were simulated using life history parameters from the three metapopulations. Three broad habitat scenarios were modeled: 1) no dams or historical habitat, 2) current dams with no passage, and 3) existing dams with optimistically high passage efficiencies (e.g., 95 % juvenile survival).

Model results indicated American shad have lost nearly 40% of their range wide historical habitat to dam construction, but that retrofitting current dams to allow passage only results in small increases in spawner potential. Based on model output, the SAS found that American shad habitat is 42, 30, and 28% of what it was historically in the northern iteroparous, southern iteroparous, and semelparous metapopulation regions, respectively. The model also revealed the use of optimistically high upstream and downstream fish passage rates at dams results in only small increases in spawner production potential relative to rivers that are wholly inaccessible upstream of dams (no passage). For example, in the Susquehanna River, Maryland, over 90% of the spawning habitat is upstream of Conowingo Dam (rkm 16.1). Given optimistic values of adult upstream (50%) and downstream passage 20% mortality from downstream iteroparous migrants at all dams, theoretical spawner numbers decrease from 7.5 million in undammed scenarios to about 0.5 million under current scenarios with only slight increases from dam retrofits. Therefore, retrofitting current dams provides marginal benefits compared to dam removal, especially dams lower in river systems.

Although the model has not been through extensive peer review, it is based on previously published models used to address dam-mediated effects on American shad spawning habitat (e.g., *shadia*; Stich et al. 2019). The large collection of river specific models and characterization of dams and river segments is impressive. The current *anadrofish* model continues to be refined. In particular, the model applies static passage efficiencies that could be refined, especially for downstream adult passage where little information is available.

The *anadrofish* model is river specific but, as applied here, relies on metapopulation life history parameters. Finer grained life history parameters might better reflect regional differences in fish passage efficiencies, though the overriding message is unlikely to change. Unlike the previously used *shadia* model, *anadrofish* does not allow for dam specific assessments of fish passage or climate-informed life-history estimates. Further, with respect to the 20% river fluctuation applied to the habitat area model, climate effects are likely to have unequal effects on discharge and subsequent spawning habitat area range wide.

The RP commends the SAS for investigating American shad in relation to broad scale habitat modifications resulting from widespread dam construction. The habitat model was innovative and very informative regarding the benefits of fishways versus dam removal. Although some values might change for individual rivers when examined more closely, the approach is a good one for assessing impacts of anthropogenic activities other than fishing. The results are useful to managers in mitigating the effects of dams on a broad scale and for managing the deleterious effects of dams within individual rivers and river segments.

The SAS analysis here examined the influence that dam removal could have on American shad across the landscape. Brown et al. (2013) found that total passage efficiency of shad on the Susquehanna, Connecticut, and Merrimack rivers was < 3%, and recommended dam removal where possible. Recently, dam removal has been federally mandated for the sole purpose of restoring fisheries (Crane 2009). Over the coming decade nearly 300 dams will require relicensing across the United States, nearly half of these in the Northeast (Fox 2020). Relicensing of dams through the Federal Energy Regulatory Commission (FERC) offers opportunities to remove large mainstem dams that are particularly harmful to the recovery of American shad and other fishes (Chaffin and Gosnell 2017). This analysis underscores the need for opportunistic yet strategic dam removal as a viable option to rehabilitate American shad stocks.

3.5 Delay Difference Model

The RP views the SAS decision to use the delay-difference (DD) model as a practical choice given the data limitations for many of the stocks at hand. The DD model is of intermediate complexity to analyze catch and index data (without age or length composition) while also incorporating time lags between spawning and recruitment. Only the spawning biomass is modeled. There is the assumption of knife-edged maturity at the age corresponding to length at 50% maturity. Recruitment is defined at this age as well. The code for the delay-difference model was obtained from the DLMtool R package, containing a suite of data-limited modeling procedures used for management strategy evaluation.

During the meeting, the code was modified to incorporate alternative assumptions about population depletion in the first year of the model. The default unfished assumption is unlikely to hold in Atlantic coastal systems because of their fishing histories, long before the first year in the modeled time series. Since density-dependence is built into the DD model, the initial state can have a strong effect on the magnitude and precision of biomass estimates. It is unlikely the initial depletion can be reliably estimated. Instead, likelihood profiling was used by the SAS during the meeting to explore initial depletion assumptions.

Uncertainty in the model fit was evaluated by sampling the covariance matrix of estimated parameters and generating confidence intervals in the estimated biomass and exploitation rate (U) time series. If the model could not reliably estimate the scale of the population, this would be manifested in large confidence intervals in biomass and a range of U anywhere between 0-1, indicating poor model performance. Sensitivity analyses would typically show increasing biomass estimates with larger values of M. Significant overlap in the confidence intervals with alternative values of M would suggest model uncertainty is much more important than parameter uncertainty.

Together, these two steps (profiling and covariance matrix sampling) were used to evaluate assumptions in model structure and performance in order to determine whether the model was suitable for stock status determination. Within the model, the stock status can be determined by calculating the mean U/U_{MSY} in the terminal 3 years, where U_{MSY} is estimated from the model. The RP recommended this approach for the current assessment.

Overall, the RP felt the current implementation of the DD model was at present suitable for shad, although several model improvements can be made for future assessments. For example, the DD currently models recruitment, spawning, pulse fishing, and natural mortality in this order within each time step. To reflect shad biology, the spawning and fishing steps should be reversed in the model (Carruthers et al. 2012). If spawning occurs after fishing, then the predicted recruitment, after accounting for time lags, from the Beverton-Holt model would be:

$$R_{y+k} = \frac{\alpha B_y (1 - U_y)}{1 + \beta B_y (1 - U_y)}$$

instead of

$$R_{y+k} = \frac{\alpha B_y}{1 + \beta B_y}$$

where R is the recruitment of age k, B is the spawning biomass at the beginning of year y and U is the exploitation rate.

The Panel also questioned the suitability of DD models for semelparous stocks because the equations used to derive the delay-difference equations assume iteroparity (Hilborn and Walters 1992). Assuming the correct order of operations within the time step, the RP suggested setting natural mortality to be near infinite in an updated model, such that all mature fish die after spawning. Thus, all fishing would be limited to recruits that return to spawning grounds. While there is no guarantee of reliable model performance, especially with the semelparous modification, the RP believes these modifications are worth exploring as future research. Currently, the RP agrees with the SAS that the current DD model is not appropriate for semelparous stocks.

The current implementation of DD is also conditioned on fishing effort, calculated as the ratio of the catch and index. This limits the model to years when both data types are available. In actuality, the catch series is much longer than the index series for most stocks. It would be appropriate to incorporate longer catch time series and to condition the model on the catch. If past historical catches have been much larger than in recent times, then catch history will provide a much different perspective on stock productivity than with truncated catches.

While the DLMtool implementation of DD conditions on effort (effort is known and catch is predicted in the model), the companion package MSEtool contains a more flexible version of DD that can condition on the catch (catch is known and effort is predicted) and use a longer catch series. MSEtool also provides convenient tools such as likelihood profiling and retrospective analysis that facilitate the diagnostic procedures the SAS undertook here. The RP recommends the SAS consider MSEtool for future assessments and collaborate with developers of the package to include features to better account for shad life history.

3.6 Age Structured Assessment Models (ASAP and SS3)

The RP commends the SAS for the development of statistical catch-at-age (SCA) models where appropriate as a major methodological advancement in the assessment of shad stocks. Although SCA models were considered in systems with active fisheries, many of the fisheries are on semelparous stocks. The RP agreed with the SAS decision to avoid using the SCA model for semelparous stocks since the model assumes iteroparous behavior in the age structure of the population. The utility of the age data and the appropriate assessment methods for semelparous shad stocks, given the current data available, remains an open and ongoing area of research that was not resolved during the review meeting.

SCA models were presented for the Potomac and Albemarle Sound systems. Growth, maturity, and natural mortality from the metapopulation analysis were incorporated in both assessments. Model estimates included selectivity, mean recruitment, and initial abundance. A thorough evaluation of model performance was provided, including sensitivity analysis, retrospective analysis, and likelihood profiling of mean recruitment. SSB estimates were most sensitive to the choice of maturity ogive (Maki vs. JoeZ methods) and natural mortality, with higher SSB predicted with either early maturity or higher natural mortality. The stock status was determined by calculating F40% internally in the assessment model as the F_{MSY} proxy. The SSB proxy was calculated by assuming mean recruitment while fishing at F40%. The RP agrees with this approach for the SCA assessments.

The SAS noted difficulty in interpreting juvenile abundance in the model since those age classes do not appear in the data. The current models assume juvenile survival from YOY to age-3 – the first age seen in fishery data – has been constant through time. Presumably, it is possible to estimate age-3 abundance from the fishery data alone. Then, if the YOY indices were known without error, juvenile survival could be estimated. However, the current models did not converge when the YOY indices were removed, indicating there is not enough information to potentially determine juvenile survival.

Retrospective behavior between the two assessments varied widely. The Potomac assessment exhibited severe retrospective bias. When the most recent four years of data were removed, the model estimated that the stock had never been overfished. Conversely, the stock had always been overfished and remained so when all years of data were considered. The contrasting signals imply the model was not able to estimate stock size consistently over time. The RP suggested the increasing trends in catch and indices since 2000 do not provide appropriate contrast to reliably estimate stock size. The likelihood profile for the mean recruitment parameter was also very flat, with a clear minimum bound needed to support observed catches, but no apparent maximum bound. The profile provided additional evidence to support this line of thinking. The Albemarle assessment had better retrospective behavior with relatively low magnitude of Mohn’s rho.

The SAS noted the selectivity ogive should match or be greater than the maturity ogive since only mature fish return. The RP agreed with this diagnostic procedure as a straight face test for appropriate model performance. This did not appear to be a problem for the Albemarle assessment. The Potomac assessment estimated selectivity between the Maki and JoeZ maturity ogives.

The RP noted two issues related to the SCA model with respect to shad life history. First, it is possible the removals of partially recruited age classes, as computed with the Baranov catch equation, exceed their availability. Availability is tied to maturity, but the catch does not discriminate between immature and mature animals. In both the SS3 and ASAP models, immature fish and mature fish are both assumed available to the fishery, whereas fisheries occurring during the spawning run harvest almost exclusively mature fish. The separability assumption used in these models does not accurately estimate the age-specific fishing mortality rates because the fishing mortality rate on the immature component of an age class does not scale up and down with increasing or decreasing apical *F*. If only mature fish are harvested, the remaining spawner biomass would be overestimated if a portion of the harvested fish are assumed in the model to be immature.

The SAS considered the use of statistical catch-at-age models that are specific to *Alosa* life history (Gibson and Myers 2003b, 2004) and have been used in river herring assessments in the past (ASMFC 2012a,b). The models differ from typical marine stock assessment models; rather than modeling the numbers-at-age as a two dimensional array (time and age), they are modelled as a three dimensional array including number of repeat spawnings (time, age, number of repeat spawnings). Using this structure, the different mortality scenarios experienced by mature and immature fish can be modelled separately, addressing many of the issues discussed above.

The RP agreed with the SAS decision not to use the *Alosa*-specific models, recognizing the previous models developed for *Alosa* may not be compatible with the available data for shad. The models require accurate previous spawning composition data. Given the issues described with reading scales, as well as their limited availability, particularly from the Potomac, the models may not be appropriate for shad at this time. To address this issue, the Panel suggested exploring the addition of plus groups in future assessments. The RP believes the SAS decision to use well-vetted models, such as SS3 and ASAP, was appropriate for the current assessment.

The RP has three research recommendations with regards to the SCA models:

- Evaluate by simulation whether and when the simple SCA models break down that do not account for shad availability. Presumably bias in SSB and F estimates increase when the fishing mortality is high, but estimates may be robust within a range of fishing scenarios.
- Address *Alosa* life history in current models. For example, separate fishing areas can be modeled within Stock Synthesis to keep mature and immature fish separate. The RP believes this might be the best path forward particularly if the scale reading issues remain unresolved.
- Develop a model specific to shad life history and current data availability. This is the most flexible option for the SAS though it requires the most time investment for upkeep and quality control, as well as additional data collection, notably spawning marks.

4. For each stock unit, recommend best estimates of biomass, abundance, and exploitation from the assessment for use in management, if possible, or specify alternative estimation methods.

The RP believes the best interpretation of the assessment results are well described in the Assessment Report. As described by the SAS, the abundance trend data were of varying time series durations. None were believed to contain information on the historical productivity potential to compare to current conditions. Increasing trends in abundance do not necessarily represent favorable abundance levels in the terminal year of the assessment, and do not provide estimates of biomass. The RP also believes the SAS provided appropriate guidance on interpreting total mortality rate estimates from the catch curve analyses for the iteroparous stocks. Estimates cannot be interpreted as fishing mortality rates. However, if rates are deemed sustainable, they may indicate fishing mortality rates are sustainable, albeit without quantifying the actual fishing mortality rate.

Total mortality rates for each stock with an accepted catch curve analysis are provided in Table 2. The RP agrees with the SAS that the estimates are best interpreted in the context of their wide confidence intervals, and notes there may be a bias associated with the estimation method (see Section 3.3).

While the delay difference model used in the assessment can in theory provide estimates of biomass and exploitation rates, the implementation for the semelparous stocks was not accepted. For iteroparous stocks, the RP agrees with SAS recommendations about interpreting the delay difference model results. The model is best used to estimate mortality status in terms of U/U_{MSY}. Although the DLMtool package can be used to provide TAC estimates, setting catch recommendations using the median value of TAC from 100 model simulations would be inappropriate in the absence of management objectives.

Similarly, while the SCA models used for the Potomac and Albemarle Sound stocks can provide estimates of biomass, abundance, and fishing mortality rates, the RP agreed the output from the Potomac model in its current form should not be used to provide estimates for management purposes. The RP accepted the SCA analysis for the Albemarle Sound stock. As described in the Assessment Report: “Over the modeled time series, spawning stock biomass increased from a low of 25.1 metric tons in 2000 to a high of 63.3 metric tons in 2009, and has averaged 50.6 metric tons since 2010. Terminal year SSB was estimated to be 49 metric tons with a corresponding 90% confidence interval of 39.6-66.0 metric tons.” Patterns in fishing mortality were described as: “Estimated fully-recruited fishing mortality generally decreased over the time series, ranging from a high of 3.96 in 2003 to a low of 0.35 in 2016 (Table 226, Figure 287). Terminal year fishing mortality was estimated to be 0.48 with a corresponding 90% confidence interval of 0.30-0.67.” The RP accepts the conclusions, while noting there may be an issue with the calculation of SSB (see Section 3), the effect of which was not fully explored during the peer review meeting.

The SAS developed a unique approach for assessing potential abundance via an analysis of the theoretical effects of dams and fish passage on the spawner potential of American shad stocks, described here in Section 3.4. Based on the analysis, coastwide production potential, if no dams existed, is more than 72.8 million spawners per year compared with the current dams and no passage scenario of just under 42.8 million spawners, a reduction of 41%. It is estimated that fishway passage coastwide may alleviate the spawner potential by less than 3 million fish annually, a relatively small difference. The RP agrees with the SAS conclusion that even with extensive fish passage, dams represent a fixed constraint of about 37% on the American shad population potential.

Table 2. Summary of the three-year average adult instantaneous total mortality rate estimates for female American shad from 11 stocks. Estimates should be interpreted in the context of the confidence intervals for the individual year estimates from which these averages are calculated (Table 33 in the Assessment Report).

	3-year average instantaneous total mortality rate estimates		
System	**Year**	**Estimate**	**$Z_{40\%}$**
Merrimack	2016	1.25	1.00
Connecticut	2017	1.4	1.00
Hudson	2017	0.59	1.07
Delaware	2017	1.3	1.07
Nanticoke	1996	0.71	1.07
Susq & Upper	2016	1.09	1.07
Potomac	2017	1.1	1.07
Rappahannock	2017	0.50	1.07
York	2017	0.53	1.07
James	2015	0.76	1.07
Albemarle Sound	2017	0.74	1.07

5. Evaluate the choice of reference points and the methods used to determine or estimate them. Recommend stock status determination from the assessment, or, if appropriate, specify alternative methods/measures for management advice.

5.1 Choice of Reference Points

Biological reference points (BRPs) are reference levels, based on the biological characteristics of a fish stock and the characteristics of its fishery, used to determine stock status and sustainable fishery harvest levels. Reference points are used to gauge whether specific management objectives are being achieved and provide both the link between stock assessment and management objectives (Caddy and Mahon 1995), and a basis for risk analysis of management actions (Punt and Hilborn 1997). The goals of many fishery stock assessments are to determine whether a stock is in a depressed state (e.g., overfished), and whether mortality rates are at appropriate levels (e.g., whether overfishing is occurring). The SAS assessed American shad stocks from two perspectives: abundance and mortality. The SAS considered BRPs based on spawner-recruit, dynamic pool, and production models.

With respect to mortality, the SAS chose to use a spawner biomass per recruit (SBPR) model. The model is appropriate for estimating reference mortality rates, though does not provide reference points associated with biomass or abundance. Given the data limitations (e.g., lack of spawner-recruit relationships) and the choice of total mortality rate estimators as one of the main assessment approaches, the RP agreed with the decision to use SBPR models for generating reference points. The models match the available data well. While SBPR models do not require a spawner-recruit relationship, the choice of an appropriate reduction in the SBPR to use as the reference level requires some assumptions about productivity. The SAS choose $Z_{40\%}$ as the reference level. $Z_{40\%}$ represents the total mortality rate that reduces the spawner biomass per recruit to 40% of what the SBPR level would be in the absence of anthropogenic mortality. Most fishery stock assessments use a SBPR level defined as a fishing mortality rate. The RP agreed with the SAS decision to use the total mortality rate, rather than a fishing mortality rate, in recognition that human activities other than fisheries (e.g., dams/hydroelectric development; water quality issues) contribute to the mortality of American shad. Mortality status was defined as sustainable if mortality was less than or equal to the reference point, or unsustainable if mortality was greater than the reference point. The RP accepted the use of $Z_{40\%}$ for the iteroparous populations. As discussed under TOR 3.2, the Panel did not accept the use of a Z-based reference point for semelparous stocks.

The RP supports the decisions and advice regarding the interpretation of total mortality estimates provided by the SAS in the assessment report. For example, if total mortality rate estimates were not available in the last three years, the SAS made an objective decision to report the most recent estimates, but determined mortality status is unknown. The SAS also provided an important caveat with respect to interpreting the results from the total mortality estimators: the status determination only applies to adult mortality rates. Even if the adult mortality rate is sustainable, abundance could decline if the mortality rate for immature fish is not sustainable, or if reproduction is inhibited.

With respect to abundance, the SAS used three sources of information for determining status: the trend analyses, the analyses of habitat availability and dams, and, where possible, the results from the delay-difference and SCAA models. The RP agreed with the SAS that the development of reference points for trends analyses was not practical because none of the existing time series contain sufficient information about the historical productivity potential to compare to current conditions. As discussed in the assessment report, the trends analyses are best used to evaluate whether abundance has increased or decreased since the beginning of the respective monitoring program (i.e., starting year abundance) or the implementation of a significant coastwide management change (i.e., 2005 abundance when the ocean intercept fishery was closed). Trend analyses are not suitable for drawing conclusions on abundance status. The RP agrees with the approach, and that the development of reference points for trend analyses would have been inappropriate, given the limited current information. Similarly, the habitat/dams analyses provide an overview of the productivity potential lost due to dams. However, a remaining challenge is that reference points within the habitat model have not yet been developed, at least on a coastwide scale.

The delay-difference and SCA models (Potomac and Albemarle Sound) provide estimates of biomass. Comparisons of unfished biomass and the biomass at MSY are outputs of the models, both calculated using standard equations. As discussed in Section 3, initial depletion is a key parameter in the delay-difference model, and the equations used to calculate the spawner biomass in the SCA models may lead to its overestimation. While TAC estimates were calculated with output from the delay-difference models, the SAS was not comfortable setting catch recommendations, choosing instead to use TAC estimates to assess the mortality status. The RP agreed this approach would work and recommended using U/U_{MSY} ratios to more directly determine fishing mortality rate status. The RP agrees with the decisions made by the SAS on interpreting the analyses pertaining to abundance, as well as their decisions regarding the development of reference points associated with the analyses. These are well-justified in the assessment report.

Where appropriate, the SAS reviewed system-specific management plans and their associated reference points. These included systems with a Sustainable Fishery Management Plan (SFMP) in place, and two systems (Hudson and Potomac) that had reference points as well. These were generally tailored to the specific histories of monitoring programs, ranging from CPUE data to more elaborate schemes. For example, the Connecticut River has three benchmark criteria that were included in the assessment.

Overall, the RP believes the approach taken by the SAS with respect to reference points was sound and thoroughly developed. The approach provided a way of assessing many stocks consistently, while at the same time considering the differences in the life history, data availability, and needs for the different stocks included in the assessment.

5.2 Status Determinations

Stock status was determined using catch curve, delay-difference, and statistical catch-at-age models. Trends in mean length were reported in order to use somatic growth as an indicator of the health of the stock. Results are provided in the Assessment Report though not summarized here. The catch curve was the most consistent method used, and it was the only method for status determination in many systems.

For the Connecticut River, the catch curve and delay-difference model provided different interpretations of stock status. Since the two methods use different data, the quality of the data and the underlying assumptions in each method should guide the decision to choose the appropriate model for status determination. Additional non-fishing components of mortality are reflected in the age composition. However, that information can only be inferred in the catch and the index data alone is conditional on the value of M. Along with the additional complexity from the initial depletion assumption in the DD model, the RP agrees with the SAS preference for the catch curve model.

The RP also agrees with the SAS regarding the DD assessment for the Neuse River. Although there appears to be high uncertainty in biomass estimates, biomass status was not determined. The recent declines in catches suggest a reduction in mortality, as inferred in the model, and the confidence interval in the recent exploitation rate is reasonable. In contrast, the Tar-Pamlico assessment had clear diagnostic issues and was rejected by the SAS.

The RP agrees with the SAS that the final status determination for the Potomac is best based on the catch curve analysis. While catch curve analysis should be the primary model for determining stock status in the Potomac, the SCA could be used to support the results of the catch curve, notwithstanding retrospective issues. The biomass status is currently unknown since no other method with biomass status determination was put forth.

The RP supports the SAS decision to use the Albemarle Sound SCA model to determine stock status. The Panel notes there is uncertainty associated with the status determination based on the model, particularly the calculation of spawner biomass (see Section 3).

Stock status is considered unknown in systems for which these methods were not accepted or data were not available. The RP highlights the additional analyses, such as the habitat model and trend analyses, are still informative and highly relevant for shad management even if status determination was not feasible. For example, management has acted to reduce juvenile mortality despite the unknown status of juvenile mortality.

Additionally, the historical narratives provide a perspective not captured in the current status determination models. The RP believes, regardless of whether status determinations were feasible or not, the full suite of methods employed in the assessment, together with additional Assessment Report content, can be used to guide management decisions about shad populations.

The RP accepts the status determinations by the SAS as described in the Assessment Report, or when modified, in the Report Addendum. Status determinations for abundance and mortality of the stocks included in the assessment are summarized in Table 3.

The trend analyses for young-of-the-year abundance (2005-2017) indicated increasing trends for 2 stocks, a declining trend for 1 stock, no trend for 7 stocks, 1 stock with conflicting results, and 12 stocks without data. With respect to adult abundance trends from 2005 to 2017, 2 stocks showed increasing trends, 11 stocks showed no trends, none of the stocks showed declining trends, 7 showed conflicting results, and 3 stocks did not have data.

Mortality status for juvenile shad could not be determined for any stock. For adult mortality status, reference total mortality rates were available for all but one stock. Of the 9 stocks where status determinations could be made, 5 stocks had sustainable mortality rates, and 4 stocks had unsustainable mortality rates. Three other stocks have recent data that are informative about mortality rate status: 1 indicated sustainable mortality rates and the other 2 unsustainable rates. Status for the remaining 11 stocks was not successfully determined. The RP believes the results of the determinations are best interpreted in the context of the wide confidence intervals associated with the individual mortality rate estimates and the potential for bias associated with their estimation.

Abundance or biomass status determinations were successfully made for one stock. The Albemarle Sound was determined not to be in an overfished state. Data to determine abundance or biomass reference points are unavailable for the majority of the stocks, precluding the ability to make abundance status determinations even when counts are available. The RP supports the decisions made by the SAS in this regard.

Table 3. Summary of status determinations pertaining to abundance and mortality rates by stock.

			Total Mortality Rate Status			Abundance Status	
System	Methods	Trend Analysis	Juvenile	Adult BRP	Adult Status	BRP	Status
Merrymeeting Bay	Index trend analysis	YOY: No trend detected 2005-2017 Adults: No data	NA	$Z_{40\%}$	NA	NA	NA
Merrimack	Index trend analysis, total mortality	YOY: No data Adults: Increasing trend detected from 2005-2017	NA	$Z_{40\%}$	NA; most recent data indicate unsustainable	NA	NA
Pawcatuck	Index trend analysis	YOY: No data Adults: Increasing trend detected from 2005-2017	NA	$Z_{40\%}$	NA	NA	NA
Connecticut	Index trend analysis, total mortality, delay-difference model	YOY: No trend detected from 2005-2017 Adults: Conflicting trends detected between two indices from 2005-2017 (one increasing, one no trend)	NA	$Z_{40\%}$	Unsustainable	NA	NA
Hudson	Index trend analysis, total mortality	YOY: No trend detected from 2005-2017 Adults: No trend detected from 2005-2017	NA	$Z_{40\%}$	Sustainable	NA	Depleted
Delaware	Index trend analysis, total mortality	YOY: No trends detected from 2005-2017 (2 indices) Adults: Conflicting trends detected from 2005-2017 between indices (one increasing, one no trend)	NA	$Z_{40\%}$	Unsustainable	NA	NA
Nanticoke	Index trend analysis, total mortality	YOY: Declining trend detected from 2005-2017 Adults: No trends detected from 2005-2017 (two indices)	NA	$Z_{40\%}$	NA	NA	NA
Susq & Upper Ches	Index trend analysis, total mortality, surplus production model	YOY: No trend detected from 2005-2017 Adults: No trends detected from 2005-2017 (two indices)	NA	$Z_{40\%}$	NA; most recent data indicate unsustainable	NA	NA
Patuxent	Index trend analysis	YOY: No data Adults: No trend detected from 2005-2014	NA	Z40%	NA	NA	NA
Potomac	Index trend analysis, total mortality, statistical catch-at-age model	YOY: no trend detected 2005-2017 Adults: no trends detected 2005-1017 (2 indices)	NA	$Z_{40\%}$	Unsustainable	NA	NA
Rappahannock	Index trend analysis, total mortality	YOY: Increasing trend detected from 2005-2017 Adults: No trends detected from 2005-2017 (two indices)	NA	$Z_{40\%}$	Sustainable	NA	NA

York	Index trend analysis, total mortality	YOY: Conflicting trends detected from 2005-2017 (one increasing, two no trends) Adults: No trend detected from 2005-2017	NA	$Z_{40\%}$	Sustainable	NA	NA
James	Index trend analysis, total mortality	YOY: No trends detected from 2005-2017 Adults: No trends detected from 2005-2017 (three indices)	NA	$Z_{40\%}$	NA; Most recent estimates indicate sustainable		
Albemarle Sound	Index trend analysis, total mortality, statistical catch-at-age model	YOY: increasing from 2005-2017 Adults: conflicting trends detected from 2005-2017 (two no trends, one increasing)	NA	$Z_{40\%}$	Sustainable	$SSB_{40\%}$	Not overfished
Tar-Pamlico	Index trend analysis, total mortality, delay-difference model	YOY: No data Adults: No trends detected from 2005-2017	NA	$Z_{40\%}$	Unknown	NA	NA
Neuse	Index trend analysis, delay-difference model	YOY: No data Adults: Conflicting trends detected from 2005-2017 (one increasing, one no trend)	NA	d-d. U_{MSY}	Sustainable	NA	NA
Cape Fear	Index trend analysis, delay-difference model	YOY: No data Adults: Increasing	NA	d-d. U_{MSY}	Unknown	NA	NA
Winyah Bay	Index trend analysis, delay-difference model	YOY: No data Adults: Conflicting trends	NA	d-d. U_{MSY}	Unknown	NA	NA
Santee-Cooper	Index trend analysis, delay-difference model	YOY: No data Adults: Conflicting	NA	d-d. U_{MSY}	Unknown	NA	NA
ACE Basin	Index trend analysis, power analysis, delay-difference model	YOY: No data Adults: No trend	NA	d-d. U_{MSY}	Unknown	NA	NA
Savannah	Index trend analysis, delay-difference model	YOY: No data Adults: No trends	NA	d-d. U_{MSY}	Unknown	NA	NA
Altamaha	Index trend analysis, delay-difference model, tag-recapture population model	YOY: No data Adults: Conflicting trends detected from 2005-2017 between indices (one increasing, one no trend)	NA	d-d. U_{MSY}	Unknown	NA	NA
St Johns	Index trend analysis	YOY: No trends detected from 2005-2017 Adults: Increasing trend detected from 2005-2017	NA	NA	Unknown	NA	NA

Coastwide and Regional Statuses

Both fishery dependent and fishery independent data were used in making coastwide status determinations. Fishery dependent data were available from agencies reporting incidental ocean catches (Delaware, New Jersey, North Carolina, as well as Canada). Data were analyzed by fleet, estimating total (retained + discarded) catches and coefficients of variation, extending from 1989-2017. A notable drop in catches began in 2001 and essentially continued for the remainder of the record (Table 272). Also, a downward trend can be discerned since 2005 (Figure 355b). Neither mortality rates nor specific stocks could be identified due to lack of abundance and genetic information, respectively. Due to the way multiple fisheries are managed together, American shad incidental catches could not be attributed to specific fisheries.

Fishery-independent data sources included state coastal trawl surveys (ME-NH, RI, CT, NJ, DE) as well as two regional surveys: the Northeast Area Monitoring and Assessment Program (NEAMAP) Mid-Atlantic Nearshore Trawl Survey and the NMFS NEFSC Bottom Trawl Survey. Trend data were presented. Additionally, mixed-stock Bayesian models were explored and examined abundance indices at small spatial scales using available survey data. A goal was to test whether the data were suitable for aggregation to metapopulation scale for regional status estimation. This turned out not to be the case because within-region differences in process error indicated differences among stocks within metapopulations. Therefore, scaling up was deemed inadvisable.

Nevertheless, spatial trends were discernible (e.g., draft Assessment Report Figures 370-371), with increased shad abundances in the Gulf of Maine and Southern New England, and declines to the south. In addition, the SAS concluded, despite 9 of 13 trawl surveys being credibly above 2005 index values, the trends observed were longer term, and "from a coastwide metapopulation perspective...American shad relative abundance in trawl surveys had no response to the closure of the ocean intercept fishery in 2005." (Assessment Report Section 4.4.1.5).

The Review Panel believes the strengths and weakness of regional and coastwide datasets are well described in the draft Assessment Report and accepts the conclusions drawn by the SAS with respect to the coastwide metapopulation.

6. Review the research, data collection, and assessment methodology recommendations provided by the TC and make any additional recommendations warranted. Clearly prioritize the activities needed to inform and maintain the current assessment, and provide recommendations to improve the reliability of future assessments.

The RP accepts and agrees with all of the research, data collection, and assessment methodology recommendations made by the SAS in their report, and provides additional, complementary recommendations.

Data Collection Recommendations

- As the SAS notes, tagging studies should be conducted to improve our understanding of repeat spawning and estimates of mortality. Tagging studies should include the potential effects of the tags on mortality and behavior.
- In addition to examining errors between ageing structures (otoliths and scales), analyses should be conducted to explore and describe geographic or environmentally based challenges in ageing fish. For example, there may be a higher likelihood that otoliths are vateritic, or just more difficult to read, in Southern stocks.
- Maturity status should be assessed from fish captured in both marine and riverine surveys. Assessing maturity status in the spring ocean surveys (where both mature and immature fish are available) should provide a more accurate means to develop a maturity ogive than sampling only from rivers (where only the mature fish are available).
- Researchers should explore using telemetry tagging technologies as they are developed (e.g., acoustic, archival, satellite) to determine skip spawning behavior and iteroparity rates.
- Juvenile surveys should be changed to stratified random designs, with some fixed index sites, where possible. Re-design will provide the necessary data to assess when juvenile shad populations have changed spatial distributions in response to changing environmental characteristics. Furthermore, stratified random design will allow researchers to fit occupancy models and other capacity models – e.g., limiting factor analysis, unit characteristic method, ecosystem diagnosis and treatment – to extrapolate indices to population abundances.
- In populations with hatchery reared fish, stocking data should be used to estimate YOY abundance and mortality rates. As described in the assessment report, there are multiple ways to mark hatchery fish, including parentage based mating designs, temperature manipulations in early development stage, and associated hatchery support (long-term, moderate priority). Mark-recapture data can then be used to estimate mortality rates or combined with a habitat analysis (see recommendation below) to estimate abundance.
- Researchers should assess the status and approach of broodstock genetics and stocking for hatchery based programs to ensure they are not producing inbreeding or outbreeding depression. If possible, broodstock for hatchery programs should only come from local populations of wild fish and their genetics should be tested prior to mixing gametes to ensure maximum genetic variability.
- In addition to monitoring in-river **commercial** catch, harvest, and discards in all systems with open fisheries, all **recreational** fisheries should also be monitored. Monitoring programs should collect total catch, effort, size, individual weight, and age data at a minimum. Surveys should be operating in systems with currently open fisheries, and in systems where new fishery openings are requested.

Assessment Methodology Recommendations

- Better define stock recruit relationships between the YOY indices and the spawning survey indices.
- Provide estimates of juvenile mortality rates. Explore linkages to other data sources such as ocean trawl surveys with improved designs (e.g., genetic stock assignments).
- Ensure biological sampling efforts (e.g., otoliths and scales) are representative for analyses of the intended outputs and their uses in assessments. Consider potential stock structure shifts within and between collection years.
- Explore the use of additional models – SS3, or a life-cycle model such as Stich et al. – for potential application in analyses of semelparous shad stocks. This may require developing a completely new approach or building off what has been done for other species (e.g., Pacific salmon and alewife). Determine acceptable levels of precision for modeling (e.g., MSE use).
- Future trend analyses should include approaches that account for within time series shifts, and account for changes in stationarity (i.e. within time-series process error). Explore use of multivariate time series analysis to investigate population trends and covariance among stocks within a region.
- Explore the use of spatio-temporal models that account for the spatial autocorrelation of dynamics and processes (e.g., Z and recruitment) between different stocks. Using a spatio-temporal model could aid in defining the different stock groups for management purposes. One way to fit such a model is by using the vector autoregressive spatial temporal (VAST) package available in R (Thorson 2019).
- Explore the development of fish tagging program(s) with a primary objective of deriving tag/return based mortality estimates to compare to other estimation methods.

Future Research Recommendations

- Explore implications of climate change on life history and ecology: in-river predator-prey relationships, recruitment success, movements and migrations, range shift, dam operations/FERC licenses, interactions with various fisheries.
- Conduct studies to quantify the impacts of novel predators (introduced, or invasive due to climate change) on juvenile stages of shad and river herring within rivers and estuaries. New predators are likely to be a growing issue over the next decade and, together with dams, may pose one of the greatest threats to stock re-building.
- Conduct maturity studies (ogive development) designed to accommodate the unique challenges American shad poses (i.e., segregating mature and immature) on traditional monitoring programs. Maturity information will also improve understanding of fishery selectivity as it relates to age at maturity, by in-river fisheries and monitoring programs. (long-term high priority)
- Conduct fish passage research at barriers with adults for both upstream and downstream migration and movements and with juveniles for downstream, as discussed in Assessment Report Section 1.1.9.5 Fish Passage.

- Develop experimental fish passage studies to examine and define passage issues and to develop and explore potential new or modified measures to improve fish passage designs and operations.
- Continue to conduct research on the ecological effects of dam removals and habitat restoration.
- Conduct research on using environmental DNA (eDNA) to quantify the abundance of juvenile and adult shad. Recent research has shown eDNA technology can be used to quantify the abundances of salmonids in Alaska, Washington, and California.

In addition to the above recommendations, the RP also encourages continued work to better quantify the age-at-maturity and information about number of previous spawnings, using scales and/or otoliths, or a combination of both. Further subdivision of the age composition data by age-at-maturity and the number of previous spawnings, or by age-at-maturity with an assumption that shad spawn each year after maturing (the effect of skipping years is negligible), allows an age class to be subdivided based on age-at-maturity and the number of times that fish has previously spawned. Maturity and spawning factors are key determinants of the survivorship to a given age because mature fish are subjected to increased mortality resulting from becoming available to in-river fisheries, passage at dams, and the energetics associated with migrations and spawning. Age-at-maturity and previous spawning data are very useful for stock assessments of *Alosa* species. The issues associated with treating selectivity based on maturity are the same as gear selectivity (Section 3), reference point estimation (Section 3.2), bias in the catch curve analyses (Section 3.3), and the issues with calculating spawner biomass in statistical-catch-at-age models (Section 3.6). Such issues would all be alleviated if previous spawning information can be incorporated into the analyses. However, the RP notes these comments are only valid if the ages and previous spawning information are representative. If the accuracy of age and previous spawning determinations from scales can be improved, the resulting data could significantly improve assessments for *Alosa* species. The best scheme might be to use otoliths for age and maturity determination, and use scales for minimum estimates of repeat spawning and a check on age-at-maturity.

7. Recommend timing of the next benchmark assessment and update, if necessary, relative to the life history and current management of the species.

As recommended by the SAS, the RP agrees another benchmark assessment should be completed no later than ten years from now, i.e. 2030, to ensure less time passes between the last two assessments (13 years), and to maintain institutional knowledge among the SAS. The RP also concurs a staggered approach, sequencing in stocks, could make the assessment workload easier. That said, the actual sequence will require thoughtful planning. For example, choose representative systems along the latitudinal gradient, 7-8 per year for three years, or select according to perceived acuity, or alternatively by model class. For example, the first round of the next benchmark assessment could start in systems with enough data available to conduct more complex analyses.

Additionally, the RP asks the SAS to consider whether 2005 is still an appropriate benchmark year, as the effect of management action to close at-sea fisheries is unclear. Or, whether objectives/benchmarks need to be revised to address climate change, dam removals, and other pressures in terms of target levels for shad.

ADVISORY REPORT

A. Status of stocks: Current and projected, where applicable

The Review Panel (RP) concluded the status of American shad stocks is varies widely in the coastal U.S. and its river systems. Many stocks remain at low levels. At the other end of the spectrum, the RP accepted the Stock Assessment Subcommittee's (SAS) conclusion that the Albemarle Sound stock is not overfished and overfishing is not occurring. The coastwide metapopulation abundance was determined to be depleted based on the decline in coastwide landings since the 1950s by more than an order of magnitude, as well as the lack of response observed in the abundance trends (Executive Summary, page viii).

Trend analyses played an important role in the assessment in order to determine whether abundance has increased, decreased, or remained the same since the last assessment in 2007. Of 11 stocks with young-of-the-year abundance indices, the trend analyses for YOY abundance from 2005-2017 indicated: increasing trends for 2 stocks; a decreasing trend for 1 stock; no trend for 7 stocks; and 1 stock with conflicting results. Over the same time period, of 20 stocks with adult abundance indices, the trend analyses for adult abundance indicated: increasing trends for 2 stocks; no stocks with a decreasing trend; no trend for 11 stocks; and 7 stocks showing conflicting results.

Total mortality estimators were used to assess whether the adult total mortality of iteroparous stocks – stocks where fish spawn in multiple years during their lives – is above or below reference points. The approach differs from many stock assessments where the emphasis is on fishing mortality. However, it is appropriate for American shad because many of the stock specific fisheries are closed and other factors influence their survival. From the draft stock assessment Executive Summary, p. vi: "Average adult mortality during the last three years of the assessment time series (2015-2017) was greater than respective regional per-recruit reference points for three stocks (Delaware, Potomac, and Connecticut), less than or equal to reference points for four stocks (Hudson, Rappahannock, York, and Albemarle Sound), and unknown for all remaining stocks."

Many factors influence the abundance and productivity of American shad stocks and their relative influence varies among stocks. These include combinations of: historical overfishing; loss of access to habitat due to damming the main stems and tributaries of rivers; mortality from passing through hydroelectric turbines; water quality issues; and possibly ecological factors (e.g., parasites, disease, competition, predation) acting in the freshwater and marine environment that are not well understood but could potentially limits a stock's response to management actions taken to rebuild populations.

Of note in the assessment is an analysis of the theoretical effects of dams and fish passage on the spawner potential of American shad stocks. From the draft stock assessment Executive Summary, p. vii: “This approach allowed the comparison of three broad scale scenarios: i) historical or “intact” rivers, ii) worst case scenario with current dams and “no passage”, and iii) dams with imposed realistic upstream and downstream passage to best reflect the “status quo.” Changes in available habitat are reported by system and coastwide. Based on the modeling exercise, coastwide production potential, if no dams existed, is more than 72.8 million spawners per year, compared with the current dams and no passage scenario of just under 42.8 million spawners, a reduction of 41%. It is estimated that fishway passage coastwide may alleviate the spawner potential by less than 3 million fish annually, a relatively small difference. This is evidence that, even with extensive fish passage, dams represent a fixed constraint of about 37% on the population potential of American shad.”

B. Stock Identification and Distribution

The Review Panel concluded the hierarchical approach taken for stock identification in the assessment was both consistent with knowledge of the ecology of American shad and practical given the data limitations for select stocks. Stocks were assessed on an individual river system basis when data were available. In some instances, there was a need for a broader system definition (Merrymeeting Bay, Albemarle Sound, Upper Chesapeake Bay, Winyah Bay, ACE Basin) when datasets could not be attributed to specific rivers. Additionally, three regional metapopulations were defined to share life history traits among system-specific stocks when there were data limitations for individual stocks. These are: the semelparous metapopulation (Florida to the Cape Fear River, NC), the southern iteroparous metapopulation (stocks north of the Cape Fear River to the Hudson River, NY), and the northern iteroparous metapopulation (stocks north of the Hudson River). At the broadest scale, stocks were aggregated and treated as a coast-wide, mixed-stock metapopulation when data sets could not be attributed to system-specific stocks. In addition to being a practical way to address data limitations, the Review Panel considered the hierarchical approach to be useful because larger groupings become important for questions where straying and meta-population structure are key determinants of overall productivity and abundance (e.g. recovery planning purposes). For other questions (e.g., fisheries assessment) stock definitions at the individual system population are more important.

C. Management Unit

Specific management units were not reviewed as part of the assessment. The Review Panel supports the Stock Assessment Subcommittee’s perspective that species assessment and management should occur at the river system level, consistent with the 2007 Stock Assessment Peer Review Report (ASMFC 2007b).

D. Landings

Commercial landings consist of the ocean, mixed-stock (OMS) component and in-river component. Landings for in-river components are documented for most stocks (see Table 2.1). Estimates of OMS incidental catch can be highly uncertain due to low observer coverage. Recreational landings are more sparse and unavailable for most stocks. The NMFS MRIP survey is primarily designed to interview coastal fishing trips and does not target in-river angling effort. Recreational creel surveys are limited in scope and often occur at a single access point. Coastwide landings are provided on a state-by-state basis and available from NMFS databases. Often the landings cannot be partitioned into individual stock components. Although there are numerous gaps and missing records, landings provide a perspective on the large magnitude of catches in prior decades and centuries relative to today. Coastwide landings have decreased since the 2005 closure of the ocean-intercept fishery and have been below half a million pounds during 2015-2017.

E. Data and Assessment

The SAS compiled and vetted a very large amount of data for the 23 stocks included in the assessment. As described in the Assessment Report, data sets were provided from numerous fishery-independent sources as part of our canvassing of data for the assessment. They included 100 individual fishery-independent survey data sets and 17 fish lift/passage counts for consideration of the development of relative abundance indices. These, along with an additional 57 (41 commercial; 16 recreational) fishery-dependent data sets submitted for possible index development, were assessed as to whether they met the criteria developed by the SAS for evaluating available data. All data sets are thoroughly described on a stock-by-stock basis in Section 3 of the Assessment Report.

An impressive variety of analytical tools were used in this assessment, including:

1. Power analyses to calculate the probability of detecting trends in the abundance indices,
2. Autoregressive integrated moving average (ARIMA) analysis of trawl survey relative abundance indices,
3. Mann-Kendall trend analysis to detect trends in each survey index of abundance and to detect temporal trends in mean length and mean length-at-age,
4. A modified Thompson-Bell spawning biomass per recruit (SBPR) model to estimate total mortality rate reference points,
5. Catch curves to estimate total mortality rates,
6. Delay difference models to evaluate the status of select stocks,
7. Habitat assessment and simulation modeling to evaluate the effects of dams and fish passage,
8. Statistical catch-at-age models to evaluate the status of two stocks, and
9. Models utilizing mark-recapture tagging data.

Collectively, the models are fully described in the methods section of the Assessment Report. Review Panel comments are provided in Section 3 of the Review Report.

F. Biological Reference Points

Catch curve analyses provided estimates of total mortality rates (*Z*) and played a large role in the assessment. A Thompson Bell spawner-biomass-per-recruit (SBPR) model was used to estimate biological reference points that total mortality rate estimates were compared with. The Review Panel considered this a reasonable approach for the iteroparous stocks while noting the recruitment dynamics in the SBPR model do not quite match those of American shad (Section 3). They did not accept the use of a *Z*-based reference point for the semelparous stocks (Section 5).

The total mortality rate that reduces the SBPR to 40% of its level in the absence of anthropogenic mortality ($Z_{40\%}$) was chosen as the reference level for evaluating status based on total mortality. The value is more conservative than the $Z_{30\%}$ value used in the 2007 assessment (ASMFC 2007a). $Z_{40\%}$ is considered appropriate given the lack of evidence the coastwide metapopulation is rebuilding. The final $Z_{40\%}$ reference points from the SBPR models for the two regions are: northern iteroparous = 1.00; and southern iteroparous = 1.07.

For the delay difference and statistical catch-at-age models, biological reference points equating either to MSY or $F_{40\%}$, respectively, were used to determine the status of stocks analyzed with these models.

G. Fishing Mortality

Fishing mortality rates are available for the Albemarle Sound from the assessment. Results for the stock indicate fishing mortality rates generally decreased over the time series and were below the reference point in the terminal year. Exploitation rates for the Connecticut River and the Neuse River are also available from the delay-difference assessments. Further model development and analyses are needed to provide estimates of the fishing mortality rates for the other stocks with open commercial fisheries. For the iteroparous stocks, evidence regarding whether fishing mortality rates are appropriate is provided by the catch curve analyses: if the total mortality rate estimate is below the reference point, then a fishing mortality rate estimate will likely also be below the corresponding reference point. Confidence intervals associated with the individual estimates should be considered (Assessment Report Table 33) if making this type of inference. For most of the iteroparous populations, there has been a moratorium on commercial harvest of American shad since the late 1990s; therefore, fishing mortality is expected to be a small component of total mortality.

H. Recruitment

Where available, young-of-the-year abundance time series were used to evaluate recruitment trends. The trend analyses for young-of-the-year abundances (2005-2017) indicated increasing trends for 2 stocks; a declining trend for 1 stock; no trend for 7 stocks; and 1 stock with conflicting results.

I. Spawning Stock Biomass

Temporal patterns in spawning stock biomass (SSB) were estimated using statistical catch at age models for two stocks, with delay difference models for two more stocks. The trend in the index of abundance was assessed for a larger number of stocks (20). The SSB in the Connecticut River declined from 1990-2010, and has been recovering since 2010 based on results from a delay-difference model fit to fish lift data. A delay difference model was also used to estimate SSB in the Neuse River, indicating it has remained relatively constant since 2000. However, there was a large amount of uncertainty in Neuse estimates throughout the time-series. A statistical catch-at-age (SCA) model for the Potomac River found the SSB has been relatively constant since 1999. Only trends in SSB, not magnitude and biomass status, were considered because a retrospective analysis indicated the Potomac model had a tendency to overestimate spawning stock biomass and underestimate fishing mortality. Another SCA model for the Albemarle Sound indicates that the spawning stock biomass increased from a low in 2000 to a high in 2009, with more acceptable retrospective behavior in the model. With respect to adult abundance trends from 2005 to 2017, 2 stocks showed increasing trends, 11 stocks showed no trends, none of the stocks showed declining trends, 7 showed conflicting results, and 3 stocks did not have data.

J. Bycatch

Bycatch of American shad occurs in both the mixed stock ocean fishery and in state waters. Shad bycatch in the mixed stock ocean fishery was quantified in the assessment using data collected by the Northeast Fisheries Observer Program (NEFOP), providing incidental catch estimates for 1989-2017. Known bycatch fisheries occur in New York, Virginia, and the New England states. In 2014, river herring and shad catch caps were implemented in both the Atlantic mackerel and herring fisheries to reduce river herring and shad bycatch. Unlike the bycatch in the ocean fishery, the bycatch in state waters is largely unquantified. The Delaware Department of Fisheries and Wildlife discontinued monitoring American shad bycatch during the commercial striped bass season since no bycatch had been reported over a 10-year period from the striped bass fishery. A mixed stock bycatch fishery occurs in Chesapeake Bay, but this bycatch is largely discarded and not quantified. There are no studies of American shad discard mortality rates in commercial fisheries. Values had to be assumed in the assessment based on general fishing practices. A discard mortality rate of 100% was applied to commercial gill net discards. A rate of 20% was applied to commercial discards from pound nets to estimate post release mortalities, because fish are held impounded and can be released following minimal interaction with the gear.

K. Other Comments

The Review Panel considers the body of work to be a major advancement in the assessment of American shad stocks. The amount of new data is noteworthy. The quality and diversity of new analyses raises this assessment up a significant level from prior benchmarks. Of particular note are the facts that two systems (Potomac and Albemarle Sound) had sufficient data to attempt the use of statistical catch-at-age models, and that for the first time, a coastwide habitat assessment of continental waters was undertaken with specific reference to dams and passage as impediments to sustainable stocks. Overall, the assessment is a valuable contribution to our knowledge base for American shad.

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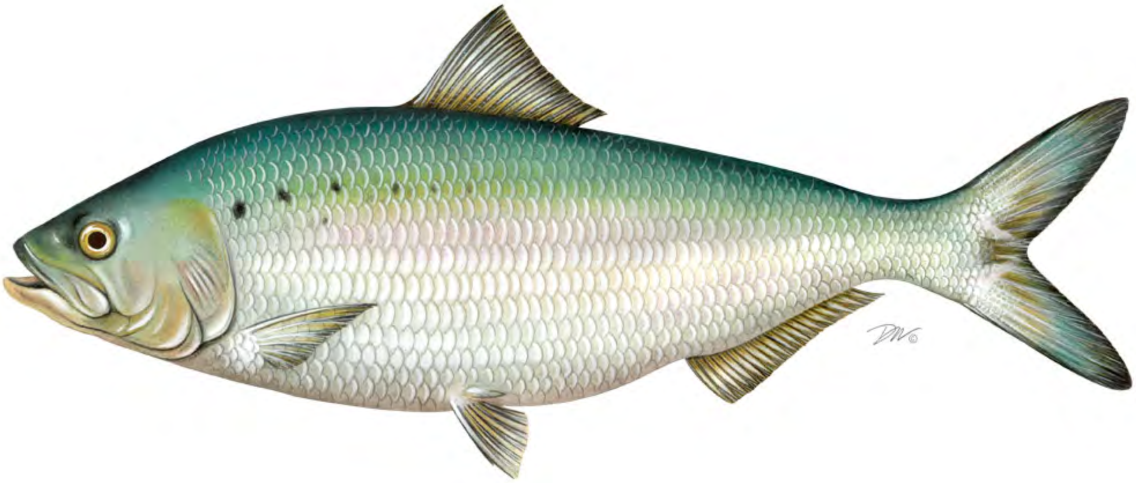
Atlantic States Marine Fisheries Commission

2020 American Shad Benchmark Stock Assessment



Prepared by the
American Shad Stock Assessment Subcommittee

August 4, 2020

EXECUTIVE SUMMARY

American shad (*Alosa sapidissima*) are an anadromous, pelagic, highly migratory, schooling species (Colette and Klein-MacPhee 2002). The historical range of American shad extended from Sand Hill River, Labrador, Newfoundland, to Indian River, Florida, in the western Atlantic Ocean (Lee et al. 1980; Morrow 1980). The present range extends from the St. Lawrence River in Canada to St. Johns River, Florida. Historical spawning range of American shad included all accessible rivers and tributaries along the Atlantic coast (MacKenzie et al. 1985). Additionally, rivers, bays, and estuaries associated with spawning reaches are used as nursery areas by American shad (ASMFC 1999).

The most recent previous American shad stock assessment in 2007 was based on individual river stocks. This allowed focus on river-specific factors such as the presence of dams (with and without fish passage), water quality problems, and estuarine and in-river fisheries. All of these factors lead to river-specific variation in patterns of abundance and in restoration potential. Most assessments were based on simple index-based approaches as data was limited and there were uncertainties about the age data. Reference points were defined in terms of total mortality (Z) due to uncertainty in components of mortality contributing to declines in age structure data analyzed with total mortality estimators

In this assessment, the SAS similarly assessed Atlantic coastal stocks on an individual river system basis when data were available and also as a coastwide, mixed-stock metapopulation with data sets that could not be attributed to system-specific stocks. Due to data limitations, regional metapopulations were defined as northern iteroparous, southern iteroparous, and semelparous to share life history traits among system-specific stocks within each regional metapopulation. As an anadromous species, ideally American shad should be assessed and managed by individual river systems. However, the majority of the life history of shad is spent in the marine environment where factors influencing survival likely have impacts upon multiple river stocks when they mix during marine migrations. The complex life history of anadromous species complicates assessment as it is difficult to partition in-river factors from marine factors governing population dynamics. Also complicating the assessment of American shad is the variability in data quantity and quality among rivers along the coast.

The data limitations for shad can be attributed mostly to the low priority the species receives in some agency monitoring efforts. This understandable prioritization results in there being few long-term fishery-independent indices, except on rivers with fish passage. Fishery-dependent data provide some long time series but most data contain gaps and are not documented as to stock composition, with few exceptions reported for some river systems. As some population have been closed to fishing, the related fishery-dependent data sets have also ceased. Some new data collection programs have been added in recent years following the passage of Amendment 3 to the ASMFC Shad and River Herring Fishery Management Plan (FMP). Some of the current fishery-independent surveys should be of sufficient length to be useful in assessments five to ten years from now if monitoring continues.

A combination of assessment approaches was used to assess the status of American shad stocks. A combination approach was warranted given the variability in data available across individual systems. First, power analyses were used to calculate the probability of detecting trends in the abundance indices using the approach of Gerrodette (1987). Second, the SAS used autoregressive integrated moving average (ARIMA) analysis of trawl survey relative abundance indices to provide a means to filter measurement error from process variability (Box and Jenkins 1976; Helser and Hayes 1995), and hence provide time series estimates of abundance where the variance of the fitted estimates is less than the variance of the observed time series (Pennington 1986). The SAS also used Mann-Kendall trend analysis to detect trends in each survey index of abundance and to detect temporal trends in mean length and mean length-at-age. The year 2005 was selected as a reference point for abundance trend analyses based on a coastwide management change (i.e., closure of the ocean intercept fishery) to assess response in abundance to this change. To establish mortality benchmarks, the SAS used a modified Thompson-Bell spawning biomass per recruit (SBPR) model to develop instantaneous total mortality (Z) biological reference points (BRP) for American shad. Next, the SAS used total mortality estimators developed using weighted catch-curve regressions as a means to assess whether the total mortality of stocks are at or below stock assessment benchmarks. The SAS also used several classes of population models to assess the status of individual stocks depending on data availability. These population models included delay difference models, habitat assessment and simulation modeling, statistical catch-at-age models, and models utilizing mark-recapture tagging data. Results of each assessment approach are summarized from a coastwide perspective below and presented by system stock in the assessment report.

Power Analysis

For this analysis, 65 individual indices were available that were vetted by the SAS and possessed uncertainty measures necessary to calculate proportional standard errors (PSE). Median PSEs ranged from 0.058 to 4.085 for the surveys analyzed and power values ranged from 0.06-1.00. As expected, surveys with low coefficients of variation (CVs) had higher power and those with high CVs had lower power. Exponential trends indicated slightly higher power than linear trends. For both linear and exponential trends, the ability to detect decreasing trends was higher than that of increasing trends. The surveys with greater than a 0.80 power of being able to detect a 50% increase in abundance were the Altamaha River Commercial CPUE, Savannah River Commercial CPUE (GA DNR), the Cooper River Recreational Creel Survey index, the Albemarle Sound Independent Gill Net Survey index, the Smithfield Beach Gillnet Survey index, the Hudson River YOY 3/8" Seine Survey, the Connecticut River Commercial CPUE, and the Delaware Bay Commercial Logbooks (NJ DFW) index. The remaining 57 surveys all fell below the desired power of 0.80 and therefore the ability to detect trends in the past 20 years is limited for many of the surveys as used in this assessment.

Autoregressive Integrated Moving Average Analysis

ARIMA was applied to fishery-independent trawl surveys along the Atlantic coast that index mixed-stocks, as trawl surveys for American shad can be quite variable, making inferences about population trends uncertain. The probability of the terminal year of a survey being above the 2005 index value had mixed results across regions, however; surveys within regions generally had similar results. Terminal year index values for surveys in the northern region were credibly above their respective 2005 index values except for the fall CT LIS trawl survey 1984-2009. Terminal year index values for surveys in the southern region were credibly below their respective 2005 index values. The coastwide NEFSC trawl surveys were credibly above their respective 2005 index values.

Nine out of 13 trawl surveys were credibly above their respective 2005 index values, however; these results do not necessarily indicate an increase in relative abundance following the management action implemented in 2005. Following the 2005 closure of the ocean intercept fishery, there were no discernable change in trends in any survey. For instance, if a trend in a given survey was increasing, decreasing or stable in the time period prior to 2005, it exhibited a similar trend after 2005 (see results of Mann-Kendall trend analysis). Therefore, from a coastwide metapopulation perspective, these results suggest American shad relative abundance in trawl surveys had no response to the closure of the ocean intercept fishery in 2005.

Mann-Kendall Abundance Trend Analysis

Mann-Kendall trend analysis found 18 increasing abundance trends, 12 decreasing abundance trends, and 57 indices with no abundance trend for the full time series of each survey. Looking at the period beginning with 2005, the reference point based on the closure of the ocean intercept fishery, Mann-Kendall analysis found 18 increasing abundance trends, 4 decreasing abundance trends, and 61 surveys with no abundance trend.

Mann-Kendall Mean Length Trend Analysis

Mean lengths of American shad were examined to determine if population demographic changes (i.e., contraction or expansion of size structure) have occurred over time. In summary, of the 27 male American shad length composition datasets analyzed with Mann-Kendall trend analysis, 1 exhibited an increasing trend, 5 exhibited a decreasing trend, and 21 had no discernable trend. Similarly, for 31 datasets analyzed for female American shad, 2 exhibited an increasing trend, 14 exhibited a decreasing trend, and 15 had no discernable trend.

Mann-Kendall Mean Length-at-Age Trend Analysis

Mean lengths-at-age of American shad using both scale and otolith-based ages were also examined to determine if population demographic changes have occurred over time.

For scales, mean length-at-age data were analyzed for 15 identified systems. Results of the analysis indicated that, in systems where a significant change in mean length-at-age over time was present, it was almost exclusively a decrease. A decrease in mean length-at-age for at least one age was detected by the Mann-Kendall trend analysis in 11 of the 15 systems for females (Connecticut, Albemarle Sound, Delaware, Hudson, James, Neuse, Potomac, Tar-Pamlico, Upper

Chesapeake Bay, York, Cape Fear) and in 5 of the 10 systems for Males (Connecticut, Albemarle Sound, Delaware, Hudson, Upper Chesapeake Bay). However, an increase in mean length-at-age for at least one age was also detected for females in 1 of the 15 systems (Hudson) examined and in 4 of the 10 systems examined for males (Albemarle Sound, Hudson, Potomac, Upper Chesapeake Bay).

For otoliths, mean length-at age data were analyzed for 3 identified systems. Results of the Mann-Kendall trend analysis only found significant declines in mean length-at-age. A decrease in mean length-at-age for at least one age was detected in 2 of the 3 systems for females (Delaware and Upper Chesapeake Bay) and in the same 2 of the 3 systems for males.

Per-Recruit Analysis

Per-recruit analyses were conducted to provide a relatively simplistic approach to assess the current mortality status of American shad stocks considering the limited data availability. A modified Thompson-Bell SBPR model was used to develop instantaneous total mortality (Z) BRPs for American shad. Due to the data-poor characterization for most stocks and the uncertainty related to American shad stock resiliency, the SAS selected $Z_{40\%}$ as the threshold BRP. $Z_{40\%}$ is the total mortality rate that will preserve 40% of the unexploited SBPR. The final $Z_{40\%}$ from SBPR models by region are: northern iteroparous = 1.00, southern iteroparous = 1.07, and semelparous = 1.43.

Total Mortality Estimators

The SAS used total mortality estimators developed using weighted catch-curve regressions as a means to assess whether the adult total mortality of iteroparous stocks is at or below stock assessment benchmarks estimated with the per-recruit analysis. Average adult mortality during the last three years of the assessment time series (2015-2017) was greater than respective regional per-recruit reference point for three stocks (Delaware, Potomac, and Connecticut), less than or equal to reference points for four stocks (Hudson, Rappahannock, York, and Albemarle Sound), and unknown for all remaining stocks.

Population Models

Several classes of population models for individual systems were used when possible, however few stocks had enough data to run these types of models. There was sufficient data to run delay-difference models for several systems as there is no need to have a simulation of age structure in the model and there are active fisheries operating in these systems. The SAS compared the median total allowable catch (TAC) estimates from delay-difference models to the average catch of the final three years to assess mortality status. One system stock assessed with delay-difference models experienced average catch in recent years that exceed TAC estimates (Savannah) while five system stocks experienced average catch in recent years that was below TAC estimates (Connecticut, Neuse, Cape Fear, Winyah Bay, and ACE Basin). Delay-difference models for one additional system stock (Santee-Cooper) had conflicting results, with one model indicating average catch in recent years was below the TAC estimate and one model indicating average catch in recent years was above the TAC estimate.

A simulation model based on habitat and life history traits was applied to most of the systems know to have American Shad to model theoretical effects of fish passage and dams on spawner potential. This approach allowed the comparison of three broad scale scenarios: i) historical or "intact" rivers, ii) worst case scenario with current dams and "no passage", and iii) dams with imposed realistic up- and downstream passage to best reflect the "status quo." Changes in available habitat are reported by system and coastwide. Based on this modeling exercise, coastwide production potential is more than 72.8 million spawners per year compared with the no passage scenario of just under 42.8 million spawners, a reduction of 41%. It is estimated that fishway passage coastwide may alleviate the spawner potential by less than 3 million fish annually. This is evidence that even with extensive fish passage efforts, dams represent a fixed constraint of about 37% on the fishery potential of American shad.

Other specialized population models were used in system-specific settings. The first of these was the development of a combined mark-recapture and biomass surplus production model (SPM) to produce population estimates of American shad in the Upper Chesapeake Bay. However, the SAS had concerns with some assumptions made to develop inputs and parameterize the model, so the results were not use to determine stock status and, instead, recommendations are provided to improve the analysis for future assessments. Data was also sufficient to model two systems, the Potomac and Albemarle Sound, using relatively simple forward-projecting statistical catch-at-age models. These models estimated mortality and abundance status relative to internally derived SBPR-based reference points. The Potomac stock abundance was estimated to be below the SBPR-based abundance reference point and mortality was estimated to be above the SBPR-based mortality reference point. The Albemarle Sound stock abundance was estimated to be above the SBPR-based abundance reference point and mortality was estimated to be below the SBPR-based mortality reference point. Finally, estimates of minimum exploitation rates and population estimates using mark-recapture studies on the Altamaha River were provided in the assessment. Similar to the Upper Chesapeake Bay population model, the SAS had concerns with some assumptions made in the model and provided recommendations to improve the analysis for future assessments. Conversely, the SAS did recommend using the estimates from this approach to determine that exploitation of the Altamaha stock has declined over time.

Stock Status and Conclusions[1]

Adult mortality for the coastwide metapopulation is unknown, but was determined to be unsustainable for some system-specific stocks indicating the continued need for action to reduce adult mortality. Specifically, adult mortality was determined to be unsustainable for 3 stocks (Connecticut, Delaware, and Potomac) and sustainable for 5 stocks (Hudson, Rappahannock, York, Albemarle Sound, and Neuse). Though adult mortality was determined to

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[1] *This summary reflects final stock status as modified in the addendum (Section 9), where applicable.*

be sustainable for some system-specific stocks, it is important to note that maintaining sustainable adult mortality will not result in favorable abundance status if juvenile mortality is unsustainable. Unfortunately, data is not being collected in any system to determine juvenile mortality status and lack of these determinations remains a significant uncertainty in assessment advice for management of American shad.

Abundance status is unknown for most systems, but was determined to be depleted for one system (Hudson) and not depleted for one system (Albemarle Sound). Despite the finding of Albemarle Sound abundance as not depleted, the coastwide metapopulation abundance was determined to be depleted based on the decline in coastwide landings since the 1950s by more than an order of magnitude and the lack of response in abundance trends. Abundance trend analyses indicate a continued lack of consistent response in coastwide abundance to the 2005 management change (ocean intercept fishery closure). There may still not have been enough time for coastwide abundance to respond to the 2005 management change, given various factors impeding consistent positive responses among systems. Trends from mixed-stocks are conflicting, confounding interpretation of what these trends represent and further support assessment of American shad stocks at the system level.

The decline of American shad is not unique as declines of many other diadromous species have been observed in the North Atlantic basin (see Limburg and Waldman 2009 for a review). Multiple factors are likely responsible for shad decline such as overfishing, inadequate fish passage at dams, predation, pollution, water withdrawals, channelization of rivers, changing ocean conditions, and climate change. It is difficult to partition mortality into these possible sources and evaluate importance in the declines. To sustain the resilience of fish populations in the face of multiple threats, Brander (2007) suggested that age and geographic structure must be preserved rather than relying solely on management of biomass. Thus, the recovery of American shad will need to address multiple factors including anthropogenic habitat alterations, predation by non-native predators, and exploitation by fisheries.

The major conclusions drawn from available data and observations during this assessment are:

- At low levels, stocks are sensitive to both biotic and abiotic perturbations that truncate age structure thereby reducing population resilience.
- Recovery of American shad stocks will need to address multiple factors (e.g., fish passage, predation, water quality, climate change, etc.) in addition to harvest.
- Habitat quantity is greatly reduced from historic levels, and even with fish passage will continue to be a limiting factor on a coastwide basis.
- There continue to be data limitations precluding the most robust population modeling.

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TERMS OF REFERENCE

For the 2020 ASMFC American Shad Benchmark Stock Assessment

Board Approved February 2018

Terms of Reference for the American Shad Benchmark Stock Assessment and Report Summary

1. **Define and justify stock structure.**

American shad (Alosa sapidissima) are an anadromous, pelagic, highly migratory, schooling species (Colette and Klein-MacPhee 2002), with adults returning mostly (97%) to their natal rivers and tributaries to spawn (Section 1.1.1). Herein, the stock assessment subcommittee (SAS) reviewed research completed on American shad stock structure using genetics, otolith microchemistry, and fish tagging methods (Section 1.1.2). Collectively, this research supports species assessment and management at the river system level (Section 1.1.2), consistent with the 2007 Peer Review Report (ASMFC 2007a). As such, for this assessment each main stem river and its identified tributaries are generally treated as an individual American shad stock unit with status assessed at the individual stock unit level (Section 1.1.2). The only exceptions to this general stock definition occurs for the Merrymeeting Bay, Albemarle Sound, Upper Chesapeake Bay, Winyah Bay, and ACE Basin stocks, where there is justification from one or more sources supporting the need for a broader system definition (Section 1.1.2).

As an anadromous species, ideally American shad would be assessed and managed at the individual river or tributary system level and attempts to this effect were made during the current assessment. However, due to data limitations, shared life history information (see Sections 2.2) from three metapopulations defined by reproductive strategy and genetic studies were used for system-specific analyses (Hasselman et al. 2013; Sections 1.1.1, 1.1.2). The semelparous metapopulation consisted of populations from Florida to the Cape Fear River, the southern iteroparous metapopulation consisted of populations north of the Cape Fear River to the Hudson River, and the northern iteroparous metapopulation consisted of populations north of the Hudson River. The Cape Fear River is considered the transition between reproductive strategies and was grouped with the semelparous metapopulation since it flows into the Atlantic Ocean south of Cape Fear

2. **Characterize age and repeat spawner data by stock and identify utility of data source.**
    a. **Provide descriptions of methods, any changes to methods, and associated peer-reviewed literature.**
    b. **Describe validation experiments, if available, and available samples.**
    c. **Where possible, explore reader consistency, potential bias, and agreement statistics.**
    d. **Where possible, explore use of correction factors when consistency in method or reader was not maintained.**

The SAS reviewed historical and current literature regarding the methodology used to characterize age and repeat spawner data for the current assessment. A broad overview of the general methodology for age determination and identification of repeat spawners is provided in Section 1.1.4, noting that historically, researchers primarily aged American shad using scales and the methods of Cating (1953). Cating's method relies on transverse groove frequencies on scales to assist with identifying the location of freshwater zones and the first three annuli for age determination. An update to this general methodology was published by Elzey et al. (2015), with several ageing programs transitioning to the use of this updated methodology for scale ages in recent years (see Section 1.1.4.2).

During the last American shad stock assessment, the assessment noted that Cating's method, and potentially scale-based ages in general, may not be a reliable source of age data (ASMFC 2007b). Issues identified with scale age estimates were low precision, age-specific bias, and the potential that Cating's method may not be applicable to all rivers along the coast. Additional work since the last stock assessment further supported these early indications and suggests otoliths are the most reliable structure for determining age (see Section 1.1.4). These findings have resulted in increasing collections of otoliths for age data and changes in ageing methodologies for scales since the last stock assessment.

Herein we include an example of a standard alosine ageing protocol, including American shad (S. Vanderkooy, editor, Gulf States Marine Fisheries Commission, personal communication), in Section 1.1.4.1 that represents the preferred methodology for ageing alosines via otoliths or scales. Further, the assessment includes source specific descriptions of current ageing protocols from the various sources suppling age and repeat spawner data for the current assessment in Section 1.1.4.2, highlighting any significant deviations from the preferred methodology.

Section 1.1.4.3 details efforts by the SAS to explore, where possible, reader consistency, and agreement statistics. For this analysis, estimates of age from paired scale and otolith samples collected from the same fish, otoliths collected from fish with known ages, scales collected from fish with known ages, and estimates of spawn marks from scales made by multiple readers were analyzed to characterize age and spawn mark data error using mean coefficients of variation (measure of precision) and symmetry tests (measure of systematic bias). The results of these analyses are generally consistent with the findings from recent published works on American shad ageing and confirm that issues observed at specific locations investigated in these publications apply to other areas along the coast. Scale ages appear more imprecise and biased than otolith ages based on the comparison to known ages. Error in ages estimated from both structures follow similar patterns of overestimation for younger ages and underestimation for older ages. This pattern is presumably worse in estimates from scales as the same pattern occurs in scale age estimates when compared to otolith age estimates. However, there were comparisons that suggest acceptable levels of ageing error between age structures can be achieved. Spawn mark data, analyzed for error for the first time in this analysis, are far more imprecise than the age data and the SAS recommended spawn mark data (a.k.a., repeat spawner data) should be used with caution until error can be shown to be reduced to acceptable levels.

Despite the findings of the age-comparison studies and recent literature, the majority of age data provided for the current assessment still derive from scale ages obtained via execution of Cating's (1953) method or the more recent method of Elzey et al. (2015). Though otolith derived age data are becoming more available, individual programs continue to struggle with competing uses of intercepted fish, particularly in regions where fisheries, and hence fishery-dependent data collection methods, no longer exist or exist at extremely small scales, leading to generally limited annual sample sizes and the lack of time-series of multi-year paired age data. Given these constraints, the SAS was unable to explore the use of correction factors and translation tables to convert scale derived ages to otolith ages at the river system level, and given the confounding effects of non-standardized ageing methodologies and data being derived from various temporal periods, chose to not develop correction factors at the regional metapopulation level.

Though the SAS recommended limited use of spawn mark data in the current assessment, there are several areas in the assessment where spawn mark data continued to be discussed. First, spawn mark data was used to identify whether individual American shad were first time spawners in the development of maturity ogives, as detailed in Section 1.1.7. However, the scale-derived information was restricted to use as a binary assessment: first time spawner or repeat spawner. Using this information, along with available otolith derived age data, the SAS developed a matrix of age-at-capture and age-at-first spawn for each region for further use in development of maturity ogives. Further, the use of repeat spawn data is semi-formalized in many individual state's sustainable fishery management plans. As such, during reviews of the system-specific stocks, found in Section 3 of the assessment report, where appropriate available repeat spawner data is still discussed, though stock status determinations were not made in the current assessment using this data.

3. **Characterize precision and accuracy of other fishery-dependent and fishery-independent data used in the assessment, including nontraditional data (i.e., entrainment, impingement, passage). Characterization should include the following but is not limited to:**
    a. **Provide descriptions of each data source (e.g., time series, geographic location, sampling methodology and changes, potential explanation for outlying or anomalous data).**
    b. **Describe calculation and potential standardization of abundance indices.**
    c. **Discuss trends and associated estimates of uncertainty (e.g., standard errors).**
    d. **Justify inclusion or elimination of available data sources.**

American shad historically supported commercial and recreational fisheries along the entire Atlantic coast (Section 1.2), providing a source of fishery-dependent catch and effort data. These fisheries exploited spring spawning migrations of American shad, exploiting them through two types of fisheries: in-river and ocean intercept fisheries. However, these fisheries have declined dramatically over the last half century.

The SAS compiled catch statistics for commercial and recreational ocean mixed-stock and in-river American shad fisheries on the Atlantic coast. Section 1.2.1 describes the historic and current ocean and mixed-stock fisheries operating on American shad; these fisheries operated as either a directed (targeted) fishery or a "known" bycatch fishery. With implementation of Amendment 1 to the Interstate Fishery Management Plan for Shad and River Herring, the directed ocean-intercept fisheries were closed beginning in 2005, though mixed-stock fisheries in Delaware Bay (Section 1.2.1.1) and the Bay of Fundy (Section 1.2.1.2) continue to operate. Section 1.2.2 describes historic and current in-river (commercial and recreational) fisheries operating on American shad. With implementation of Amendment 3, which required the prohibition of American shad harvest without a sustainable fishery management plan (SFMP) beginning in 2013, directed in-river commercial fisheries have continued to occur in Connecticut, New Jersey, Delaware, North Carolina, South Carolina, and Georgia. Data on recreational in-river fisheries for American shad are limited or are non-existent. The Marine Recreational Information Program (MRIP) does not adequately capture information on anadromous fisheries and few states conduct creel surveys or other consistent survey instruments in inland waters. Though data are limited, it is readily apparent that substantial American shad sport fisheries occur on several individual river systems and are more limited on several other systems.

Section 3 described, by individual river system (i.e., stock unit), in-river fishery-dependent data sources (landings, biological data, indices, etc.) available. Discussions are found in system specific sections devoted to "Fishery and Management History" (e.g., Section 3.1.2 for Merrymeeting Bay) and "Fishery-Dependent Data Sources" (e.g., Section 3.1.4 for Merrymeeting Bay). Discussions of fishery-dependent data related to ocean and mixed-stock fisheries are provided in Section 4.1 as part of the coastwide metapopulation and mixed-stock analyses.

Data was provided on numerous fishery-independent data sets as part of our canvassing of data for the assessment. This included 100 individual fishery-independent survey data sets and 17 fish lift/passage counts for consideration of the development of relative abundance indices (Section 2.3.1 and Table 15-Table 20). These, along with an additional 57 (41 commercial-Table 14; 16 recreational-Table 13) fishery-dependent data sets submitted for possible index development, were assessed as to whether they met the criteria developed by the SAS for evaluating available data. Seventy-three, comprising two fishery-dependent recreational, 22 fishery-dependent commercial, 42 fishery-independent, and seven fish lift/passage count data sets, met the SAS inclusion criteria. If they met the inclusion criteria, the SAS applied regression models to data sets with complementary data that could explain variation in catchability to develop standardized indices or used nominal indices for data sets without supporting catchability data in analyses. See fishery-dependent and fishery-independent data source subsections in Sections 3 and 4 for details on system specific and mixed-stock data sets, respectively. Additionally, the SAS explored combining multiple abundance indices using the methods of Conn (2010) to develop a composite index for modelling abundance trends. The first attempt combined two indices of young-of-year (YOY) abundances in the Delaware system for modeling YOY trends (Section 3.6.5.2.3). A second composite index explored using the Conn (2010) method to combine various indices of abundance with small spatial scales for possible estimation of underlying metapopulation trends of abundance (Section 4.2.1.9), with data sets *grouped based on the coastwide or regional metapopulation structure defined in Section 1.1.2 and life stage encountered by the surveys.*

4. **Estimate bycatch where and when possible.**

Section 4.1.4 of the assessment report contains an accounting of the estimated incidental catch of American shad in U.S. oceanic state and federal waters. Using the methods described in the most recent river herring assessment (ASMFC 2017a), the total (retained and discarded) incidental catch of American shad from 1989-2017 was quantified, with uncertainty measures, by fleet using the combined ratio method (Wigley et al. 2007). Fleets considered were only those sampled by the Northeast Fisheries Observer Program (NEFOP) and were stratified by region fished, time, gear group, and mesh size. However, due to a lack of genetic information and the likely extent of stock mixing on the shelf, it is not possible to attribute these incidental catch estimates to particular stocks of American shad, or is it possible to determine the level of mortality that these catch estimates represent because of the lack of coastwide estimates of absolute abundance.

While absolute incidental catch estimates from ocean fisheries covered by the NEFOP have become available since the last stock assessment, genetics for partitioning among stocks is still a considerable data limitation that needs to be addressed (Section 5.2.1). Further, quantification of discards is still needed for the Delaware Bay mixed-stock, the Bay of Fundy Fisheries, and in-river and coastal fisheries not well covered by NEFOP to identify fisheries discarding shad (Section 5.2.3).

5. **Summarize data availability and trends by stock.**

Section 3 of the assessment report provides a system specific accounting of the data available (fishery-dependent and fishery-independent) by individual stocks. Based on the available data, the trends of each stock were assessed using any combination of Mann-Kendall analysis (Sections 2.3.3 and 2.4), delay difference models (Section 2.7.1), or other population models (Section 2.7.3). The SAS also used power analysis (Section 2.3.4) to calculate the probability of detecting trends in the abundance indices given the observed levels of uncertainty of individual surveys. Methods attempted, based on data availability, to summarize trends and results obtained for each stock are detailed in individual system accounts (e.g., Sections 3.1.6 and 3.1.7 for the Merrymeeting Bay stock).

Likewise, Sections 4.1 and 4.2 provides an accounting of the available fishery-dependent and fishery-independent data available to assess trends of American shad at the coastwide metapopulation level. Similar to individual stock accounts, Mann-Kendall analysis (2.3.3), and autoregressive integrated moving averages (ARIMA, Section 2.3.2) were used to evaluate trends in abundance at the metapopulation level and power analysis (Section 2.3.4) was used to assess the power to detect trends in the mixed-stock abundance indices given the observed levels of uncertainty of individual surveys. The SAS notes that due to the unknown stock composition of American shad captured in mixed-stock surveys, it is difficult to infer trends in population status *relative to any one specific stock from these analyses. Therefore, the SAS recommends the coastwide metapopulation trend analyses should only be interpreted as trends in relative abundance of American shad metapopulation status relative to the 2005 index value in each survey, respectively.*

6. **If possible, develop models used to estimate population parameters (e.g., Z, biomass, abundance) and biological reference points, and analyze model performance.**
    a. **Briefly describe history of model usage, its theory and framework, and document associated peer-reviewed literature. If using a new model, test using simulated data.**
    b. **Clearly and thoroughly explain model strengths and limitations.**
    c. **Discuss the effects of data strengths and weaknesses (e.g., temporal and spatial scale, gear selectivity, ageing accuracy, sample size) on model inputs and outputs.**
    d. **State assumptions made for all models and explain the likely effects of assumption violations on synthesis of input data and model outputs. Examples of assumptions may include (but are not limited to):**
        - **Choice of stock-recruitment function.**
        - **Calculation of M. Choice to use (or estimate) constant or time-varying M and catchability.**
        - **Choice of equilibrium reference points or proxies for MSY-based reference points.**
        - **Choice of a plus group for age-structured species.**
        - **Constant ecosystem (abiotic and trophic) conditions.**
    e. **Justify choice of coefficients of variation (CVs), effective sample sizes, or likelihood weighting schemes.**
    f. **Describe stability of model (e.g., ability to find a stable solution, invert Hessian).**
    g. **Perform sensitivity analyses for starting parameter values, priors, etc. and conduct other model diagnostics as necessary.**
    h. **Characterize uncertainty of model estimates and biological or empirical reference points.**
    i. **If multiple models were considered, justify the choice of preferred model and the explanation of any differences in results among models.**

The current assessment used a combination of assessment approaches to assess the status of American shad at the individual river system level. A combination approach was warranted given the variability in data available across individual stocks (i.e. systems).

First, power analyses were used to calculate the probability of detecting trends in the abundance indices using the approach of Gerrodette (1987; Section 2.3.4). The SAS established a reference point of a power of 0.80 for surveys to detect an increasing trend. All surveys that were developed into abundance indices and possessed annual estimates of uncertainty in abundance were tested.

Second, the SAS used ARIMA analysis of trawl survey relative abundance indices (Section 2.3.2) to provide a means to filter measurement error from process variability (Box and Jenkins 1976; Helser and Hayes 1995), and hence provide time series estimates of abundance where the variance of the fitted estimates is less than the variance of the observed time series (Pennington 1986). As a reference point, ARIMA models used the 2005 bootstrapped fitted abundance index value; this reference point allows for the evaluation of the status of American shad in response to the closure of the ocean intercept fishery. For surveys starting after 2005, the terminal year was compared to the first year of the survey.

The SAS also used Mann-Kendall trend analysis to detect trends in each survey index of abundance (Section 2.3.3) and to detect temporal trends in mean length and mean length-at-age (Section 2.4). For the indices, two separate Mann-Kendall analyses were completed for each available survey, one using the complete time series provided for each survey, as well as the period of all years from 2005 forward. The second time period, similar to the use of the ARIMA analysis, was used to examine possible responses in indices after the closure of the ocean-intercept fishery. For detection of trends in mean length and mean length-at-age, only datasets containing sex information and a minimum time series of 10 years with at least thirty fish sampled per year were analyzed. Changes in mean length over time can be indicative of demographic shifts in a population.

Next, the SAS used total mortality estimators developed using weighted catch-curve regressions (Section 2.6) as a means to assess whether the total mortality of stocks are at or below stock assessment benchmarks. To establish mortality benchmarks, the SAS used a modified Thompson-Bell spawning biomass per recruit (SBPR) model (Section 2.5) to develop instantaneous total mortality (Z) biological reference points (BRP) for American shad. Based on available, and region specific life history data, regional SBPR BRPs were developed for the northern iteroparous, southern iteroparous, and semelparous stocks, with the total mortality that reduced SBPR to 40% of unfished levels ($Z_{40\%}$) being chosen as the region specific BRP.

The SAS also used several classes of population models to assess the status of individual stocks (Section 2.7) depending on data availability. These included the use of delay difference models (Section 2.7.1), and habitat assessment and simulation modeling (Section 2.7.2). The SAS used delay difference models, as implemented in the DLMtool package (Carruthers and Hordyk 2019) in R to calculate total allowable catch (TAC) for several systems possessing the underlying data requirements (time series of annual catch, index of abundance and estimates of life history parameters) and active fisheries. Habitat assessment and simulation models were used to assess the theoretical impact of impoundments on American shad range wide, which also required the SAS to simulate the population for each identified system. This approach allowed the comparison of three broad scale scenarios: i) historical or "intact" rivers, ii) worst case scenario with current dams and "no passage", and iii) dams with imposed realistic up- and downstream passage to best reflect the "status quo."

Other specialized population models were used in system specific settings. The first of these was the development of a combined mark-recapture and biomass surplus production model (SPM) to *produce population estimates of American shad in the Conowingo Dam tailrace (Section 3.8.7.1) by the Maryland Department of Natural Resources. Data was also sufficient to model two populations, the Potomac River (Section 3.10.7.1) and Albemarle Sound (Section 3.14.7.1), using relatively simple forward-projecting statistical catch-at-age models. The Potomac River model was developed using the integrated statistical framework software Stock Synthesis, version 3.30.14 (Methot and Wetzel 2013). The Albemarle Sound model was developed using the An Age Structured Assessment Program (ASAP), which is an age-structured model that uses forward computations, assuming separability of fishing mortality into year and age components, to estimate population sizes given observed catches, catch-at-age, and indices of abundance. Both the Stock Synthesis and ASAP frameworks allowed for the integration of the relatively robust data sets available for the Potomac River and Albemarle Sound populations into a unified statistical catch-at-age model. Finally, the Georgia Department of Natural Resources provided estimates of minimum exploitation rates and population estimates using mark-recapture studies on the Altamaha River (Section 3.22.5.1).*

As multiple models were available at both the individual system and coastal metapopulation and mixed-stock analyses scales, the methods used to assess individual stocks and the coastwide metapopulation are discussed in Sections 3 and 4, as appropriate.

7. **Recommend stock status as related to reference points, if available.**

The SAS discusses the broad stock status determination framework used in the current assessment in Section 2.8. The SAS considered the status of stocks from two perspectives: abundance and mortality. There were two categories of analyses for the SAS to make stock status determination: total mortality estimators compared to per-recruit reference points and population models compared to per-recruit reference points or TAC reference points. The SAS used abundance trends to assess abundance relative to reference points to investigate abundance changes since the beginning of the respective monitoring program or the implementation of a significant coastwide management change; abundance trends were not used to make conclusions on abundance status. For total mortality status, the SAS made an objective decision that mortality status could only be made for systems with estimates in the last three years of the assessment time series, with a determination made of whether mortality status was sustainable, unsustainable, or unknown if terminal three year average mortality was less than or equal to the reference point, greater than the reference point, or unknown, respectively. Section 2.5 contains greater detail on the methodology used to calculate per-recruit reference points for comparison to total mortality estimators. Status determination for systems with population models applied are dependent on objectives of two types of models: delay-difference models used to estimate mortality status and statistical catch-at-age models used to estimate both abundance and mortality status relative to internally estimated per-recruit reference points. The SAS was not comfortable setting catch recommendations using delay-difference models, instead choosing to compare the median TAC values to the average catch of the final three years to assess mortality status and the 25th and 75th percentiles are compared to the average catch of the final three years to characterize uncertainty of stock status. The SAS also provided qualitative determinations of Hudson River and coastwide *metapopulation abundance statuses based on historical landings time series and recent trends of abundance.*

Status determinations, where available, are found in individual "Stock Status and Conclusions" for individual systems in Section 3 and for the coastwide metapopulation in Section 4.5.

8. **Other potential scientific issues:**
    a. **Compare trends in population parameters and reference points with current and proposed modeling approaches. If outcomes differ, discuss potential causes of observed discrepancies.**
    b. **Compare reference points derived in this assessment with what is known about the general life history of the exploited stock. Explain any inconsistencies.**
    c. **Explore climate change impacts on the species.**
    d. **Explore predation impacts on the species.**
    e. **Discuss all known anthropogenic sources of mortality and productivity (i.e., stocking, passage mortality) by stock.**

Interwoven throughout the assessment report is an undercurrent of discussion regarding caveats and other potential scientific issues affecting the stock specific abundance of American shad. In Section 1.1, several subsections about the life history of American shad discuss potential scientific issues. These include a brief discussion of their distribution and migration (Section 1.1.1), particularly with respect to their spawning migrations and behaviors and how they vary across their geographic range. Section 1.1.5 (Growth) includes an extensive discussion of how growth shows a clinal relationship with latitude and how current climate change forecasts may affect growth of American shad in the coming decades. In the section devoted to reproduction (Section 1.1.6), the SAS includes brief discussions of clinal changes in spawning periods and regional differences in reproductive strategy (semelparous vs iteroparous). The maturity section (Section 1.1.7) discusses in great detail the difficulties the SAS has in developing maturity ogives for American shad populations, given the fishery operates near exclusively on mature individuals, there is a geographic displacement of mature and immature fish of the same age during the execution of the fisheries and surveys, the limited information available on rates and sources of mortality in the oceanic environment, and the difficulty of identifying first time vs repeat spawners. The Natural Mortality section (Section 1.1.8) includes a discussion highlighting the current difficulty the SAS faces with regard to estimating natural mortality due to the impact habitat modification (e.g., dams) has had on natural rates. Finally, Section 1.1.9 (Habitat Requirements) discusses the habitat requirements of American shad, particularly the reduction in available freshwater spawning and nursery habitat available due to the construction of dams across the range of the species, how dams and associated fish passages have affected the mortality experienced by migrating (up- and down-drainage) American shad, and the vulnerability of American shad to climate change.

One attempt to account for the broad scale impact that habitat alteration via dams has had on the productivity of individual American shad stocks was the Habitat Assessment and Simulation Modeling (Section 2.7.2) conducted as part of the assessment. This was an attempt to estimate the opportunity cost realized by this species through dam construction. In order to assess the theoretical impact of impoundments on American shad range wide, the SAS simulated the population potential for each identified system, and compared three broad scale scenarios: i) historical or "intact" rivers, ii) worst case scenario with current dams and "no passage", and iii) dams with imposed realistic up and downstream passage to best reflect the "status quo."

Individual system assessments (Section 3) provide a brief review of the in-river habitat available in the system, impacts of dams and other barriers on the available habitat based on the habitat assessment and simulation modeling, passage efficiency estimates at dams, water quality impacts, including water withdrawals, and invasive species impacts. These are coalesced, where available, into an understanding of how anthropogenic sources of mortality and productivity are affecting American shad in individual systems. Finally, in Section 4.4.2 the SAS provides the results of the coastwide habitat assessment and simulation modeling.

9. **If a minority report has been filed, explain majority reasoning against adopting approach suggested in that report. The minority report should explain reasoning against adopting approach suggested by the majority.**

A minority report has not been filed.

10. **Develop detailed short and long-term prioritized lists of recommendations for future research, data collection, and assessment methodology. Highlight improvements to be made by initiation of next benchmark stock assessment. Note research recommendations from the previous assessment that have not been addressed and those that have been partially or fully addressed.**

The SAS developed a detailed list of research recommendations (Section 5.2) for future data collection (Section 5.2.1), assessment methodology (Section 5.2.2), research (Section 5.2.3), and management (Section 5.2.4) of American shad. While all recommendations are high priority, they are identified as low, moderate and high priority research objectives. Each category is further broken down into recommendations that can be completed in the short-term and recommendations that will require long-term commitment.

Section 5.3 addresses research recommendations made during the 2007 American shad stock assessment peer review, and efforts made during the current assessment to address said recommendations. The SAS identified prior recommendations that have been only partially addressed or not addressed at all during the current assessment, where appropriate.

11. **Recommend timing of next benchmark assessment and intermediate updates, if necessary relative to biology and current management of the species.**

The SAS recommends the next American shad stock assessment be conducted in ten years (2030) as a benchmark stock assessment (Section 5.1). The basis for this time frame is current *data limitations and uncertainty. Given the large number of individual systems assessed, the SAS recommends conducting the assessment in a staggered approach assessing systems within each region (northern iteroparous, southern iteroparous, semelparous; not necessarily in this order) subsequently during the stock assessment.*

Terms of Reference for Peer Review of ASMFC American Shad Benchmark Stock Assessment

1. **Evaluate choice of stock structure.**

2. **Evaluate the thoroughness of data collection and the presentation and treatment of fishery-dependent and fishery-independent data in the assessment, including the following but not limited to:**
    a. **Presentation of data source variance (e.g., standard errors).**
    b. **Justification for inclusion or elimination of available data sources.**
    c. **Consideration of data strengths and weaknesses (e.g., temporal and spatial scale, gear selectivities, ageing accuracy, sample size).**
    d. **Calculation and/or standardization of abundance indices.**
    e. **Estimation of bycatch.**

3. **Evaluate the methods and models used to estimate population parameters (e.g., Z, biomass, abundance) and biological reference points, including but not limited to:**
    a. **Evaluate the choice and justification of the preferred model(s). Was the most appropriate model (or model averaging approach) chosen given available data and life history of the species?**
    b. **If multiple models were considered, evaluate the analysts' explanation of any differences in results.**
    c. **Evaluate model parameterization and specification (e.g., choice of CVs, effective sample sizes, likelihood weighting schemes, calculation/specification of M, stock-recruitment relationship, choice of time-varying parameters, plus group treatment).**
    d. **Evaluate the diagnostic analyses performed, including but not limited to:**
        - **Sensitivity analyses to determine model stability and potential consequences of major model assumptions.**
    e. **Evaluate the methods used to characterize uncertainty in estimated parameters. Ensure that the implications of uncertainty in technical conclusions are clearly stated.**

4. **If a minority report has been filed, review minority opinion and any associated analyses. If possible, make recommendation on current or future use of alternative assessment approach presented in minority report.**

5. **Recommend best estimates of stock biomass, abundance, and exploitation from the assessment by stock for use in management, if possible, or specify alternative estimation methods.**

6. **Evaluate the choice of reference points and the methods used to determine or estimate them. Recommend stock status determination from the assessment, or, if appropriate, specify alternative methods/measures for management advice.**

7. **Review the research, data collection, and assessment methodology recommendations provided by the TC and make any additional recommendations warranted. Clearly prioritize the activities needed to inform and maintain the current assessment, and provide recommendations to improve the reliability of future assessments.**

8. **Recommend timing of the next benchmark assessment and updates, if necessary, relative to the life history and current management of the species.**

9. **Prepare a peer review panel terms of reference and advisory report summarizing the panel's evaluation of the stock assessment and addressing each peer review term of reference. Develop a list of tasks to be completed following the workshop. Complete and submit the report within 4 weeks of workshop conclusion.**

1 INTRODUCTION

This document provides a benchmark assessment of American shad (*Alosa sapidissima*) stocks of the U.S. Atlantic Coast from Maine through Florida. It is organized into three major sections: (1) an introductory overview that provides background information on the species biology and fishery management history at the coastwide level; (2) a general methods section that explains the assessment approach and analyses performed for this assessment; and (3) individual assessments of American shad stocks with system-specific and mixed-stock analyses and stock status determinations.

This document was prepared by the Atlantic States Marine Fisheries Commission's (ASMFC) Shad and River Herring Technical Committee (TC) and Shad and River Herring Stock Assessment Subcommittee (SAS). Data were obtained from Federal, State, and regional freshwater and marine resource management agencies, power generating companies, and universities. The SAS and TC routinely interacted with data collectors and data managers to ensure that application and interpretation of data were appropriate. Data collation and review occurred at a Data Workshop attended by TC and SAS members (Baltimore, MD; March 5-8, 2018), methods to assess stocks were identified at a Methods Workshop attended by SAS members (Providence, RI; November 5-8 2018), and assessment results were reviewed at an Assessment Workshop attended by SAS members (Charleston, SC; November 18-22, 2019). Assessment results were subsequently reviewed by the TC and approved for peer review at a webinar on March 23, 2020.

1.1 Biology and Life History

A broad overview of American shad life history information pertinent to assessment of the species is provided below. Additional information on system-specific life history, where available, can be found within the individual system stock assessment sections (Section 3).

1.1.1 Distribution and Migration

American shad are an anadromous, pelagic, highly migratory, schooling species (Collette and Klein-MacPhee 2002). The historical range of American shad extended from Sand Hill River, Labrador, Newfoundland, to Indian River, Florida, in the western Atlantic Ocean (Lee et al. 1980; Morrow 1980). The present range extends from the St. Lawrence River in Canada to St. Johns River, Florida. In addition, American shad were introduced to the Sacramento River in California, and the Columbia, Snake, and Willamette rivers in Oregon in the late 1800s. Since that time, the species' range in the Pacific Ocean has expanded to Cook Inlet, Alaska, and the Kamchatka Peninsula, Russia, south to Todos Santos Bay, Baja California (Lee et al. 1980; Howe 1981). Attempts to introduce the species in the Gulf of Mexico, Mississippi River drainage, Colorado streams, and the Great Lakes were unsuccessful (Walburg and Nichols 1967; Whitehead 1985). Interestingly, a landlocked population exists in a reservoir of the San Joaquin River on the Pacific coast, but no landlocked populations have been reported along the Atlantic coast (Zydlewski and McCormick 1997a). This document will focus on behaviors of Atlantic populations of anadromous American shad.

American shad spend most of their lives in marine waters, with adults migrating into coastal rivers and tributaries to spawn. On average, American shad spend four to five years at sea, and some individuals from the southernmost range may travel over 20,000 km during this time period (Dadswell et al. 1987). Researchers believe the historical spawning range of American shad included all accessible rivers and tributaries along the Atlantic coast (MacKenzie et al. 1985). Additionally, rivers, bays, and estuaries associated with spawning reaches are used as nursery areas by juvenile American shad (ASMFC 1999).

The existing Atlantic coast stocks of American shad have a geographic range that currently extends from the St. Johns River, Florida, to the St. Lawrence River, Canada (see above for historic range). Scientists estimate that this species once ascended at least 130 rivers along the Atlantic coast to spawn, but today spawning runs occur in fewer than 70 systems (Limburg et al. 2003). Most American shad return to their natal rivers and tributaries to spawn (Fredin 1954; Talbot 1954; Hill 1959; Nichols 1966a; Carscadden and Leggett 1975), although on average, 3% stray to non-natal river systems (Mansueti and Kolb 1953; Williams and Daborn 1984; Melvin et al. 1985). In fact, Hendricks et al. (2002) demonstrated that hatchery-reared American shad homed to a specific tributary within the Delaware River system several years after stocking, and also preferred the side of the tributary influenced by the plume of their natal river. The degree of homing by American shad may depend on the nature of the drainage system. If so, mixing of stocks and consequent straying would more likely occur in large and diversified estuarine systems, such as the Chesapeake Bay, while more precise homing could be expected in systems that have a single large river, such as the Hudson River (Richkus and DiNardo 1984).

American shad spring spawning migrations begin in the south and move gradually north as the season progresses and water temperatures increase (Walburg 1960). Spawning runs typically last 2-3 months, but may vary depending on weather conditions (Limburg et al. 2003). The diel timing of migration may not vary greatly from region to region. In the James River, Virginia, spawning adults ascended mostly between 0900 and 1600 hours (Weaver et al. 2003). Arnold (2000) reported similar results in the Lehigh River, Pennsylvania, where American shad passed primarily between 0900 and 1400 hours. Male American shad arrive at riverine spawning grounds before females (Leim 1924).

American shad show varied preferences for migration distance upstream depending on the river system. There does not seem to be a minimum distance from brackish waters at which spawning occurs (Leim 1924; Massmann 1952), but upstream and mid-river segments appear to be favored (Massmann 1952; Bilkovic et al. 2002). It is not unusual for American shad to travel 25 to 100 miles upstream to spawn; some populations historically migrated over 300 miles upstream (Stevenson 1899; Walburg and Nichols 1967). In the 18th and 19th centuries, American shad runs were reported as far inland as 451 miles along the Great Pee Dee and Yadkin rivers in North Carolina (Smith 1907) and over 500 miles in the Susquehanna River (Stevenson 1899).

Another interesting aspect of American shad migration is the regional difference in spawning periodicity. Generally, American shad that spawn north of Cape Hatteras are iteroparous (spawn more than once), while American shad spawning south of Cape Hatteras are semelparous (die after one spawning season). This may be due to the fact that south of North Carolina the physiological limits of American shad are stretched during long oceanic migrations; higher southern water temperatures may also have an effect (Leggett 1969). Moreover, Leggett and Carscadden (1978) suggest that southern stocks produce more eggs per unit of body weight than northern populations to compensate for not spawning repeatedly.

1.1.2 Metapopulation and Stock Structure

As an anadromous species, ideally American shad should be assessed and managed as individual river or tributary stocks. However, the majority of the life history of American shad is spent in the marine environment where factors influencing survival likely have impacts upon multiple river stocks when they mix during marine migrations. The complex life history of anadromous species complicates assessments on a coastwide scale, as it is difficult to partition in-river factors from marine factors governing population dynamics.

Since the 2007 Benchmark American Shad Assessment (ASMFC 2007b) was completed, additional research on stock structure has been published using genetic microsatellite, otolith microchemistry, and fish tagging and marking methods. Collectively, this research all continues to support species assessment and management at the river system level, consistent with the 2007 Peer Review Report (ASMFC 2007a). Specific Peer Review items related to stock structure included (abbreviated here): need for better identification of stock composition in mixed-stock harvest and spatially delineate between mixed-stock and Delaware stock areas within the Delaware River system.

Genetic differentiation among individual populations, especially south of the U.S.-Canadian border, varies at scale and on technique (e.g. number of loci used). Hasselman et al. (2013) examined 33 populations across the species range, using 13 microsatellite loci, increasing statistical power from earlier studies using fewer loci. The extent of detected genetic differentiation, based on several different measures, varied widely over space with the authors concluding, “Although this study largely supports the hypothesis that rivers comprise genetically distinguishable American shad populations, genetic differentiation among some U. S. rivers was not significant.” Analysis within the U. S. revealed two genetic groupings: central and northern iteroparous populations versus southern semelparous populations (Hasselman et al. 2013). Causes for lack of genetic variation within the northern U.S. groups were partially attributed by Hasselman et al. (2013) to human activities such as widespread stock transfers for restoration in New England and parts of the Middle Atlantic, and the last glaciation which may have reduced existing genetic differences. For example, American shad from the Potomac River have been collected for restoration stocking programs in Maryland rivers, Virginia's Rappahannock River, the Susquehanna River (MD/PA) and some of Delaware's rivers for approximately 15 years. The Potomac River-sourced stocking programs could further influence future genetic differentiation of these specific river populations.

In addition, in the northern U. S. populations, habitat modification and declining populations may have also disrupted patterns of genetic variation through alterations of natural movement patterns between populations, and declining populations may have reduced genetic differentiation. In the southern U. S. populations, Hasselman et al. (2013) suggested environmental conditions such as a longer duration of favorable spawning temperatures might have contributed to a greater potential for straying and therefore increased gene flow among southern populations. Hasselman et al. 2013 inferred that the differentiation between the northern and southern groupings was likely due to differences in reproductive strategies, but that this delineation was also supported by differences in environmental and physical (such as biogeographical provinces) changes along the coast.

A greater degree of genetic distinction between rivers was noted among studied Canadian rivers by Hasselman et al. (2010) and later discussed in Hasselman et al. (2013), where transfers between rivers and habitat modifications have had less of an impact to populations. The authors stated that their findings "suggested that effective management of Canadian American shad populations require 'river level' approach."

The ability to differentiate among American shad populations has increased with the development and application of advancing genetic methods. Initially, ability to discriminate among populations was limited (Bentzen et al. 1989), and increased only slightly when able to evaluate mitochondrial DNA haplotype diversity (Epifanio et al. 1995). With the application of nuclear DNA-based microsatellite markers, greater differentiation was detected among native regions (Hasselman et al. 2013), allowing for analysis of individual population composition to mixed-stock fisheries.

Waldman et al. (2014) was able to apply the baselines for American shad populations developed by Hasselman et al. (2013) to test the ability to discriminate among population origin of two mixed-stock fisheries: Delaware Bay and Bay of Fundy. For stock identification among both mixtures, they used potential source populations from throughout the range of American shad along the eastern coast of North America. Typically, mixed-stock analyses include an assessment of the ability to genetically differentiate among source populations by providing a metric of self-classification. This metric is based on the genetic differences (i.e. differences in allele frequencies) among populations. For example, a population that is genetically distinct from the other populations would be correctly reassigned to its own population ideally 100% of the time. Waldman et al. (2014) provided classification abilities only for the discriminatory power between the Hudson and Delaware Rivers, which was 73%. Population differentiation, inferred from metrics provided in Hasselman et al. (2013, e.g. pairwise Fst values, Structure results), indicate population assignment to populations in the northern part of the range would likely be feasible based on significant differences in allele frequencies, but moving southward in the range the ability to discriminate among source populations would not likely be possible due to low and insignificant differences in allele frequencies (Hasselman et al. 2013).

Evaluation of a mixed-stocked fishery by Waldman et al. (2014) considered samples collected in two different collection years, 2009 and 2010, and was based on allele frequencies from 12 microsatellite loci. When considering just the Hudson and Delaware populations as potential sources for the two collection years, composition of the 2009 sample (n=71) was 46.7%

(CI=0.309-0.707) Hudson River and 53.3% (CI=0.293-0.691) Delaware River. From the 2010 sample (n=229), the composition was 53.3% (CI=0.423-0.672) Hudson River and 46.7% (CI=0.328-0.577) Delaware River (Waldman et al. 2014). Assignments to other potential source populations was also conducted for the 2010 sample year, but the ability to differentiate among those sources was not reported.

A similar analysis was conducted by the United States Fish and Wildlife Service (USFWS) Northeast Fishery Center, Lamar, Pennsylvania to evaluate the composition of Delaware Bay captured American shad during the spring of 2017. In total, 361 individuals were sampled, ranging from the outer portion of the bay to upriver within the Delaware River at Smithfield Beach, PA. Individuals sampled, as well as a reference baseline of American shad sampled from numerous rivers along the Atlantic coast, were characterized at 16 microsatellite loci, which included the 12 loci referenced in Waldman et al. (2014). Using similar methods, baseline assignment to either the Hudson or Delaware populations were similar to that identified by Waldman et al. (2014), with 75.6% -78.1% of the Hudson River being correctly assigned back to the Hudson River population, and 62.8% -77.0% of the Delaware River population being correctly assigned to the Delaware River population with the range representing different years the reference population was sampled. Of the samples collected from the Delaware Bay in 2017, 27.1% of the 2017 samples were assigned to the Hudson River, and 72.9% were assigned to the Delaware River. Samples from American shad were also collected in 2018 and 2019 from the Delaware Bay and will be similarly analyzed to determine assignment to potential source populations, including the Hudson and Delaware Rivers.

Among southern U.S. populations, where genetic differences were less evident (Hasselman et al. 2013), Moyer and Williams (2012) evaluated five collections in South Carolina to determine if spatial genetic structure could be detected at a fine scale using microsatellite loci. They evaluated samples from the Cooper, Santee, Wateree rivers, as well as a hatchery stock from the Santee River. Moyer and Williams (2012) found no genetic differences or structure within the system. Structure analyses identified only two genetic groups within the collection. However, recent studies have used similar methods on some overlapping rivers to provide sufficient resolution to detect weak differentiation among rivers in North and South Carolina (Cushman et al. 2019).

The addition of more genetic markers such as increasing the number of microsatellite loci, the use of single nucleotide polymorphisms (SNPs), or next-generation sequencing technology may provide further resolution of genetic structure. However, even if additional structure is observed, the current state of the science is not necessarily negated, in that genetic differentiation among populations is likely weak especially among U. S. populations, otherwise genetic structure would be more apparent in the studies conducted to date.

Other supporting research for American shad stock discrimination is based on otolith microchemistry. Walther et al. (2008) used both isotope and elemental-based otolith signatures to examine juvenile American shad from Georgia to New Hampshire, and identified a low stray rate (6%) of adults not native to the York River, Virginia. In addition, the authors did not detect any evidence of tributary-specific homing between the two primary tributaries of the York. The degree of natal river homing is also supported in Hoenig et al. (2008) where they report four fish sampled in the James River, Virginia, from 419 examined over a five year period had been stocked in the nearby Pamunkey River, Virginia, identified by otolith hatchery marks.

Evaluation of other information, such as life history traits (especially homing/straying), tagging studies, habitat distribution, management frameworks, and migratory patterns are important factors to consider in addition to the genetic data to consider the appropriate geographic scale of stock structure.

In this assessment, stock structure for American shad treats each main stem river and it's identified tributaries as an individual stock unit, unless there is justification from one of the above sources that supports the need for a broader system definition (e.g., Merrymeeting Bay, Albemarle Sound, Upper Chesapeake Bay, Winyah Bay, ACE Basin). Additionally, due to data limitations, three regional metapopulations were identified based on reproductive strategy and genetic studies (Hasselman et al. 2013) to share life history information in assessment approaches. The semelparous metapopulation consists of stocks from Florida to the Cape Fear River, NC, the southern iteroparous metapopulation consists of stocks north of the Cape Fear River to the Hudson River, NY, and the northern iteroparous metapopulation consists of stocks north of the Hudson River. The Cape Fear River is considered the transition between reproductive strategies (J. McCargo, North Carolina Wildlife Resources Commission-NCWRC, personal communication) and is grouped with the semelparous metapopulation since it flows into the Atlantic Ocean south of Cape Fear, NC. Table 1-Table 3 list all systems, including tributaries, in each regional metapopulation. Due to the mixed-stock composition of many data sets available for the assessment and the lack of data to define stock composition, analyses of these mixed-stock data sets are also provided in the assessment to inform condition of the coastwide metapopulation.

1.1.3 Morphometric Relationships

1.1.3.1 Length-Length Conversions

Length data from coastwide monitoring programs across 48 waterbodies in 27 identified systems were submitted for potential use in the assessment (Table 13-Table 20). Fork length (FL) in millimeters (mm) was selected as the preferred length type and unit in the assessment, but data from several monitoring programs only included total length (TL) information. Paired TL- FL measurements were provided from 60 separate monitoring programs across 31 waterbodies in 22 identified systems. The SAS decided that there was no biological basis to use sex, region, or stock-specific conversion of FL to TL, therefore only a single relationship was used in this assessment to covert TL to FL. A single linear regression analysis was applied to a composite data sets of all paired TL-FL measurements (n = 195,127; FL = 0.882 TL + 0.28; R^2 = 1.00).

1.1.3.2 Length-Weight Relationships

Paired length-weight observations provided in biological sampling data (Table 13-Table 20) were combined to develop regional metapopulation length-weight relationship parameters due to latitudinal differences in weight-at-length (Leggett and Carscadden 1978). TL observations were converted to FL with the coastwide regression estimates, where necessary (Section 1.1.3.1). Observations without sex determination were dropped from the analysis and only data sets from monitoring programs that collected at least 100 samples were included in the final data set. As would be expected, there was indication of different length-weight relationships among maturity statuses (i.e., gravid/not yet ripe, flowing, spent). However, these data were too limited to estimate relationships by maturity status, particularly from the semelparous and northern iteroparous regions.

Predicted and observed length-weight relationships are provided in Figure 1-Figure 6. Relationship parameter estimates and data summaries are provided in Table 4. Weight-at-length of smaller, immature fish (≈≤400 mm FL) increases moving from southern, semelparous stocks to northern iteroparous stocks (Figure 7). This pattern reverses starting at approximately 400 mm FL when weight-at-length decreases moving from southern, semelparous stocks to northern iteroparous stocks.

1.1.4 Age

Historically, American shad have primarily been aged from scales according to Cating (1953). Cating's method relies on transverse groove frequencies on scales to assist with identifying the location of freshwater zones and the first three annuli for age determination. The method was validated for ages 4-6 in the Connecticut River using recaptures of hatchery-reared fish that had pelvic fin clips (Judy 1960). During the last American shad stock assessment, there was some indication that scales aged using Cating's method, and potentially scale-based ages in general, may not be reliable sources of age data (ASMFC 2007b). Issues identified with scale age estimates were low precision (between readers and compared to otolith age estimates), bias that resulted in patterns of overestimated age for younger fish and underestimated age for older fish, and the potential that Cating's method may not be applicable to other rivers along the coast.

Additional work investigating these issues since the last assessment has further supported these early indications and suggests otoliths are the most reliable structure for determining age. Duffy et al. (2011) found that transverse groove frequencies are more closely related to scale size than age and appear to vary over time and between latitudinal locations. At about the same time, Upton et al. (2012) used natural isotopic signatures in otoliths from fish in the York River to obtain known age fish and found that scale age estimates using Cating's method were often (≈50%) inaccurate. To follow this work, Duffy et al. (2012) validated otolith ages from hatchery-reared fish marked with oxytetracycline (OTC) and recaptured 3-9 years later as spawning adults in the Delaware River. Elzey et al. (2015) compared precision among ages derived from four structures collected from American shad in the Merrimack River: otoliths, vertebrae, scales, and opercula. The authors found scale age estimates were overestimated in young fish (<5 years) and underestimated in older fish (>7 years) relative to otolith age estimates. Otolith age estimates from multiple readers were determined to be the most precise (mean coefficient of variation of 2.99%) and the authors concluded that otoliths provide the most reliable age estimates for American shad.

These findings have resulted in increasing collection of otoliths for age data and changes in ageing procedures for scales since the last stock assessment.

1.1.4.1 Example Ageing Protocol

The following is an example of a standard alosine ageing protocol, including American shad, developed concurrent to this assessment (S. Vanderkooy, editor, Gulf States Marine Fisheries Commission, personal communication). The protocol is generalized for alosine species with similar ageing nuances, including river herring species (blueback herring-*Alosa aestivalis* and alewife-*Alosa pseudoharengus*), and is included here as an example to assist with standardizing current agency-specific ageing protocols (see Section 1.1.4.2) in the future, a research recommendation provided as part of the stock assessment (see Section 5).

1.1.4.1.1 Otolith Description

Otoliths (sagittae) from the herring family are thin with a well-defined rostrum (Figure 8). Crystalized otoliths are seen somewhat frequently and are often broken during removal. The relative position of the sagittae in the neurocranium is illustrated in Figure 9.

1.1.4.1.2 Otolith Extraction

The sagittal otoliths are thin and may break during extraction if handled roughly. Removal of both otoliths is preferred as it is not uncommon to find that one is crystallized. While many extraction techniques can be used, removal using a mostly horizontal cut over the eye sockets is the most simple. Once the top of the cranium is removed, the otoliths are fairly easy to get out using a pair of very fine forceps and following the procedure illustrated in Figure 10.

1.1.4.1.3 Otolith Preparation

Otoliths should be clean and dry prior to ageing. Otoliths freshly removed from fish will appear slightly translucent and will be much more difficult to age than otoliths that have had several hours to air dry. The thinness of the otoliths makes them easy to read whole, so no sectioning is needed. For alosine species, whole otoliths are recommended for ageing, so little preparation is necessary; make sure otoliths are clean before ageing and use water to clean off any debris.

1.1.4.1.4 Scale Description

Alosine scales are cycloid and have a strong boundary (baseline) between the anterior and posterior portions. The scales are thin and flexible with transverse grooves vertically (note that in all scale pictures the anterior portion of the scale is up) across the scale (Figure 11). Alosines are anadromous, therefore the area closest to the center of the scale is formed in fresh water and is therefore referred to as the freshwater zone. Typically a strong check mark is laid down when the fish leave freshwater.

1.1.4.1.5 Scale Collection

A patch of scales should be removed from just ventral of the dorsal fin as shown in Figure 12. The collector should try to avoid areas of obvious damage or scale regeneration. Scales are easily collected by scraping posterior to anterior with a knife or scalpel. The knife should be wiped clean after each fish to avoid cross contamination. When working with dead fish it is best to scrape away the mucus coating prior to removing the scale sample. This will make cleaning the scales easier.

1.1.4.1.6 Scale Processing

Scales need to be cleaned and mounted between two glass slides before being aged. Do not put tape directly over the scales as the edges can become distorted and the scales may mold over time.

1.1.4.1.7 Age Determination

Otoliths

For all alosine species, it is recommended to view whole otoliths immersed in a clearing fluid, (mineral oil, cedar oil or water work well) sulcus side down, on a black background using a stereomicroscope with reflected light. In practice, annuli are counted as the transition between the narrow translucent (dark) zones and the wider opaque (white) zones (Figure 13). The translucent zones should be continuous around the otolith with no breaks. Annuli are typically counted from the middle outward along the pararostrum or antirostrum. Check marks typically are not continuous, appear outside of expected growth rates, lack a defined edge or connect with translucent zone. It should be noted that the first annulus in alosines can be the most difficult to determine. The look of the otolith inside the first annulus depends on how long the fish stayed in fresh water. It is therefore highly dependent on the characteristics of the river system where the fish was hatched. The first annulus is typically marked by a well-defined transition between hyaline and opaque zones.

Scales

When ageing alosines from scales, annuli appear as continuous breakages in the circuli that continue past the baseline. The first well defined mark is usually the outside of the freshwater zone (Figure 14). The first annulus is frequently weak and doesn’t always follow the annulus criteria. In blueback herring and alewife, the second annulus is typically the “strongest” looking. As a general rule, false annuli will not cross over the baseline, cannot be followed throughout the scale or cannot be seen on every scale. On older fish, annuli can become crowded together at the edge of the scale but will separate beneath the baseline. Spawning marks are identified as annuli that appear fuzzy and jagged above the baseline or that show that they’ve resorbed over another annulus above the baseline.

Annulus formation was validated in American shad otoliths by Duffy et al. (2012) using released hatchery fish marked with OTC but the timing of formation was only described as a ‘winter’ band. American shad spawn from the late winter to early spring with timing getting later moving from south to north (Figure 15, Section 1.1.6). In general, American shad that are aged are collected from the spawning period and annulus formation has already occurred in most fish (S. Elzey, MA DMF, personal communication) indicating that the formation occurs only a month or two prior to the onset of spawning.

1.1.4.2 Current Agency Ageing Protocols

1.1.4.2.1 Maine Division of Marine Resources

Currently, the Maine Division of Marine Fisheries (ME DMR) uses Cating’s method of examining and counting the annuli present on American shad scales to determine age (Cating 1953).

Fisheries staff from the ME DMR reads the actual scales collected from shad unlike several other states that use scale impressions to determine scale age. Scales selected for ageing are collected approximately one inch below and just posterior of the dorsal fin. Scales are cleaned to remove biological material and placed between two glass slides to secure the scales. The prepared slides are place into a microfiche and aged by the assigned reader. Scales are read by two different scale agers. Scales ages that are not in agreement between the two assigned readers are reread by the original ager. The scale age is recorded when there is consensus between the two readers for each scale sample aged.

The ME DMR collects a limited amount of age data in any given year. Typically, only those shad trapped at the Saco River fishways, the Milford fishway on the Penobscot River and the Brunswick fishway on the Androscoggin River are available for ageing. Age data are obtained primarily from mortalities on these river systems, but occasionally shad collected for other scientific studies are also aged. Due to the low number of American shad returning to Maine rivers, shad are passed directly upstream without sampling. The ME DMR does not routinely sample smaller coastal rivers and streams with American shad populations.

1.1.4.2.2 Massachusetts Division of Marine Fisheries

The Massachusetts Division of Marine Fisheries (MA DMF) was a primary contributor to the example ageing protocol provided in Section 1.1.4.1 and has published ageing protocols in a technical report (Elzey et al. 2015). See the example protocol and technical report for details on MA DMF American shad ageing practices.

1.1.4.2.3 Rhode Island Department of Fisheries and Wildlife

Scale samples collected from the Rhode Island Division of Fish and Wildlife’s (RIDFW) sampling programs were pressed between glass slides and aged using the approach described by Cating (1953). The age of each fish and number of spawning marks were recorded. Regenerated scales are not considered reliable for ageing. Two groups have carried out most of the ageing work for American scales since the re-establishment of the spawning run in the Pawcatuck River in the late 1970s. The first group processed the majority of scales from 1979–1992 and the second group aged archived scales collected from 1993–1997 and scales sampled from 2000 to the present. Biologists from both groups have worked together to ensure consistency of methodology in the collection, processing, and age determination of scale samples.

In considering the Pawcatuck system, the short length of the river (44 km at most) reduces residency time; freshwater marks are much smaller than marks on fish from larger rivers of several hundred (or more) kilometers. Spawning marks may also not always be obvious, given the short length of river.

1.1.4.2.4 Connecticut Department of Energy and Environmental Protection

From 2015 to present, the Connecticut Department of Energy and Environmental Protection (CT DEEP) viewed and aged shad scale samples using an image analysis equipment system. Shad scale samples collected are cleaned, dried and mounted between two glass microscope slides. Scales are magnified with a microscope using transmitted light, viewed through a Luminera camera, and displayed on a computer screen using Image Pro Premier Software. Digital photos are taken of each sample and cataloged. Image files of each scale sample are identified only by a sample number.

Age determinations were made with consensus of two or more readers on the projected images by counting annuli and spawning scars according to the criteria of Cating (1953). When discrepancies between the two readers could not be resolved, the scales were examined by a third reader. Samples that were poor quality or did not have two or more viable scales were not aged. Shad were noted to be repeat spawners when the presence of spawning scar(s) at the periphery of the scale were identified. All annuli and spawning scars on scale images were digitally marked and stored as a line profile using Image Pro Premier Software.

Prior to 2015, scale samples were processed by cleaning with an ultrasonic cleaner and pressed onto acetate using a roller press. The pressed scale images were read using a microfiche reader. When the new image analysis system was implemented, comparisons of scale ages were made using both the microfiche and image analysis equipment to ensure that the interpretation of scale ages remained consistent.

1.1.4.2.5 New York State Department of Environmental Conservation

Hudson River American shad are aged from scales by the New York State Department of Environmental Conservation (NYSDEC). Scale samples are removed from an area approximately one inch below the dorsal fin and placed in an individually identified envelope. From 1983 through 2001, scale impressions were made on cellulose acetate slides and the impressions were examined with a microfiche reader. Ages were estimated from a random sample of all fish collected using the ageing methodology developed by Cating (1953) on Hudson River shad. Annual samples were generally spread out both temporally and by size. In years between 2003 and 2015, age samples were not evaluated. Instead, age structure was estimated using an age-length key developed from spawning stock samples from 1983-2001 and 2016 to present.

From 2016 to present, different methodologies have been used for scale selection, sample preparation and scale ageing. Current sample selection follows the Ketchen (1950) method of selecting a stratified sub-sample of fixed numbers of fish aged per length bin by sex. In 2016, 30 fish per 20 mm length bin were randomly selected. All fish were aged when there were fewer than 30 fish in a length bin. Due to time restraints and based on new literature (Coggins et al. 2013), the examination of 10 fish per length bin began in 2017. Rather than using scale impressions, the current scale preparation methods are to place the collected scales between two microscope slides and evaluate samples on a digital microscope. Finally, the current ageing protocol for Hudson River shad scale ageing is under development but is based on the working protocol used by the Delaware River Basin Fish and Wildlife Management Cooperative (Co-op, Section 1.1.4.2.7).

In both ageing stanzas, two independent age determinations were made by different readers and agreement on age and placement of annuli was sought for each fish. In some cases, a third independent reader resolved differences. If differences could not be resolved the sample was not used.

1.1.4.2.6 New Jersey Division of Fish and Wildlife

New Jersey Division of Fish and Wildlife (NJ DFW) collects otoliths from commercial fishermen from the Delaware Bay directed fishery. These otoliths are archived for future analysis due to staff and resource shortcomings. The remainder of New Jersey’s ageing takes place as part of the Co-op’s ageing efforts and protocols detailed in Section 1.1.4.2.7.

1.1.4.2.7 Delaware River Basin Fish and Wildlife Management Cooperative

Since the implementation of the Delaware River Sustainable Fishing Plan for American Shad (SFP, Del Coop 2012), the Co-op has begun revisiting ageing Delaware River American shad scales. The goal was to determine if Co-op members could consistently age American shad via scales under a single agreed upon set of protocols. In September 2012, an initial two-day ageing workshop was held (Hancock, New York) by Co-op members. Scales and otoliths were viewed by the collective group, with extensive discussions on how each agency identified and aged scales and otoliths. Personnel were in general agreement on interpreting various scale microstructures; assignment of age 1 was quickly identified as problematic among agencies. A review of otoliths also quickly revealed similar problematic issues. Co-op members decided to focus on pursuing scales for determining shad ages. A follow up ageing workshop was held a year later (September 2013 at Hancock, New York) where scales and protocols were further discussed.

An outcome of the second ageing workshop was a blind test set of scales and initial set of ageing protocols. The intent of the blind test set was to provide a measure of agreement between agency personnel. Only date, location of capture, and scales were included. Scales were randomly selected by size class from four locations: Smithfield Beach (n=25), Raubsville (n=25), Lambertville (n=25), and upper Delaware Estuary (n=25). Personnel with various levels of experience ageing American shad scales then derived ages and frequency of repeat spawning marks for each scale. Agencies were allowed to age the scales using their own preferred methods, but all readers would age the same scale samples.

Comparison of age assignments among readers were analyzed using a standard precision template developed by NOAA's Northeast Fisheries Science Center (NEFSC). Templates can be found at http://www.nefsc.noaa.gov/fbp/age-prec/. Precision was evaluated by examination of the mean coefficient of variation (CV), percent agreement and the Bowker's test of symmetry. Ageing laboratories around the world view a measure of mean CV of 5% or less to be acceptable. Mean CVs of the blind test set ranged from 3.66% and 21.14%. Percent agreement ranged from 76% agreement to 4% agreement. Readers from within the same agency consistently had the lowest CVs and highest percent agreement. Readers with minimal experience ageing shad scales consistently had the highest CVs and lowest percent agreement when compared to all readers regardless of experience. Therefore, age determinations of inexperienced readers must be interpreted with caution. Co-op members agreed that the differences between experienced readers from various agencies were in the identification of the first annulus, resulting in a one-year discrepancy of assigned ages.

Based on the blind test results, Co-op members held a third ageing workshop, December 2014 at New Paltz, New York. The intent was for Co-op members familiar with American shad scale ageing to develop an agreed upon reference set of scales. A reference set would aid in uniformity of identifying scale structures, possibly increasing consistency of age derivations. Differences in scale microstructure interpretations were discussed including, identification characteristics and assignment of annuli, identification of the first annulus and repeat spawning marks. A total of 50 specimens were accepted as reference scales. In order to assess the suitability of the reference set, the Co-op sought third party confirmation from the MA DMF ageing lab in Gloucester, MA. The reference set was independently examined by the MA DMF ageing lab. Results of their age determinations were compared to the Co-op ages using a standard precision template as described above. Percent agreement was 73.6% with a CV of 3.65%. These values fall within the accepted ranges for precision. Final results of the December 2014 workshop were an agreed upon reference set and an update of the informal ageing protocol, for Co-op member use.

The goal for these workshops (and future workshops) is to train and re-train Co-op members in interpreting American shad scale microstructures. Specific objectives are to: (1) develop and use a standard ageing protocol for assisting Co-op members to consistently interpret American shad scale microstructure for age and repeat spawning marks; (2) provide the mechanism for production ageing of Delaware River American shad scales; and (3) provide a mechanism for developing total mortality estimates usable as benchmarks in an American shad SFP.

1.1.4.2.8 Delaware Division of Fish and Wildlife

American shad scales are aged by the Delaware Division of Fish and Wildlife (DE DFW) using techniques described by Cating (1953). Ages are determined and analyses of age and repeat spawning marks are performed, but were not provided for the assessment.

1.1.4.2.9 Pennsylvania Fish and Boat Commission

The Pennsylvania Fish and Boat Commission (PFBC) collected scales and otoliths from adult American shad randomly sampled from the fish-lifts at Conowingo Dam. Three to five scales from each fish (sampled ventral of dorsal fin) were cleaned and pressed sculptured side down on acetate sheets (1.27 mm thick) by using pressure (5000 psi) and heat (100° C) for five minutes. Scale impressions were viewed under a microfiche reader for age and repeat spawning interpretation. A single consistent reader interpreted age and repeat spawn history from scale impressions using Cating's (1953) method and traditional annuli counts between 1996 and 2007. Two-reader consensus ageing was conducted between 2008 and 2013, followed by single consistent reader ageing from 2014 to present. Beginning in 2015, age and repeat spawn interpretations followed methods outlined by Elzey et al. (2015) and were evaluated from cleaned scales placed between glass slides and viewed under a microfiche reader. Scale interpretation was refined further in 2017, where cleaned scales between glass slides were viewed under a stereoscope with transmitted light mirror base and image projection to a computer monitor via digital camera.

Sagittal otolith pairs were extracted, cleaned and stored dry until age interpretation. Ageing was carried out by a single consistent reader (1995 through 2007), followed by two reader consensus ageing (2008 through 2013), and then by a single consistent reader (2014 to present). Prior to ageing, otoliths were submerged fully in mineral oil sulcus side down and viewed under a stereoscope (equipped with video camera and monitor), on a black background, with reflected light. When viewed under white light, the annuli appear dark or translucent, while the growth zones appear white or opaque. The first annulus is often very difficult to see, but the second growth zone is wide and readily apparent. Consequently, ages were assigned by counting growth zones, not annuli, starting with the second growth zone and counting outward to the edge of the otolith. Since adult shad are collected during their spring spawning run, the edge is considered the last annulus. Most counts are done in the pararostrum area where the growth zones and annuli are most obvious.

1.1.4.2.10 Maryland Department of Natural Resources

The Maryland Department of Natural Resources (MD DNR) has relied exclusively on scales for ageing American shad. Scales were preferably removed from below the insertion of the dorsal fin. Beginning in 2014, scales were aged following "Massachusetts Division of Marine Fisheries Age and Growth Laboratory: Fish Aging Protocols" (Elzey et al. 2015), as suggested by Atlantic states' ageing experts (ASMFC 2013). Prior to 2014, Cating's (1953) method was used to age all American shad scales. A minimum of four scales per sample were cleaned, mounted between two glass slides and read for age and spawning history using a microfiche reader. The scale edge was counted as an annulus due to the assumption that each fish had completed a full year's growth at the time of capture. Ages were not assigned to regenerated scales or to scales that were difficult to read.

Maryland's American shad age samples were read by a single, consistent reader from 1980 to 2012. Since 2012, at least two scale readers contributed to age determination. For any sample that the readers did not fully agree on both age and spawning mark count, the sample was jointly read until consensus estimates were agreed upon. If no consensus could be reached, the sample was removed from the analysis and replaced with another sample if available.

1.1.4.2.11 Virginia Department of Game and Inland Fisheries

Virginia Department of Game and Inland Fisheries (VDGIF) staff has set gill nets in the Potomac River since 2004 to collect American shad broodfish to support stocking activities for the Rappahannock River. Otoliths and scale samples were taken from every tenth fish during sampling. The age of each sub-sampled fish was determined from the otoliths by personnel from the VDGIF's Age and Growth Section. The otoliths were also examined for an OTC mark.

1.1.4.2.12 Virginia Institute of Marine Science

Scales for age determination are removed from a mid-lateral area on the left side posterior to the pectoral-fin base of each fish; all individuals captured are sampled. Scales are cleaned with a dilute bleach solution, mounted and pressed on acetate sheets, and read on a microfilm projector by one individual (B. Watkins, Virginia Institute of Marine Science-VIMS, personal communication) using the methods of Cating (1953). Ages were determined by a different reader in 1998-2002 (K. Maki). To ensure consistency, B. Watkins read all scale samples collected during the monitoring program.

1.1.4.2.13 North Carolina Division of Marine Fisheries

The North Carolina Division of Marine Fisheries (NCDMF) estimates the age of American shad using scales. Scale-based ageing of American shad from fishery-dependent sources has occurred from 1972 to 1993 and 2000 to present. Project personnel collected fishery-dependent age data as the commercial catch was unloaded at local fish houses (licensed finfish dealers) on a weekly basis, during the commercial season for American shad. Scale samples were taken from the left side below the insertion of the dorsal fin and just above the mid-line (Marcy 1969).

NCDMF began collecting American shad age data from fishery-independent surveys in 2000. Fish were collected from various gill net surveys operated within the State's coastal waters. Starting in 2004, scale samples were taken from the left side below the insertion of the dorsal fin and just above the mid-line (Marcy 1969).

Age determination was based on Cating (1953) and Judy (1961). At least four of the most legible scales from each fish were read using a binocular microscope, an Eberbach projector, or a microfiche reader. For the majority of the time period two independent readings were made of scales for each fish. If readings were not in agreement, the fish was deleted from the sample. Following the method of Cating (1953), it was assumed that each fish had completed a full year's growth at the time of capture; thus, the scale edge was counted as a year mark. Starting in 2008, ages were determined from one independent reading due to staffing issues. The single reader has been consistent from 2008 to present. If the reader could not obtain a consensus age from the cleaned scales for a sample, the sample was not assigned an age.

For fishery-dependent age data, stratified sub-sampling for ageing was conducted during 1981 to 1993 and 2000 to 2003 due to the large number of American shad scale samples taken and the time-consuming process of ageing. The technique used, in which modal length groups were sub-sampled, was similar to that developed by Ketchen (1950). Shad were separated by sex into 25 mm modal size groups. If 15 or more samples were present, at least half of the scales in each size group were aged; in those groups with less than 15, all were aged. The subsamples were expanded to obtain the age composition estimated for American shad.

When fishery-dependent sampling of American shad was reinstated in 2000, an annual collection target of 200 fish per system was established (Albemarle Sound, Tar-Pamlico, Neuse, and Cape Fear), with a minimum ageing target of 125 fish from each system. Age sub-sampling for expansion to modal length groups was discontinued in 2004, due to the decline in commercial landings. Age samples, separated by sex, were stratified by month and length (FL), when the collection target was exceeded; else all collections were processed for ageing. For fishery-independent age data, all collections were processed for ageing.

1.1.4.2.14 North Carolina Wildlife Resources Commission

The NCWRC began ageing American shad upon inception of electrofishing surveys in the Roanoke River, Tar River, Neuse River, and Cape Fear River in 2000. American shad scales were aged using similar methods as described for NCDMF sampling programs from 2000–2010. A sub-set of scales (based on sex and fish length) was cleaned and read using a microfiche reader. In the previous stock assessment, discrepancies between NCDMF and NCWRC ages and spawning mark counts were described and NCWRC scale ageing data were deemed unreliable. In 2011, NCWRC staff began using otoliths to age American shad collected from spawning grounds surveys. NCWRC staff was initially trained for otolith ageing by M. Hendricks, PFBC (retired), and after initial training, followed protocols described by Duffy et al. (2012). A subset of up to 10 fish per 10-mm length group per sex was sacrificed for otolith removal. In the Roanoke and Neuse rivers, broodfish collected from the same area as weekly electrofishing surveys were used to supplement otolith collections. The primary otolith reader aged all otoliths from the sample using a binocular dissecting microscope, and a secondary reader aged all otoliths using digital images taken by the primary reader. Ages were compared and consensus ages were reached in concert. Otoliths were excluded from the sample if consensus could not be reached. Multiple readers have been used for scales and otoliths throughout the time series. In some years, ageing structures were not taken and an age-length key developed from otolith ages of previous years' samples was applied to the sample. Lastly, known ages from parentage-based tagging analyses are available for stocked fish in the Roanoke River 2013–2017, but 2017 was the first year when the majority of the spawning stock was of the ages identifiable by PBT. Thus, using PBT ages for age-length keys was not appropriate in years prior to 2017.

1.1.4.2.15 South Carolina Department of Natural Resources

South Carolina Department of Natural Resources (SCDNR) personnel age shad using Cating's method (Cating 1953). From 1979 to 1985, a single group of readers read SCDNR samples, but there have been multiple shad ageing technicians with variable experience and training since then. The maximum age for American shad in South Carolina rivers recorded by SCDNR is age 6 (males) and age 7 (females).

1.1.4.2.16 Georgia Department of Natural Resources

The Georgia Department of Natural Resources (GADNR) has collected age data since completion of the previous coastwide stock assessment. Scale samples for ageing are currently taken from 1) shad captured during tagging studies in the lower Altamaha River; 2) shad captured during electrofishing efforts in the Savannah River; and 3) shad captured during electrofishing efforts in the Ogeechee River. GADNR does not sample shad from the Satilla or St. Mary's rivers. In each instance, several scales are removed from captured shad and placed into small envelopes. Envelopes are marked with the date and location of capture, fish sex, and fish length/weight. Envelopes containing scales are brought back to the office and scales are read using a Micron microfiche reader. American shad are aged using the scale methodology developed by Cating (1953). No validation of scale annuli has been conducted on shad from Georgia rivers.

Age and spawning mark data are available from shad collected on the Altamaha from 1967 to 1968 (Georgia Fish and Game Commission—predecessor to GADNR), 1982 to 1991 (GADNR), and 2000 to 2018 (GADNR). Depending on weather conditions, adult shad normally enter Georgia rivers from early January to the middle of April.

1.1.4.2.17 Florida Fish and Wildlife Conservation Commission

The Florida Fish and Wildlife Conservation Commission (FL FWC) has collected an age sub-sample of American shad from a fishery independent spawning stock survey in the St. Johns River each year since 2011. Aging is accomplished from whole otoliths. The subsample in each year comprised five to ten individuals of each sex per centimeter group (maximum total length). Otoliths were removed from iced/chilled specimens within 48 hours of capture. Otoliths were stored dry in 24-cell culture trays. The method for reading the whole otoliths follows methods described by Elzey et al. 2015 and Duffy et al. 2012. Reading was accomplished by placing otoliths sulcus-down in mineral oil on a black background and viewing with reflected light under a dissecting stereomicroscope. Annuli were defined as continuous transparent bands between wider opaque zones. An attempt was made to count along the pararostrum and antirostrum to achieve complementary counts. If the two counts did not agree then whichever was judged best by the reader for having well delineated marks was taken. Age was the number of annuli plus one because all fish were collected during the spawning run. Crystalized and partially crystalized otoliths were excluded from analysis. To date, only a single reader has read the otoliths. The reader read the otoliths twice, blinded to sex and length during readings and then attempted to rule out gross outliers based on sex and length.

1.1.4.3 Ageing Error Analysis

Estimates of age from paired scale and otolith samples collected from the same fish, otoliths collected from fish with known ages, scales collected from fish with known ages, and estimates of spawn marks from scales made by multiple readers were analyzed in this assessment to characterize age and spawn mark data error. Data were analyzed by river (i.e., monitoring program) and year to isolate error due to interpretation differences over time from potential spatial sources of error (e.g., difference in the physical appearance of the age/spawn mark structures due to varying distances traveled up river during spawning, etc.).

Mean CVs are calculated as a measure of precision by diving the standard deviation and mean of paired estimates (or estimate and known value) and averaging over all samples. A mean CV of 5% was considered a target for precision, as recommended by Campana (2001). Tests of symmetry were used to identify systematic bias. Counts of paired estimate combinations are tabulated in contingency tables with the diagonal 1:1 line through this table indicating no difference between estimates (i.e., perfect agreement). The tests of symmetry determine if the expected values between estimates fall along the diagonal 1:1 line (null hypothesis of no difference between estimates) or deviate from this 1:1 line (alternative hypothesis of difference between estimates). McBride (2015) found that the symmetry test introduced by Evans and Hoenig (1998) resulted in fewer type II error rates (i.e., accepting the null hypothesis of no difference between estimates when a true difference exists) in simulation analysis. Therefore, results of this test are considered more precautionary when trying to detect bias and are provided from this analysis. A p-value threshold of >0.05 was used to reject the null hypothesis. To visualize the comparisons between estimates, Bland-Altman plots are provided (McBride 2015).

1.1.4.3.1 Scale Age vs. Otolith Age

The objective of these comparisons was to identify interpretation differences due to the age structure being read. Comparison data were available from 1995-2017 from the Penobscot, Merrimack, Connecticut (for a single year in 2015), Delaware (Delaware, Lehigh, and Schuylkill Rivers), Upper Chesapeake (Susquehanna River), Potomac, Albemarle Sound (Roanoke River), and Neuse Systems. Age data from the Penobscot River were provided by the University of Maine from some opportunistic sampling efforts, not ME DMR. The data from the Merrimack River were the data from Elzey et al. 2015.

Mean CVs were generally greater during and prior to the mid-2000s and often exceeded the 5% threshold (Figure 16). Mean CVs declined in the late 2000s and were often below the 5% threshold, with the exception of Penobscot data. Systematic bias was detected in all systems with more than three years of data (Table 5). Overall, 47% of the comparisons suffered from systematic bias. There has been a decline in the proportion of comparisons suffering systematic bias over time. Bland-Altman plots show a consistent pattern in differences where and when they occurred (Figure 17-Figure 26). Scales were typically overaged relative to otoliths up to approximately otolith age-5 or 6 and are typically under-aged relative to otoliths for older ages.

1.1.4.3.2 Otolith Age vs. Known Age

The objective of these comparisons was to quantify ageing error of otoliths. Data were available from 1998-2017 from the Delaware (Delaware, Lehigh, and Schuylkill Rivers), Potomac, and

Albemarle Sound (Roanoke River) Systems. There are also some otoliths from known-age fish collected from the Upper Chesapeake (Susquehanna River) from 2010-2016, but otolith ages provided for these fish were apparently entered with knowledge of the known age as they are in perfect agreement with known ages and were dropped from the analysis. Known ages were determined from OTC marking of stocked fish (Delaware, Upper Chesapeake, and Potomac) or genetic parentage-based tagging of stocked fish (Albemarle Sound), both of which are subject to potential error. Data from the Delaware System include the known ages used by Duffy et al. 2012. Sample sizes for the known-age data sets were general small with the largest data sets from the Lehigh and Roanoke Rivers.

Mean CVs are variable and fluctuate around the 5% threshold with no apparent pattern (Figure 27). Some mean CVs are zero (e.g., Delaware River in 2006 and 2008), but these are from comparisons of very small sample sizes. Systematic bias was detected in all systems with more than one year of data, except the Lehigh River which had nine comparisons with no systematic bias detected (Table 6). Overall, 19% of the comparisons suffered from systematic bias. There does appear to be a consistent pattern in error with otoliths overaged at young ages and under-aged at older ages (Figure 28-Figure 32).

1.1.4.3.3 Scale Age vs. Known Age

The objectives of these comparisons was to quantify ageing error of scales. Data were available from 1998-2014 from the Delaware (Delaware, Lehigh, and Schuylkill Rivers) and Potomac systems. There are also some scales from known-age fish collected from the Upper Chesapeake (Susquehanna River) from 2010-2016, but scale ages provided for these fish were apparently entered with knowledge of the known age as they are in perfect agreement with known ages for all years except two and were dropped from the analysis. Known ages were determined from OTC marking of stocked fish which is subject to potential error. Data from the Delaware System include the know ages used by Duffy et al. 2012. Sample sizes for these data sets were general small with the largest data set from the Lehigh River.

Most mean CVs exceeded the 5% threshold (Figure 33). Systematic bias was detected in all systems with more than one year of data (Table 7). Overall, 24% of the comparisons suffered from systematic bias. There does appear to be a consistent pattern in error with scales overaged at young ages and under-aged at older ages (Figure 34-Figure 37).

1.1.4.3.4 Multiple Reads of Spawn Marks

The objective of these comparisons was to identify interpretation differences due to reader. This was the only option to explore error in these data as there are only a few known spawn mark samples from tag-recaptures in the Susquehanna River (Josh Tryninewski, PFBC, personal communication) and estimates cannot be made from alternative structures. Data were available from 2014-2017 from the Delaware, Nanticoke, Upper Chesapeake (Susquehanna River), and Potomac Systems.

Mean CVs were highly variable within and among systems and all exceeded the 5% threshold (Figure 38). Systematic bias was detected in all systems, except the Nanticoke which had three comparisons with no systematic bias detected (Table 8). Overall, 31% of the comparisons suffered from systematic bias. Bland-Altman plots show error was common for all counts of marks including differentiating between virgin and repeat spawners (Figure 39-Figure 42).

1.1.4.3.5 Conclusions

The results of this analysis are generally consistent with the findings from recent published works on American shad ageing (Duffy et al. 2012, Elzey et al. 2015) and confirm that issues observed at specific locations investigated in these publications apply to other areas along the coast. Scale ages appear more imprecise and biased than otolith ages based on the comparison to known ages, particularly from the Lehigh River which has the most robust data sets. Error in ages estimated from both structures follow similar patterns of overestimation for younger ages and underestimation for older ages. This pattern is presumably worse in estimates from scales as the same pattern occurs in scale age estimates when compared to otolith age estimates. However, there were comparisons that suggest acceptable levels of ageing error between age structures can be achieved. Spawn mark data, analyzed for error for the first time in this analysis, are far more imprecise than the age data and should be used with caution until error can be shown to be reduced to acceptable levels.

1.1.5 Growth

There have been no American shad growth studies published since the last stock assessment. Historical growth studies conducted at the system level are covered in Life History subsections of Section 3. For this assessment, a Bayesian hierarchical framework was used for development of a coastwide growth curve that shared information among regions and allowed for system-specific assessment. The von Bertalanffy (1938) growth function as described by Beverton and Holt (1957) was used to represent fish growth:

$$L_t = L_\infty \left(1 - e^{-K\cdot(t-t_0)}\right)$$

Mean length of an individual at time t is represented by Lt, the mean asymptotic length of fish is represented as $L\infty$, the Brody growth coefficient, K, controls how quickly fish reach this $L\infty$, and t_0 is the hypothetical age at which fish length equals zero, this is the x-intercept.

Ages were provided using both scale- and otolith-based approaches. Although age determination for American shad in the past has used scales as the primary age structure, otolith-based ages are now being collected throughout the coast. Differences in growth curves fit to scale and otolith ages were investigated. Scale-based approaches often overestimated length-at-age compared to otoliths, this was especially true for the semelparous region (Figure 43). Because of these differences, and the general consensus that otoliths were more accurate than scale ages, only the results for otolith-aged fish are reported.

A total of 11 systems were represented in otolith data, a reduction from the 46 systems represented in scale data. Therefore, the SAS used a Bayesian hierarchical approach to estimate von Bertalanffy growth functions (VBGFs) that incorporated not only system-specific parameter estimates, but also regional and coastwide parameters that could be used for understanding growth in systems not represented in otolith data. These included a total of 3 VBGF parameterizations (models): a sex-aggregated model and one model each for male and female fish.

A total of 105,042 fish were used in growth analyses. Systems that included only young-of-year (YOY) data were removed prior to analysis. In systems where no YOY data were available, a random sample of 30 YOY was drawn from the nearest neighboring system within that same region. This constrained growth curves to realistic values for young fish, and prevented underestimating t_0 and K due to lack of information. Sharing information between neighboring systems allowed t_0 to still vary among systems instead of setting a fixed x-intercept, which can have important consequences when using growth parameters to estimate mortality (Pardo et al. 2013). To aid with model speed and convergence, systems with a large abundance of a single age class (i.e., YOY data) were randomly sampled for 1,000 fish per age class. For age classes that contained less than 1,000 fish within a given sex or system, all available data were used. The subsample size was evaluated prior to final analyses to ensure timely model estimation while not imposing artificial age structures on the population (e.g., Goodyear 2019).

Differences in growth were also evaluated relative to hind-casted sea surface temperatures from 1981 to 2017. Temperatures were compiled by the Gulf of Maine Research Institute from NOAA's Optimum Interpolation Sea Surface Temperature (OISST) using the Northeast Continental Shelf Large Marine Ecosystem. This contains the area of the continental shelf from the Bay of Fundy to Cape Lookout, NC. This region was chosen based on the migration patterns described by Neves and Depres (1979). Regardless of region, all populations relied on the same sea surface temperatures based on research suggesting that populations mix and travel together in the marine environment (Leggett and Carscadden 1978).

River-specific variability was included into the VBGF as a random effect on L_∞, K, and t_0, and sea surface temperature was included as a continuous covariate on L_∞ and K:

$$\log\begin{pmatrix} L_{\infty i} \\ K_i \\ t_{0i} \end{pmatrix} \sim \begin{pmatrix} \mu\beta_{cor}[L_{\infty j}] + \left(\beta_{0_{L_\infty}} + \beta_{SST_{L_\infty}} \cdot \mathrm{SST}_i\right) \\ \mu\beta_{cor}[K_j] + \left(\beta_{0_K} + \beta_{SST_K} \cdot \mathrm{SST}_i\right) \\ \mu\beta_{cor}[t_{0j}] + \beta_{0_{t_0}} + 10 \end{pmatrix}, \mu\beta_{cor} = \mathrm{diag}(\tau) \cdot L_\Omega \cdot \mu\beta_{raw}.$$

Each parameter was modeled on the $\log_e$ scale as an outcome of a linear predictor and all parameters included an intercept (β_0) at minimum. A coefficient relating annual sea surface temperature to VBGF parameters was included as a slope (β_{SST}) for L_∞ and K, and data were scaled and centered in each linear predictor. Weakly informative, normal priors with a mean of zero and standard deviation of one on the $\log_e$ scale were used for each β_{SST}. A constant of 10 was added to t_0 since it is constrained to be less than zero and is on the $\log_e$ scale (e.g., Kimura 2008, Midway et al. 2015). The matrix $\mu\beta_{cor}$ contains correlated, $\log_e$ scaled offsets (3 x J) that were formed from the $\log_e$ hyperparameters for each j^{th} system (from 1 to J). These offsets for $\mu\beta_{cor}$ were the product of a scale vector that forced all VBGF parameters to be positive by constraining all the diagonal elements in the Cholesky factor (L_Ω) (Golub and van Loan 1996), the L_Ω of the correlation matrix between VBGF parameters (Ω), and a 3 x J matrix of uncorrelated values for each set of the site-specific parameters drawn from a weakly informative, normal prior with a mean of zero and standard deviation of one on the $\log_e$ scale ($\mu\beta_{raw}$). The LKJ distribution (Lewandowski et al. 2009) with $\eta = 1$ was used to draw L_Ω, which provided a uniform prior on the correlation matrix Ω. The intercept β_0 was a vector of length 3 and contained $\log_e$-scaled hyperparameters for the VBGF with weakly informative, normal priors described above on the loge scale:

$$\beta_0 = \log(\bar{L}_\infty, \bar{K}, \bar{t}_0).$$

The posterior distributions for all analyses were estimated using Hamiltonian Monte Carlo (HMC) methods with the No-U-Turn sampler performed in Stan (Carpenter et al. 2017) using the "rstan" package (Stan Development Team 2018) in R (R Core Team 2019). The SAS took 3,000 samples, using a warm-up of 2,500 iterations from 3 chains, totaling 1,500 samples for each parameter from the posterior distribution. The Gelman-Rubin convergence diagnostic ($\hat{r}$, Gelman and Rubin 1992) was used to confirm the convergence of separate chains ($\hat{r} \leq 1.01$ for all parameters) and effective sample sizes were evaluated to ensure adequate sampling from the posterior. Statistical significance for $\beta_{SST_{L_\infty}}$ and β_{SST_K} was determined by evaluating 95% credible intervals (CRI) for overlap with zero. If zero was not included in the range of the credible intervals, then a statistically significant relationship was present between sea surface temperatures and the parameter of interest.

Projected sea surface temperatures (1982-2099) were used to project growth parameters under different representative concentration pathway (RCP) scenarios. RCP 4.5 and RCP 8.5 were chosen for these analyses. RCP 4.5 is a scenario that projects future temperatures increasing until mid-century, when they begin to plateau due to changes in emissions, reforestation, human population, and the increased use of renewable resources. RCP 8.5 is the "business-as-usual, worst case" scenario (Oliver et al. 2015). This path projects temperatures continuing to increase through 2099 on current trajectories. Projected temperatures under both scenarios were gathered and prepared by the Gulf of Maine Research Institute. Monthly anomalies and 1982-2011 climatology (collected from NOAA National Center for Atmospheric Research in Boulder, CO) were combined based on the OISST data to get bias-corrected projected mean temperatures for every month. Temperatures were averaged for each year and changes in $L\infty$ and K were projected out until 2099 based on the observed, historical relationships between SST and VBGF parameters.

1.1.5.1 Results

A latitudinal trend in regional growth was observed. Fish in the northern iteroparous region had the largest $L\infty$ value and lowest K, while the semelparous region had the lowest $L\infty$ and highest K (Table 9). The northern iteroparous and southern iteroparous regions shared similar growth patterns and both had older maximum ages represented in the data than the semelparous region.

Although there was a trend in growth among the regions, system-specific growth still varied substantially among populations, even within a given region (Table 9). The SAS believed this variability is likely a combination of true inter-system variability and observation error and opted to use regional growth parameters in assessment approaches.

1.1.5.2 Climate Impacts on Growth

During the 36-year time period (1981-2017), an inverse relationship between sea surface temperatures and the von Bertalanffy growth parameters was observed. As time progressed, an increase in temperature was observed, and alternatively, asymptotic size of fish (L_∞) decreased along with the speed at which they reached these lengths (*K*). In 1981, mean L_∞ was 483 mm (95% CRI: 459 mm-505 mm) and by 2017 mean L_∞ decreased to 473 mm (95% CRI: 450 mm-496 mm) (Figure 44). Mean estimates of *K* decreased from 0.45 (95% CRI: 0.39-0.53) in 1981 to 0.43 (95% CRI: 0.37-0.50) in 2017 (Figure 44), indicating that the effect on L_∞ was stronger than that observed for *K*. This trend was recapitulated in sex-specific growth curves in which strong influences of SST on L_∞ were found, but marginal or insignificant effects on *K*.

The SAS used relationships between SST and VBGF parameters to project changes in growth parameters during the next 100 years using projected SST from each climate change scenario. For RCP 8.5, a mean L_∞ of 463 mm (95% CRI: 440 mm-487 mm) was projected along with a mean *K* estimate of 0.40 (95% CRI: 0.34-0.47) for the year 2099 (Figure 45). Estimates using climate scenario 4.5 had less extreme declines, projecting a mean L_∞ of 471 mm (95% CRI: 448 mm-494 mm) and a *K* of 0.42 (95% CRI: 0.36-0.49) by 2099 (Figure 45).

1.1.6 Reproduction

1.1.6.1 Spawning Periodicity and Timing

American shad migration shows regional difference in spawning periodicity. American shad spawn from the late winter to early spring with timing getting later moving from south to north (Figure 15). In their southern range, Walburg and Nichols (1967) found spawning could begin as early as mid-November but peaked in mid-January to February. Most spawning was complete by March in the St. John's River, Florida. Walburg and Nichols (1967) reported spawning in Georgia and South Carolina rivers may begin as early as January but is done by the end of April. American shad being spawning in the Chesapeake Bay as early as mid-February and continue until mid-May and in the Delaware River, they are most abundant in early May (Walburg and Nichols 1967). S. Elzey (MA DMF, personal communication) reports spawning fish entering Massachusetts waters as early as May. Spawning fish enter the Hudson and Connecticut rivers by the end of March and complete spawning by June (Walburg and Nichols 1967). Finally, in their most northern range, American shad spawning typically begins in June and continues until July in Maine and Canada (Walburg and Nichols 1967).

American shad that spawn north of Cape Hatteras are iteroparous, while almost all American shad spawning south of Cape Hatteras are semelparous. This may be due to the fact that south of North Carolina the physiological limits of American shad are stretched during long oceanic migrations. Higher southern water temperatures may also have an effect (Leggett 1969).

Moreover, Leggett and Carscadden (1978) suggested that southern stocks produce more eggs per unit of body weight than northern populations to compensate for not spawning repeatedly. Studies show the percentage of iteroparous adult American shad increases northward along the Atlantic coast. However, the percentage of repeat spawners may fluctuate over time within the same river due to pollution, fishing pressure, land-use change, or other factors (Limburg et al. 2003). Furthermore, almost 59% of American shad in the St. Lawrence River did not spawn every year following the onset of maturation, skipping one or more seasons (Provost 1987). Additionally, some fish spawn up to five times before they die (Carscadden and Leggett 1975). Members of this species exhibit asynchronous ovarian development and batch spawning. In addition, American shad spawn repeatedly as they move upriver (Glebe and Leggett 1981a), which some researchers think may be a function of their high fecundity (Collette and Klein-MacPhee 2002). Estimates of egg production for the York River, Virginia, are 20,000 to 70,000 eggs per kg somatic weight spawned every four days (Olney et al. 2001).

Interestingly, Olney et al. (2001) found that approximately 70 percent of post-spawning American shad females leaving the York River had only partially spent ovaries, which suggests that the maximum reproduction level of most females in the river system each year is not achieved. Even with energy reserves, spent adults are usually very emaciated and return to sea soon after spawning (Chittenden 1976b, Raabe and Hightower 2014), sometimes feeding before reaching saltwater (Atkins 1887).

1.1.6.2 Fecundity

Annual fecundity of American shad decreases with increasing latitude (Leggett and Carscadden 1978), but lifetime fecundity does not due to a reciprocal rate of repeat survival (McBride et al. 2016). Historically, the determinate fecundity method was used (Leggett and Carscadden 1978); however, Hyle et al. (2014) determined that the indeterminate method was required for the Mattaponi River, Virginia. With the indeterminate method, fecundity was approximately double the historic estimate (Hyle et al. 2014). Reevaluation of fecundity for Connecticut River shad found that the determinate method estimate overlapped historic estimates and the indeterminate method estimate was not significantly different from the determinate method estimate. Use of historical estimates of American shad annual fecundity is dependent on the pattern of oogenesis exhibited by the population, which differs by latitude (McBride et al. 2016). It is not currently known at which latitude the determinate approach is no longer valid as only the Connecticut River and Mattaponi River have been investigated.

1.1.7 Maturity

Maturity schedules or ogives are often calculated by the capture of mature and immature fish and determining the proportion of mature and immature fish as a function of age for both male and females of a species. (e.g., sea bream, *Pagellus erythrinus*, Coelho et al. 2010; Galapagos sailfin grouper, *Mycteroperca olfax*, Usseglio et al., 2015). Where age data is not available, length may be used as a surrogate (e.g., albacore tuna, *Thunnus alalunga*, Farley et al., 2014). In either case, this approach depends upon the satisfying the assumptions of equal mixing of mature and immature fish, as well as equal recruitment to gear. This is not the case for data collected for many anadromous fishes because of their migratory nature. Mature fish in each cohort undertake a spawning run into fresh water, thereby separating themselves from immature members of their cohorts. Mature fish recruited to gear used for assessment or as part of commercial catches far more, and in some cases, exclusively. This is the case for American shad captured during their spawning ruin into freshwater systems. Thus, the assumption is made for “in river” captures range wide, that all encountered fish are reproductively mature.

Together with age data, the considerable amount of in-river maturity data submitted for the assessment affords the opportunity to model the probability of maturation-at-age for this species among regions of life history variation. The accuracy of any such approach relies on the ability to estimate the age of the fish and the ability to identify previous spawning activity (as these fish will have matured prior to the time of observation). Two methods are regularly used in the estimation of ages in American shad, scale and otolith. The abundance of scale-derived age data is clearly valuable as there is data from more than 40 thousand fish over five decades. In contrast, there is otolith data from some seven thousand fish beginning in 2007.

For any method to assign probability of maturity based on age, however, information associated with previous spawning is a necessity in all but the southern semelparous populations. Scales provide this information as an erosion mark on the scale edge that occurs during the spawning migration (Moss 1946). This pattern can be used to distinguish between first time and repeat spawners. While evidence of skipped years of spawning is an infrequent finding from scale analysis, there is some suggestion from stable isotope analysis of otoliths that American shad occasionally skip spawning (Secor and Rooker 2000). If these marks can be referenced in relation to their observed age, they can inform estimates of maturity schedules.

Maki et al. (2001) developed a novel approach to estimate maturity probability using scale-derived age in conjunction with the scale-derived patterns of spawning. For this approach, maturation probability (proportion mature at age) is estimated assuming a multinomial distribution and using maximum likelihood estimation. This approach can be done by following a cohort over time (“longitudinal”) or by making the assumption that there is no trend in maturation among year-classes and using a single year (“cross sectional”) or aggregate data among years. These authors’ were able to effectively use data from the York River, Virginia to demonstrate the efficacy of this method. Given this demonstrated utility, our intent was to use this method for our coastwide analysis during this assessment.

In applying this method, however, the SAS encountered difficulty in estimation likely due to error associated with scale-derived ageing. This stems from the fact that estimates of probability of maturation derived through this method are based on a sequence of calculations beginning with data from fish identified as being the oldest, and working backwards to younger age classes. Whether using scale- or otolith-derived ages in conjunction with scale-derived spawning, a small number of fish identified as first time spawners resulted in maturation curves that were skewed towards older age classes and biologically unrealistic. As a result, the proportion of mature fish at the oldest year classes are in the denominator and dominate the calculation. Because of this result, the SAS sought to use at sea mortality estimates to inform a maturity ogive. Consistent with the Maki et al. (2001) method, it was assumed that all fish observed returning to river systems were reproductively mature. Only otolith data was used as age information with the highest confidence and therefore identified the subset of fish for which otolith age existed. Scale information continues to be used to identify spawning in previous years, but this scale-derived information was restricted to use as a binary assessment: first time spawner or repeat spawner. Thus for each regional metapopulation (northern iteroparous, southern iteroparous, and semelparous) and for each sex (female and male) a matrix of age-at-capture and age-at-first spawn (restricting our data to only first time spawners) was created and resulted in data for each group (e.g., as shown in Table 11 for southern iteroparous females).

A life table such as this could be used to estimate mortality if sampling was not biased, however the SAS had already accepted (and assumed) that returning fish are exclusively mature (and therefore biased). If it is assumed that the capture across years was proportional and that all mature fish are susceptible to capture (all mature fish return to the river of origin) then the differences between age classes represents both the probability of maturing at age a, and those that remain immature at age a.

Those that are mature at age a ($observed_a$) are those fish that are observed at a given age class assumed to be between years 1 and 9 (one fish reported to be spawning at age 0 was removed from the analysis). The proportion of those fish mature at age a (p_a) must therefore be calculated by the ratio of mature fish to total fish at age a, including both $observed_a$ and the proportion of immature fish ($immature_a$), given by:

$$p_a = (observed_a)/(observed_a + immature_a)$$

but, as discussed above, there were no observations of immature fish at a given age. The cumulative proportion observed in the run cannot simply be used because some of those unobserved immature fish at age a (that would be destined to return to first spawn at a greater age) die at sea. This cumulative curve is therefore known to be biased low with regard to a true maturity schedule as a result of expected mortality. However, if a constant rate of mortality at sea for immature fish was assumed, the probability of mortality between years can be estimated, thereby correcting for the theoretical losses incurred at sea. In other words, $immature_a$ can be estimated by summing the all returns greater than age a, and adding to each returning cohort by incorporating estimated mortality (M) as shown in the following:

$$immature_a = \sum_{j=a+1}^{9} \frac{(observed_j)}{e^{-M(j-a)}}$$

This allows p_a to be calculated, providing a mortality corrected estimate of maturity at age, using region appropriate estimates of natural mortality (see Table 10).

The results of the maturity correction approach with respect to a cumulative curve for observed spawners-at-age (Figure 46). The maturity outputs generated by this method for each region and sex are in Table 12 and Figure 47-Figure 49.

This method is robust to assumptions of *M* over the range of values estimated coastwide. This is demonstrated for the southern iteroparous female data as shown in Figure 50. We used this method to derive maturity curves for this set of data under different values of M across a realistic range that encompassed all estimates coast-wide (0.40 to 0.75). The resulting curves were all shifted to all maturity curves were the corrected maturity probability curves, as expected, are shifted to the right where cumulative probabilities of maturity are lower compared to the cumulative curve of all observed mature fish. Increasing M shifts the corrected curve further to the right (reducing cumulative probability of being mature at a given age) but the shift is relatively small in magnitude. A shift in M from 0.4 to 0.75 (a change in annual mortality from 67 to 47%) changes the cumulative probability of maturation from 29% to 20% for a five-year-old fish and from 66% to 56% for a six-year-old.

1.1.8 Natural Mortality

American shad have a complex life history strategy and natural mortality likely varies by life stage. Mortality while at sea is unknown but would represent a combination of natural death, bycatch, and directed ocean harvest (U.S. and Canadian Waters). There is very little information about at-sea survival except for some analyses done on cohorts of stocked fish. Contribution of fishing mortality (*F*) and natural mortality (*M*) to total mortality (*Z*) is poorly understood because of limitations in tagging programs and fishery records. The SAS determined that use of regional life history parameter estimates was the most appropriate approach to account for limited observations of age classes in some systems. Further, the southern and iteroparous regions were combined due to concerns about a longer history of barriers in the northern iteroparous region biasing natural mortality data (i.e., maximum ages). Therefore, natural mortality estimates for the assessment are defined on a broader scale of iteroparous or semelparous.

In the 2007 assessment, *M* was calculated based on the maximum age using methods described in Hoenig 1983. In this assessment, *M* was calculated based on maximum age using methods described in more recent literature from Then et al. 2015 which results in higher values of *M* at any given maximum age compared to the Hoenig 1983 method (Table 10). This result is in line with patterns seen in Then et al. (2015) and is based on maximum age T_{max} (not adjusted for sample size) seen in a population. The change in method does not provide clarity on actual values of M and natural mortality is likely still confounded with at-sea and non-targeted fisheries, and natural and man-made mortality associated with spawning migrations.

The SAS had a difficult time in using the term *M*, as this term for American shad incorporates multiple factors that are not classically referred to as 'natural'. The components of mortality that are not well characterized for American shad include mortality associated with dams and other man-made habitat modifications, both upstream and downstream, for juveniles or adults. The SAS explored these factors in this assessment (2.7.2 Habitat Assessment and Simulation

Modeling). In many systems it is expected that these dam-driven factors associated with *M* far exceed *F* and are likely limiting population recovery (Stich et al. 2018).

There are limited studies to draw from when looking at post-spawning mortality that is not influenced strongly by dams. Post-spawning mortality is primarily inferred by the presence or absence of spawning marks on scales, however, as noted in section 1.1.4, these marks are in question. Post-spawning mortality of adults has been observed in many rivers, including in quantitative work on the Delaware River in the 1970s and more recent work on tributaries of the Neuse River. Weight loss during their freshwater stay varied by size and sex, with an average somatic weight loss of 30-42% for males and up to about 50% for females in two studies (Chittenden 1976; Raabe and Hightower 2014). The weight loss is attributed to the lack of suitable prey resources and energetic costs of migration, final gonadal development, and spawning (Chittenden 1976) and fat loss may limit their ability to pass barriers (Bayse et al. 2019).

1.1.8.1 Predation

Juvenile American shad are likely forage for many of the same marine predators that prey upon river herring such as striped bass, spiny dogfish, bluefish, Atlantic cod, and pollock (Bowman et al., 2000). Adult American shad are large enough to avoid many species in marine and riverine ecosystems, however they are known to be fed on by seals and other large predators (Scott and Crossman 1973). Mature American shad do not appear to be an important food item for striped bass along the Atlantic coast. Walter et al. (2003) surveyed over 35 published and unpublished reports on striped bass diets in Atlantic coastal rivers, estuaries, and ocean waters. In the previous American shad stock assessment select rivers were investigated for links between striped bass and American shad abundance as striped bass have been implicated with reduction in some river herring and shad runs (Savoy and Crecco 2004). The last assessment was unable to find strong evidence from adult abundance data over two decades that increased abundance of striped bass concurred with decreased abundance of American shad. There were several data sets in which both American shad and striped bass abundance changed in the same direction for all or part of the time series. Such concurrent changes suggest change in environmental conditions or mortality factors that affected both species in a similar manner.

More recent work has suggested that non-native species, specifically flathead catfish (Schmitt et al 2017) select for American shad and river herring with high temporal overlap of spawning. Blue catfish also preyed on alosines, but were more omnivorous and did not appear to be selecting for alosines. Both of these species are present in many Atlantic slope drainages that already have major habitat degradation and other factors reducing American shad populations. Both of these invasive species are expected to expand into more drainages where natural predation regimes already exist.

Two regional fishery-independent trawl surveys (the Northeast Area Monitoring and Assessment Program Trawl Survey, henceforth NEAMAP Trawl Survey; and Northeast Fisheries Science Center Bottom Trawl Survey, henceforth NEFSC Bottom Trawl Survey) that collect diet data were also explored for information on predation of American shad. However, these data were very limited and did not provide any additional insight on predation. For example, the NEAMAP Trawl Survey only identified American shad in four predator stomachs from 2007-2017 (two in spiny dogfish, 1 in a monkfish, and 1 in a striped bass).

1.1.9 Habitat Requirements

American shad are an anadromous, highly migratory species that uses a wide range of freshwater, estuarine, and marine habitats to complete their life cycle (Limburg et al. 2003). Given the current native range of the species from St. Lawrence River in Canada, to the St. Johns River, Florida the types of habitats and habitat conditions used across such a geographic span are diverse (Green et al. 2009). The ASMFC's "Atlantic Coast Diadromous Fish habitat: A review of Utilization, Threats, Recommendations, for Conservation and Research Needs" provides an extensive overall synthesis of information for habitat use by all life stages (Green et al. 2009). The ASMFC has also required all states and jurisdictions to produce American Shad Habitat Plans as part of Amendment 3. Sixteen state and cooperative river basin habitat plans provide greater local detail on American shad and were developed and approved in 2014 (available at http://www.asmfc.org/species/shad-river-herring). Freshwater riverine habitat for American shad has been degraded in many systems from a suite of human caused factors including nutrient loading/run-off, loss of submerged aquatic vegetation, sedimentation, dam impoundments/loss of riverine habitats, and flow alterations from dams.

Access to freshwater spawning and nursery habitat has been dramatically reduced due to the construction of dams across the range of the species, an estimated loss of approximately 4,000 km of habitat (Limberg et al. 2003). Passage of American shad at dams and other barriers, both up and downstream, remains problematic for restoration (Haro and Castro-Santos 2012; Bunt et al. 2012). However, there has been a dramatic increase in the removal of dams along the U.S. Atlantic Coast in recent decades, many of which have directly or indirectly benefitted American shad (American Rivers 2019). Examples of large main stem dam removals that have benefitted American shad include both Veazie (2013) and Great Works (2012) dams on the lower Penobscot River, Maine as part of a coordinated, system scale restoration program. Other more recent system based removals include the Bloede Dam (2018), one of three removed on the Patapsco River, Maryland; removals in the Naugatuck River, Connecticut and in the Pawcatuck River, Rhode Island. Both American Rivers and the U.S. Geological Survey (USGS) have user interface web sites that provide geographic information systems that document dam removals and select related details documenting the extent of this preferred habitat restoration strategy (American Rivers 2020; USGS 2020).

For this assessment, the amount of currently available habitat in Atlantic Coast rivers was assessed and compared to historic habitat availability. See section 2.7.2 for a description of this analysis. Results are presented for individual systems in each system stock section (Section 3), and overall coastwide results are provided in section 4.4.2.

1.1.9.1 Spawning Habitat

Mature American shad return from the ocean to their natal river systems to spawn based on suitable riverine conditions with a limited amount of straying (Bentzen et al. 1989; Nolan et al. 1991; Walther et al. 2008). Given their geographic range, temporal differences are predictably observed for their spawning migration related to water temperature regimes that typically last 2-3 months (Limburg et al. 2003). In Florida and Georgia, adults enter rivers from December to February, respectively and progressively later in the spring moving northward along the Atlantic Coast. Middle Atlantic rivers typically have fish entering rivers in March and April compared to May and June in New England (Green et al. 2009).

River conditions can vary substantially on a south to north gradient based on spring flow regimes, with northern systems having spring snowpack runoff or freshet flows creating less stable environmental conditions. Migration of adults into freshwater has been reported from 5-23°C, range wide (Walburg and Nichols 1967; Leggett and Whitney 1972; Ross et al. 1993). Spawning temperatures have been reported to range from 8-26°C, across the species range (Walburg and Nichols 1967; Marcy 1976; Ross et al. 1993). Spawning migration distance varies depending on river system and may be limited or effected by manmade barriers and any existing fish passage measures. Historic (pre-barrier construction) migration on river systems extended as far as 1,000 km in the Susquehanna River basin with 13 other river systems having runs with migrations over 300 km (Limburg et al. 2003). Run habitat in the Delaware River was shown to be of significantly greater use for spawning than riffle pool habitat type with avoidance of deep and slow water (Ross et al. 1993). Bilkovic et al. (2002) reported a similar preference for spawning activity in the York River, Virginia. Studies in the lower Connecticut River detected spawning in all areas but significantly increased spawning in three distinct reaches upstream of river kilometer 51 (Marcy 1976). Spawning activity and egg incubation has been reported as optimal in a range from 0.3 to 0.9 m/sec (Greene at al 2009).

Male American shad arrive at riverine spawning grounds before females (Leim 1924). Females release their eggs close to the water surface to be fertilized by one or several males. Diel patterns of egg release depend upon water turbidity and light intensity. In clear open water, eggs are released and fertilized after sunset (Leim 1924; Whitney 1961), with peak spawning around midnight (Massmann 1952; Miller et al. 1971; 1975). In turbid waters (or on overcast days; Miller et al. 1982), eggs are released and fertilized during the day (Chittenden 1976a). For example, in the Pamunkey River, Virginia, spawning has been observed throughout the day, which may be due to relatively turbid waters damping light intensity (Massmann 1952). These findings support the hypothesis of Miller et al. (1982) that daily spawning is regulated by light intensity.

Layzer (1974) found that American shad selected discrete spawning sites in the Connecticut River and remained there for most of the season despite the large area available for spawning. Sometimes spawners forego areas with highly suitable habitats that are further downstream, suggesting that there are other variables that influence habitat choice (Bilkovic 2000). Ross et al. (1993) suggest that choice of spawning habitat may be unrelated to physical variables, but rather may reflect a selective pressure such as fewer egg predators in selected habitat.

1.1.9.1.1 Spawning Substrate Associations

Spawning often occurs far upstream or in river channels dominated by flats of sand, silt, muck, gravel, or boulders (Mansueti and Kolb 1953; Walburg 1960; Walburg and Nichols 1967; Leggett 1976; Jones et al. 1978). The importance of substrate type to American shad spawning behavior is still debated. Bilkovic et al. (2002) concluded that substrate type was not predictive of spawning and nursery habitat in two Virginia rivers that were surveyed. Similarly, Krauthamer and Richkus (1987) do not consider substrate type to be an important factor at the spawning site since eggs are released into the water column.

However, eggs are semi-buoyant and may eventually sink to the bottom. Thus, areas predominated by sand and gravel may enhance survival because there is sufficient water velocity to remove particles and prevent suffocation if eggs settle to the bottom (Walburg and Nichols 1967). Furthermore, Layzer (1974) noted that survival rates of shad eggs were highest where gravel and rubble substrates were present. Likewise, Hightower and Sparks (2003) hypothesize that larger substrates are important for American shad reproduction, based on observations of spawning in the Roanoke River, North Carolina. Other researchers have also observed American shad spawning primarily over sandy bottoms free of mud and silt (Williams and Bruger 1972).

1.1.9.1.2 Spawning Depth Associations

Depth is not considered a critical habitat parameter for American shad in spawning habitat (Weiss-Glanz et al. 1986), although Witherell and Kynard (1990) observed adult American shad in the lower half of the water column during the upstream migration. Once they reach preferred spawning areas, adults have been found at river depths ranging from 0.45 to 10 m (Mansueti and Kolb 1953; Walburg and Nichols 1967). However, depths less than 4 m are generally considered ideal (Bilkovic 2000).

Ross et al. (1993) observed that the greatest level of spawning occurred where the water depth was less than 1 m in the Delaware River. Other studies suggest that adults select river areas that are less than 10 ft deep (3.3 m) or have broad flats (Mansueti and Kolb 1953; Leggett 1976; Kuzmeskus 1977). Adults may reside in slow, deep pools during the day, and in the evening move to shallower water where riffle-pools may be present to spawn (Chittenden 1969; Layzer 1974). During the spawning event, females and males can be found close to the surface for the release and fertilization of eggs (Medcof 1957).

Stier and Crance (1985) suggest that for all life history stages, including spawning, egg incubation, larvae, and juveniles, the optimum depth range is between 1.5 and 6.1 m. Depths less than 0.46 m (for spawning adults, larvae, and juveniles) and 0.15 m (for egg incubation), and depths greater than 15.24 (for all life history stages) are considered unsuitable (Stier and Crance 1985). However, recent studies on optimal habitat for spawning events have found that these areas may be defined more narrowly than indicated by studies focused primarily on egg collection. For example, sites deeper than 2 m in the Neuse River, North Carolina, were used less extensively than expected for spawning based on depth availability within the spawning grounds and over the entire river (Beasley and Hightower 2000; Bowman and Hightower 2001).

Spawning for American shad may occur across a broad range of temperatures. Water temperature is the primary factor that triggers spawning, but photoperiod, water flow and velocity, and turbidity also exert some influence (Leggett and Whitney 1972). Based on the temperature range reported by Leggett and Whitney (1972), Parker (1990) suggests that pre-spawning adults tolerate higher temperatures as they undergo physiological changes and become sexually ripe.

Most spawning occurs in waters with temperatures between 12-21°C (Walburg and Nichols 1967; Leggett and Whitney 1972). Generally, water temperatures below 12°C cause total or partial cessation of spawning (Leim 1924). However, Jones et al. (1978) reported American shad moving into natal rivers when water temperatures were 4° C or lower. Additionally, Marcy (1976) found that peak spawning temperatures varied from year to year. For example, peak spawning temperatures in the Connecticut River were 22°C and 14.8°C in 1968 and 1969, respectively (Marcy 1976). Other factors, such as the pace of gonadal and egg development may also be related to water temperature. Mansueti and Kolb (1953) found that shad ovaries developed more slowly at 12.8°C than at 20 to 25°C. In theory, eggs may develop slowly at first then mature rapidly with higher temperatures (DBC 1980).

1.1.9.2 Habitat Requirements for Egg, Larval and Juvenile Life Stages

American shad eggs are initially semi-buoyant or demersal as they develop in relation to water temperature from 2 to as many as 15.5 days (Greene et al. 2009). The reported range of near surface water temperatures suitable for development and survival of eggs ranges from 8 to 30°C (Greene at al. 2009). Once the eggs hatch, the yolk sac larvae typically have 4 to 7 days (also dependent on temperature) before they must start feeding. The yolk-sac larvae are reported to be found deeper than post yolk-sac larvae that are more common near surface (Marcy 1976). No habitat selection was detected for either the egg or yolk-sac in the Delaware River, with location dependent on flow characteristics (Ross et al. 1993). The minimum dissolved oxygen levels for eggs through the juvenile life stage is reported as greater than 5 mg/l (Greene et al. 2009). Low pH tolerance and corresponding aluminum effects is related to time of exposure for eggs and early life stages. Klauda (1994) in laboratory studies, determined for eggs a critical pH of 5.7 and pH 6.5 (96 hours), with varied Al levels. The post-larvae (6-16 days old) were more sensitive to the pH and aluminum treatments than either the eggs or yolk-sac larvae.

High river discharge has been shown to reduce larval fish survival from mechanisms that may include transport from favorable to unfavorable habitat, increased turbidity and a subsequent inability to effectively feed, in both Connecticut and Hudson River studies (Crecco and Savoy 1984; Limburg 1996). Crecco et al. (1983) in the Connecticut River described the initial high rate of mortality 70-85% between days 4-9 of first feeding stage larvae. From this initial first feeding stage, transformation to the juvenile stage did not occur until approximately day 30, with reported outmigration calculated at ages from 75 to 100 days old, at a size of 87 to 106 mm (Crecco et al. 1983). As juvenile shad (>28mm) develop the extent to which they passively drift or actively move downstream requires more research. O'Donnell and Letcher's (2008) study of Connecticut River juvenile shad age, size and growth presented data that supports the hypothesis that early hatch juveniles move downstream as they grow and age. Their study also showed that when juvenile shad become approximately 80 days old they begin to migrate to the ocean in that system. Limburg (1996) reported downstream movements of small juveniles as early as June in the Hudson River.

Juvenile shad have been primarily characterized as habitat generalists with some supporting examples for associations with riffle and run habitat preferences (Odum 1997). Research on the Connecticut River showed juveniles captured at depth during the day versus near surface at night (Marcy 1976). Stier and Crance (1985) report an optimal range for river depth between 1.5 and 6.1 m (for all freshwater life history stages). Optimal temperature ranges for juveniles has been reported from 10 - 25°C (Stier and Crance 1985) and from 10 - 30°C in the Connecticut River (Marcy et al. 1972). Preferred water velocity rates are reported to range between 0.06 and 0.75 m/sec (Klauda et al. 1991). In the Connecticut River, decreasing water temperature, not flow, determined the time juvenile migration began with a peak in activity from 14-19°C (O'Leary and Kynard 1986).

Juvenile American shad may migrate directly to the marine environment or may spend their first year in lower estuarine reaches of their natal rivers (Greene et al. 2009). Examples of estuarine habitat use include Long Island Sound (Savoy 1993), Potomac River (Hammer 1942), and Neuse River (Holland and Yelverton 1973). The ability of juvenile American shad to transition to full salinity saltwater is dependent on both fish size and water temperature (Zydlewski and McCormick 1997). Research by Walther and Thorrold (2010) using otolith microchemistry supports the hypothesis that shad exhibited diverse migratory behaviors and immature individuals from populations throughout the native range do not all mix on northern summer feeding grounds of the Gulf of Maine and Bay of Fundy, Canada. The researchers concluded that "…juvenile and immature American shad appear to exhibit high degrees of inter- and intra-population variability in the timing and extent of their migratory movements." Waldman et al. (2014) using genetic markers determined origins of shad from samples in the Bay of Fundy, Canada from as far south as the Savannah River, Georgia and representation of many other stocks along the East Coast as well as stocks from the St. Lawrence River, Canada. These findings support earlier research by Dadswell et al. (1987) that individuals from across the species range are known to occur in the Bay of Fundy.

1.1.9.3 Marine Habitat

Tagging studies have revealed discrete, widely separated aggregations of juvenile and adult American shad occur at sea (Talbot and Sykes 1958; Dadswell et al. 1987; Melvin et al. 1992). Dadswell et al. (1987) using tag recapture data, reported three primary offshore areas where American shad overwinter: 1) off the Scotian Shelf/Bay of Fundy, 2) in the mid-Atlantic Bight, and 3) off the Florida coast. Summer aggregation areas were reported by the researchers in the areas of upper Bay of Fundy, the St. Lawrence Estuary, and off Newfoundland and Labrador with many other additional analyses of movements also described. American shad from all systems have been collected in the Gulf of Maine during the summer (Neves and Depres 1979). More recent genetic work by Waldman et al. (2014), described mixed-stock origins of shad captured in Delaware Bay in the spring, including fish from the range extremes of the St.

Lawrence River Quebec, and the St. Johns River, Florida. Water temperature ranges of 13 to 18°C (Leggett and Whitney 1972) and 3 to 15°C for near bottom offshore, with a preferred range of 7 to 13°C (Neves and Depres 1979) have been reported for migration corridors for the species. However, Dadswell et al. (1987) notes that although shad move north to south and vice versa seasonally, the belief that certain temperatures serve as primary cues is not supported by the available data. Rather, the authors hypothesize temperature changes interacting with other stimuli may initiate migratory behavior, related to their life stage or origin.

1.1.9.4 Vulnerability to Climate Change

A climate vulnerability assessment of 82 fish and invertebrate species, including American shad, was completed in 2016 for the NE US Continental Shelf (Hare et al 2016). To evaluate the overall climate vulnerability of each species, both the exposure and sensitivity of each species to climate change and decadal variability were examined. The vulnerability of American shad to climate change was categorized as very high. Their climate exposure was classified as very high due to their anadromous life history and resulting exposure to changes in ocean surface temperature, air temperature, ocean acidification, and to a lesser extent, sea level rise. American shad also exhibited a high biological sensitivity to climate change due to their spawning cycle, complexity in reproductive strategy, early life history requirements, dispersal of early life stages, and exposure to other stressors such as habitat destruction, blockage of spawning habitats and contaminants. The ability of American shad to shift distribution is limited by their relatively high degree of spawning fidelity to river systems.

1.1.9.5 Fish Passage

Fish passage refers to the movement of migratory fish across manmade barriers that obstruct the migration pathway, usually through a fishway. A fishway is the combination of structures and elements (facilities, devices, project operations, and measures) necessary to ensure the “safe, timely, and effective” movement of fish past a barrier. Examples include, but are not limited to, volitional fish ladders, fish lifts, bypasses, guidance devices, zones of passage, operational flows, and unit shutdowns (USFWS 2019). Examples of structures are fish ladders, fish lifts, bypass structures and guidance devices. Examples of operations are modification of direction and magnitude of flow, for both up and downstream passage. Fish passage concerns for American shad include, 1) upstream passage of adults, 2) downstream passage of adults where needed (iteroparous populations), and 3) downstream passage of juveniles. The USFWS’s Northeast Fish Passage Engineering Design Criteria (USFWS 2019) is an important tool in helping to ensure fishway design elements are based on the best information available and meet established criteria for fishway prescription development and evaluation.

Science-based evaluation of passage effectiveness and efficiency remains a critical need for the ongoing restoration and management of American shad and other alosines (Bunt et al. 2012; Haro and Castro-Santos 2012; Groux et al. 2015; Silvia et al. 2017). The potential negative impacts from inappropriately designed, operated, maintained fishways and/or other unmet protection measures associated with hydropower or pump-storage facilities and non-hydropower barriers may include:

1. loss/reduction of population occurrence range/distribution (within system) for both adults and juvenile production
2. reduced adult stock abundance
3. loss/reduced ecological contributions as forage in riverine, estuarine, and marine habitats
4. altered age-structure or repeat spawner component
5. reduced or closed commercial and/or recreational fisheries

A fishway has three primary components: 1) fishway attraction, both far field and near field attraction to the entry location(s); 2) entry, typically a relatively small area(s); and 3) passage, movement within and through the structure (Mulligan et al. 2018). Haro and Castro-Santos (2012) provided a synthesis of published information on the history and status of American shad passage, fishway designs and operations. The authors conclude, 1) there have been few improvements in fishway design based on knowledge of shad swimming performance and schooling/migratory behavior; 2) provisions of effective downstream passage for both juvenile and post-spawn adult shad has been given little consideration in most passage projects; and 3) approaches to attract and guide shad to both fishway entrances and downstream bypasses remain marginally understood. They further note that the root causes of poor fishway performance for American shad are for the most part unknown and may lie as much in the lack of attraction to fishway entrances.

Fishway attraction flow is typically limited to 3% (up to 5%) of total project generation flow and may be negatively impacted by "competing" sources of flow (turbine discharge, gate spill, high flows) (USFWS 2019). Increasing fishway attraction flow to address competing flows may improve a fish's ability to locate the fishway entrance (Larinier 1998; Haro and Castro-Santos 2012; Towler and Orvis 2013; Groux et al. 2015). The NOAA approach on attraction flow on the West Coast provides substantially greater attraction flow (3 to 6 times), than the Service's historical approach on the East Coast (USFWS 2019).

Efficiencies and related statistics of upstream passage facilities for American shad at 22 sites are described from the Cooper River, SC to the Merrimack River, MA, with overall efficiencies (attraction to passage) reported from 0.0% to 85%, with a mean of 33% (Groux et al. 2015). Sample sizes used for these reported estimates can be extremely low, supporting the recommendations for better evaluations by Haro and Castro-Santos (2012). In another meta-analyses, Noonan et al. (2012) reports a mean upstream passage efficiency of 41.7% for the 65 studies examined among various species, stating *"it is clear that current fishways are not achieving their primary conservation goal of restoring the connectivity of freshwater ecosystems."* Upstream American shad passage efficiency of 50% is noted as "excellent" and 75% efficiency as "exceptional" with conventional fishway designs (Lanier and Travade 2002; Haro and Castro-Santos 2012). There are also management concerns of physiological costs of passage delay with consequences for both energetics and reproductive success described in Castro-Santos and Letcher (2010).

Management concerns related to downstream passage of American shad at hydroelectric facilities include turbine passage or potentially other routes of passage that may be, to varying degrees, lethal and/or injurious to both juveniles and post-spawn adults. The conventional mitigation strategy is to install a dedicated downstream fishway that allows out-migrating juveniles and post-spawn adults an opportunity to safely bypass the turbines. This may consist of complete exclusion based on screen spacing, behavioral guidance, or a combination of the two (USFWS 2019). Adult shad are relatively large fish, females are larger than males and therefore more susceptible to blade strike (Dadswell et al. 2018; Towler and Pica 2019). Cumulative effects, for populations that must negotiate multiple hydropower projects, can be a problem that requires careful attention and consideration from fisheries managers (Stich et al. 2018). For example, 85% downstream survival at each of three projects results in nearly 40% cumulative mortality.

Study results of juvenile shad mortality based on blade strike model probabilities have shown some consistency with short-term (24 hr) mortality estimates based on field studies at several hydroelectric projects using balloon tagged juveniles passed through turbines of similar design and size (Heisey et al. 1992; Franke et al. 1997). However, juvenile shad field studies have been unable to quantify long-term delayed mortality (>48 hr) that may occur from injuries (injury rates are often quantified in study recovered juveniles), primarily due to difficulty in retaining control fish for >48 hours.

The impacts of a hydroelectric project on an American shad population have been studied at a tidal hydroelectric station located in the estuary of the Annapolis River, Nova Scotia, Canada. In the early 1960s, a causeway (tidal dam) was built across the estuary as a water control structure to allow for the marshland upriver to be used for agriculture without the risk of tidal flooding. The Annapolis Tidal Generating Station (TiGS) was constructed at the causeway and began routine operation in 1985 (it is not being operated at present). The TiGS has a 7.6 meter (m) diameter turbine, operating at 50 RPMs, under a head range of 1.4 – 6.8 m. Upstream passage at the site is provided via the sluice gate that is used to fill the headpond on incoming tides. Two fishways are present to augment downstream fish passage. Fishway utilization for downstream fish passage is not well understood for any of the 46 species present near this station, although the majority of fish are thought to passage through the turbine tube (Fisheries and Oceans Canada 2019).

Mortality of fish passing through the turbine, including American shad, was studied during 1985 and 1986 and again in 1999. The results of these studies were peer reviewed by Fisheries and Oceans Canada in 2019 (Gibson et al. 2019, Fisheries and Oceans Canada 2019). The turbine mortality rate of adult American shad was estimated to be 46.3% (90% C.I.: ±34.7%) in 1985 (Hogans and Melvin 1985) and 21.3% (90% C.I: ±15.2) in 1986 (Hogans 1987). The 1986 estimate is considered the better estimate due to significantly reduced handling mortality compared with the 1985 study (Hogans 1987, Fisheries and Oceans Canada 2019). With respect to young-of-the year American shad, capture and handling mortality has not been fully corrected for in any study (Fisheries and Oceans Canada 2019). The Gibson and Myers (2002) turbine mortality rate estimate of 23.4% (95% C.I.: 6.1% to 58.8%) is considered the better estimate. However, it has a large confidence interval and is larger than for other similarly-sized Alosa species in the study (alewife – 7.7%; blueback herring – 8.1%). All estimates are for short-term mortality rates; delayed mortality for Alosa at this station has not been successfully studied. Pre- and post-operational assessments of the American shad populations have been used to assess changes that have been largely attributed to this hydropower facility (summarized in Dadswell et al. 2018, Gibson et al. 2019 and Fisheries and Oceans Canada 2019). The researchers provide data demonstrating declines in American shad adult lengths, mass, age, and percent repeat spawners with a corresponding increase in total annual adult mortality, consistent with what would be expected with ongoing mortality at the Annapolis TiGS (Dadswell et al. 2018; Fisheries and Oceans Canada 2019).

The 2007 Peer Review requested the development of modeling tools on the topic of fish passage. New tools were developed in 2018, including “A dam passage performance standard model for American shad” (Stich et al. 2018). The researchers utilized a stochastic life-history based model “to estimate effects *of dam passage and migratory delay on abundance, spatial distribution of spawning adults, and demographic structuring in space and time*.” The model was developed in response to state and federal fishery managers’ need for a support tool to help evaluate passage performance criteria in relation to management plan goals. Stich et al. (2018) provides details of the model design, parameters, inputs and R code scripts examining long-term population modeling outcomes for American shad in the Penobscot River, Maine. The Penobscot River model included six main stem dams and four dams on a major tributary, allowing for examination of cumulative effects from exposure to dams under varied fish passage settings, including a no barrier scenario and first barrier complete exclusion scenario. In support of this modeling approach, the FERC (2004) stated, *“…it is important to recognize the significance of modeling tools for assessing fish passage improvements at multiple projects in a river basin. Considering fish passage effectiveness from this level of analysis provides a meaningful approach because cumulative benefits of fish passage and all other restoration measures in the basin can be assessed*."

The Penobscot Shad Passage Model examined sensitivity of modeled population metrics and probability of achieving specific management goals to various inputs. The model demonstrated that spawner abundance and percentage of repeat spawners were most sensitive to survival and migration delay at dams, marine survival, and temperature cues for migratory events. The Penobscot River interim American shad goal of 633,000 spawners, with production targets for defined river segments, were shown achievable under multiple model scenarios, but high rates of upstream (primarily time-to-pass) and downstream passage survival were necessary to achieve the most upstream production targets. The model demonstrated increased downstream passage performance was required to maintain or increase spawner abundance in conjunction with increased upstream passage performance to achieve the most upstream restoration targets.

The USFWS’s Northeast Fish Passage Engineering group developed a fish passage modeling tool to assess downstream passage survival rates (Towler and Pica 2019). The USFWS Turbine Blade Strike Model Tool (www.fws.gov/northeast/fisheries/fishpassageengineering.html) is a probabilistic Microsoft Excel^{TM} based, VBA application of the methods outlined in Idaho National Engineering Laboratory's "Development of Environmentally Advanced Hydropower Turbine System Design Concepts" by G. Franke et al. (1997) for evaluating fish mortalities due to turbine entrainment. The method outcome is highly sensitive to the selection of lambda (probability of a fish blade strike that can be halved or doubled; 0). For this reason, the review of any Franke et al. (1997) based model outputs should take into consideration the lambda value used. The model tool allows users to set a range of inputs that includes routing probabilities (i.e., spill, bypasses, other) that have their own estimates of survival (e.g., balloon tag studies) that can be included to estimate "overall" or, through-project passage success rates.

The USFWS Fish Passage Engineering Design Criteria (2019) documents a number of significant improvements to fishway designs, facility operational conditions, understanding of fish behavior, options for fish exclusion from turbines, and bypass designs that can address the challenges of designing effective passage facilities. The development of specific passage performance criteria that quantitatively defines measures for "safe," "timely," and "effective" has also become increasingly important to fishery managers [Susquehanna River (SRAFRC 2010); Penobscot River (MEDMR and MEDIFW 2008); Connecticut River (CRASC 2019)]. The establishment of performance measures is supported, in part, by the Federal Energy Regulatory Commission's (FERC) draft environmental assessment for the American Tissue Project (FERC No. 2809), which states: "Commerce and Interior have not included any specific performance standards that would be used to test the effectiveness of the fish passage facilities…Without specific performance standards to analyze, there is no basis for assessing the benefits of effectiveness testing for fish passage and determining whether effectiveness testing would or would not provide benefits to Alosines..." (FERC 2018A). Without effective fish passage to provide access to historical spawning and nursery habitats, the species will not be able to achieve the abundance, size and age structure, and within-system range distribution that define population restoration goals and objectives (MEDMR/MEDIFW 2008; ASMFC 2010; SRAFRC 2010; CRASC 2017) and the ASMFC goal of providing for sustainable fisheries.

1.2 History of the Fisheries

American shad historically supported important commercial and recreational fisheries along the entire Atlantic coast; however, these fisheries have declined dramatically over the last half century. Before interstate management required effort reductions across the Atlantic coast, spring spawning migrations of American shad were exploited via two types of fisheries: in-river and ocean-intercept. In-river fisheries only exploit the stock native to that system, whereas ocean-intercept fisheries exploit mixed-stocks of different river origins. There are some estuarine fisheries (e.g., Delaware Bay) that also exploit mixed-stocks.

Both the NOAA National Marine Fisheries Service (NOAA Fisheries) and state agencies have compiled catch statistics for commercial and recreational ocean and in-river American shad fisheries on the Atlantic coast; however, there are data gaps in these records. It is important to note that harvest from fishers operating in-river, or from fisheries that are not federally licensed, might not be reported to NOAA Fisheries. In addition, bycatch in non-directed fisheries is poorly documented. Information provided below is based on state reports (e.g. annual Compliance Reports) and data available from NOAA Fisheries.

1.2.1 Ocean and Mixed-Stock Fisheries

A directed fishery for the coastal migratory mixed-stock of American shad historically occurred in oceanic state and federal waters. While total commercial landings (coastal ocean and in-river) of American have experienced overall declines since the 1950s, between the late 1970s to late 1980s coastal ocean landings of American shad more than tripled. Beginning in the early 1980s, changes in interstate management focused on increasing restrictions to aid in the recovery of the striped bass stock; this may have forced fishers to look to other species like American shad to fill the gaps. In 1980, coastal ocean landings equaled approximately 623,000 pounds; however, by 1989, this number had peaked to 2.1 million pounds and, in 1996, landings were 1.1 million pounds. Ocean harvest contributed about 11% of total East Coast landings in 1978; however, this contribution increased yearly to approximately 67% by 1996.

The ocean and mixed-stock (OMS) fisheries for American shad occurred primarily on pre-spawn shad beginning in late winter in southern states (North Carolina to South Carolina), late February through April in mid-Atlantic states, and from summer through fall in New England waters. OMS fisheries can be characterized as either a directed (targeted) fishery or a “known” bycatch fishery (documented by NMFS landings). Directed fisheries occurred in Rhode Island and states from New Jersey to South Carolina. With the implementation of Amendment 1 to the Interstate Fishery Management Plan for Shad and River Herring, these directed ocean-intercept fishery were closed in the beginning of 2005 (ASMFC 2007b). Known bycatch fisheries occur in New York and to a lesser degree, in the New England states (Maine to Massachusetts). The few exceptions that have had neither type of OMS fishery are the states of Georgia, Florida, Pennsylvania and, very minimally, Connecticut.

In 2014, river herring and shad catch caps were implemented in both the Atlantic mackerel and herring fisheries to reduce river herring and shad bycatch. Due to an absence of coastwide absolute abundance estimates, the catch caps are not biologically-based but aim to provide a strong incentive to avoid river herring and shad while allowing for the full harvest of Atlantic mackerel and herring (NMFS 2019). The Northeast Fisheries Observer Program (NEFOP) began in 1989, which has provided incidental catch estimates for 1989-2017.

Bycatch of American shad in state waters is largely unquantified. A mixed-stock bycatch fishery occurs in Chesapeake Bay, but this bycatch is likely discarded and is not quantified. Harvest of American shad in the Chesapeake Bay is banned and there are no reporting requirements for discards by pound nets and other gears.

Another component of bycatch is more nebulous: fisheries where young shad are landed as unidentified bait. One such fishery was observed on many occasions by individual states biologists, but could not be tracked well by any data reporting system since young fish were often difficult to identify and were lumped into the ubiquitous baitfish category in the NMFS reporting system.

Stock composition of OMS landings of American shad is important to assessing impacts of the losses to individual stocks. Good data on stock composition of shad OMS harvest are not available. However, published and unpublished tag release recapture studies of American shad have been conducted at several locations along the U.S. Atlantic coast. Studies include tag release locations in spawning estuaries and in mixed-stock locations along the coast. There have also been a few DNA studies of stock composition of the OMS harvest. Both tag release recapture and DNA studies provide some insight on stocks that might have contributed to the mixed-stock harvest.

1.2.1.1 Delaware Bay Fishery

A mixed-stock fishery continues to occur within the non-ocean waters of Delaware and New Jersey in lower Delaware Bay. This fishery has the potential to harvest fish from a wide range of shad stocks from South Carolina to Quebec. Based on best available genetic data (Waldman 2006), the mixed-stock fishery is considered to mainly take place in the section of Delaware Bay below a line from Bowers Beach, DE to Gandys Beach, NJ. A new benchmark was developed to limit expansion of the fishery in this mixed-stock area. Mixed-stock landings were highest in the early 1990s and have been generally declining since that time. Landings on the mixed-stock have been below the time-series mean (1985-2018) since 2006.

1.2.1.2 Bay of Fundy Fishery

In the Bay of Fundy shad are exploited in commercial, recreational, and First Nations fisheries. There are directed fisheries (gill net and brush weir) and bycatch from river herring fisheries. Shad are generally exploited in May to June in the Bay of Fundy, but landings of shad are reported from February until November. Fisheries landings have declines in the past decades but these may be attributed to reduced effort and there is insufficient information to draw conclusions on the trends of the populations (Chaput and Bradford 2003).

Individuals from across the species' entire range are known to occur in the Bay of Fundy (Dadswell et al. 1987). Waldman et al. (2014) used microsatellites to determine the stocks from fisheries in the Bay of Fundy. The mixed-stock sample from the Bay of Fundy included several rivers and in highly different proportions. Populations from the St. Lawrence River to the Savannah River were represented. The St. Lawrence River stock was by far the largest contributor at 30.5%; the next largest was the Merrimack River stock with a 15.0% contribution. The estimated contributions from the Connecticut, Hudson, and Delaware River stocks were all less than 5%.

1.2.2 In-River Fisheries

American shad landings from commercial in-river fisheries have steadily decreased since the mid-1900s, based on individual state landings records. In 1980, three million pounds of American shad were landed; however, by 1996, this figure had dropped to approximately 594,000 pounds. From 1980-1996, the majority of commercial American shad harvest from in-river fisheries was taken in New York (33%), North Carolina (17%), Connecticut (15%) and Virginia (14%).

In-river fisheries are persecuted using a variety of gear types, including stake and anchored gill nets, drifting gill nets, weirs, seines, pound nets and scoop nets. Fishers principally harvest shad during the spring spawning migration, which varies in seasonality along a latitudinal gradient. On the St. Johns River in Florida, the spawning season lasts from late December to early May, with peak activity from mid-January to mid-March. In Maine, adult shad normally enter rivers from mid-May to the end of June, with some spawning extending into July and August.

Since the implementation of Amendment 3, which required the prohibition of American shad harvest without a sustainable fishery management plan (SFMP) beginning in 2013, directed in-river commercial fisheries have continued to occur in Connecticut, New Jersey, Delaware, North Carolina, South Carolina and Georgia. American shad in-river commercial fisheries are not allowed in Maine, New Hampshire, Massachusetts, Rhode Island, New York, Pennsylvania, Maryland and Virginia and Florida.

Data on recreational fisheries for American shad are limited or non-existent. NOAA Fisheries operates the Marine Recreational Information Program (MRIP) to obtain information on recreational fisheries for marine species. MRIP does not adequately capture information on anadromous fisheries, including those for American shad because the current survey design focuses on active fishing sites along coastal and estuarine areas rather than inland non-tidal waters where most recreational fishing for American shad occurs. Error associated with data on harvest, catch, and effort is often high. Few states conduct creel surveys or other consistent survey instruments (diary or log books) in inland waters to collect data on recreational shad and river herring catch.

Although data are limited, it is readily apparent that substantial shad sport fisheries occurred on the Connecticut (CT and MA), the Hudson (NY), the Delaware (NY, PA and NJ), the Susquehanna (MD), the Santee-Cooper (SC), the Savannah (GA), and the St. Johns (FL) Rivers, while limited shad recreational fisheries occurred on several other rivers in Maine, New Hampshire, Massachusetts, Virginia, North Carolina, South Carolina, and Georgia. Under the current management program required by Amendment 3, recreational harvest is only allowed in systems with approved SFMPs. For most systems, hook and line is the only gear type permitted in recreational fisheries for American shad, though some states allow the use of recreational gill nets and bow nets. Currently, recreational creel limits range from 0 to 10 fish per day, with the exception of the Santee River (SC), which is permitted to have a 20 fish per day creel limit due to the approval of a conservation equivalency plan in 2000. It is estimated that tens of thousands of shad are caught in recreational hook and line fisheries in Atlantic coast rivers each year. However, the actual harvest (i.e. catch and removal) may amount to only about 20-40% of total catch due to the prevalence of catch-and-release angling practices (ASMFC 2007b).

1.3 General Regulatory History

At the turn of the 19th century American shad were among the top three species harvested on the Atlantic coast (U.S. Fish Commission 1872-1881). Coastwide, nearly 50 million pounds of shad were harvested annually from the late 1880s through the early 1900s. However, in the years shortly following, most East Coast stocks of this once important food fish experienced serious declines. Stock collapses were a coastwide event generated by a number of contributing factors including overfishing, habitat loss from dam construction, dredge and fill operations, and habitat degradation and pollution (see Section 1.1.9).

Human practices were slow to change, and within 50 years the same pattern of events occurred in most all Atlantic states. Following WWII, some East Coast stocks experienced a second collapse, faulted primarily to overfishing during the war and the seven to ten year period that followed (Talbot 1954; Fredin 1954). Environmental degradation that began in the 1800s grew worse, further contributing to the declines. Major dams were constructed, significantly reducing fish passage and causing the destruction or filling of shallow water spawning habitat. Restricted access to spawning habitat was compounded by decreasing water quality associated with pollution, which created low and no-oxygen blocks in major portions of large rivers (two of the most infamous occurring in the Delaware and the Hudson).

By the early 1980s, stock sizes for most Atlantic coast shad stocks had dwindled to a mere fraction of historic populations. Though a few states implemented moratoria (Maryland and New England), commercial harvest of American shad continued in others. Despite stock declines and moratoria, fisheries for roe—shad eggs are considered a delicacy—expanded in recent years to include late winter and early spring seasons in ocean waters and large coastal bays, though they were traditionally only conducted in-river in the spring. These ocean and bay fisheries exploited the pre-spawning migration of American shad, likely resulting in reduced levels of recruitment. Current fisheries are relatively small compared to the magnitude of past fisheries, but it should be noted that American shad stocks also remain much smaller than those present 50 or even 30 years ago.

The earliest records of regulations pertaining to management of American shad fisheries date back to the 1700s when Massachusetts, Maryland, and Virginia took legislative action toward managing their fisheries (A.C. Carpenter, pers. comm.). Since this time, individual state regulations have managed American shad stocks through gear and effort restrictions, as well as season and area closures for both recreational and commercial fisheries, and catch and effort data reporting for commercial fisheries. Regulatory histories and current regulations by system stock are contained in the individual reports.

The driving forces behind the development of fish management strategies for states along the East Coast are difficult to discern from the written historical record, which is often vague and inconsistent. Beginning around 1868, mid-Atlantic and New England states legislated the creation of fish commissions recognizing the tremendous importance of fish, particularly shad, as a food source. Accounts from the New York Forest, Fish and Game Commission (1908) reported that state commissioners from Maine to Pennsylvania met at a convention in New

York City in 1868 to “promote uniformity of law and action among the States” and to discuss “the regulation of nets and netting, the limitation of fishing seasons, and the selection of suitable fishways” with most all of these rules pertaining to take of shad. This is one of the first references to actions taken to regulate fisheries. However, subsequent reference to management actions quickly disappeared, with the primary focus centered on hatchery culture development.

The results of the 1868 convention are thought to have directly “influenced the foundation” of the US Commission of Fish and Fisheries (New York Forest, Fish and Game Commission 1908). Established in 1871, this federal commission took on the task of increasing the supply of “readily available fish,” with American shad as the most prominent species, to meet the increasing demands of a growing population in an expanding country. The Commission deemed federal investment of time and money in hatchery programs necessary so that “no one state would be burdened with such an enormous task” (U.S. Fish Commission 1875), although many states had already made the commitment on their own.

During this time period (1870-1890) shad stocks were still quite large, yet it appears from documentation of the U.S. Fish Commission (USFC) and New York Forest, Fish and Game Commission that runs were experiencing the first serious decline (recorded in the written record). One reference from a New York report mentions there were “few fish to speak of from southern rivers,” referring specifically to the Potomac River. New York was in search of brood stock to assist in replenishing the Hudson stock, perceived to be in major decline. At the same time, the USFC reported landings of about 6 million fish per year from the Potomac. Another USFC report indicated that Potomac River landings were five times higher about 10 to 20 years earlier—about 33 million pounds—and hence the New York assertion that few fish were in mid-Atlantic rivers.

On the federal level, USFC reports rarely refer to any issues with overfishing, but state that hatchery production would solve the “problems related to fishing practices” and the “other drawback of pollution” in spawning areas. Some states, however, did try to address changes in fishing practices, legislating fishing license requirements, escapement periods and some gear restrictions (Legislature of the State of New York, 1868, cited by Harper’s Weekly 1872). But in spite of these attempts at management, most states focused on hatchery production as the best solution to augment declining runs.

As J.L. McHugh (1970) stated, “[i]t is easy, armed with hindsight, to be critical of the past,” concerning fisheries management practices. He also indicated that the philosophy of leaders at the time, Spencer Baird of the USFC along with others in many East Coast states, placed great import on hatchery culture as a solution to the problems of marine and freshwater fisheries. Under these leaders, the federal and state governments “embarked on a vigorous and apparently completely futile program of fish culture for more than 60 years.”

The lack of success of these culture programs can be attributed to the prevalent attitudes of the time. Although some individuals recognized the need to regulate fishermen, the prevalent attitude was that fish commissions could not regulate business nor take away a person’s livelihood. In addition, the growing human population created a different set of problems, none of which could be controlled by fish commissions. The environmental degradation from pollution (i.e., sewage wastes, mill effluents, ash and cinder dumped on spawning areas) was tolerated and accepted as "difficulties to be endured." So in the face of these obstacles, fisheries policy was developed for what could be done—hatchery stocking—and not what should be addressed—pollution and fishing (New York Forest, Fish and Game Commission 1908). Unfortunately this policy continued for the next 100 years.

It is unclear precisely when the emphasis on hatchery culture began to wane. Most references on hatchery culture practices began to disappear after World War II, a period when a slow but evident awakening in fisheries management was about to begin.

At the beginning of WWII, the "pioneer experiment" began with a consortium of seven states recognizing the need for cooperation to address the condition of coastal fish stocks. The creation of the Atlantic States Marine Fisheries Commission in 1941 initially focused on increasing the food fish supply as it was commonly thought that "food will win the war" (ASMFC 1942). Increasing and maintaining fisheries production was of utmost importance to the war effort. The ASMFC used USFWS staff to serve as the primary research arm of the newly formed commission. Early work focused on the need to create a statistical catch reporting system so that consequences of states' actions could be tracked to avoid harm to production levels. Also recognized was the need for a [single] management plan to be implemented as "soon as the war was over."

Some species were recognized as needing special attention: striped bass, flounder, and red drum. Other concerns focused on methods to increase fishing efficiency following the loss of vessels and crew to the war effort and allowing of expansion of fishing areas to inshore areas for trawling. During this period of cooperation, states were still responsible for regulating their own fisheries. Many states relaxed or suspended fishing rules during the war years from 1942 through then end of WWII. Although this temporarily increased production, fishing under relaxed regulations took its toll on shad stocks. The condition of American shad stocks, particularly those of the mid-Atlantic, began to decline throughout the war years, leading up to a second major collapse within a century.

In 1949, the Beaufort, North Carolina Laboratory, under the U.S. Bureau of Commercial Fisheries, reactivated following its closure during WWII, to investigate the declines in East Coast American shad stocks. Overfishing was still not thought of as an important factor on stock size. Mansueti and Kolb (1953) listed overfishing as a possible effect after pollution, siltation of spawning areas, and dam construction. The Lab's "Shad Project" (Talbot, Sykes, Fredin, Walburg, and Nichols, among others) received their initial instruction by Dr. R.J.H. Beverton, the "father" of fish population dynamics analyses. After which they began a series of in-depth investigations in shad populations and factors influencing their abundance in several East Coast systems. The investigators produced what are now considered the "classics" in shad research: studies from the Hudson River (Talbot 1954), Connecticut River (Fredin 1954), Maryland rivers (Walburg 1955), York River (Nichols and Massman 1963), Neuse River (Walburg 1957), Edisto

River (Walburg 1956), and St. Johns River, Florida (Walburg 1960). These studies were among the first steps toward understanding population dynamics through analyzing statistical data. Although many factors were identified as influencing shad abundance the recurrent cause of stock decline in most systems during the WWII period was overfishing.

When the anadromous fish program ended in 1967, major shad research projects were completed in systems from the Connecticut River south to the St. Johns River, Florida. A James Sykes, a leader of some of the anadromous fish projects, retrospectively stated that “the greater accomplishment came by way of laying the ground work for future state management of fisheries through provision of baseline population data and methods of stock assessment” that were made available to state marine research agencies, many of which were non-existent at the time (Wolfe 2000).

1.3.1 Shad Fishery Management Plan

By 1980, coastwide landings of American shad had fallen from approximately 50 million pounds at the beginning of the twentieth century to 3.8 million pounds. Large declines in commercial landings were perceived as an indication that management action would be required to restore American shad to their former levels of abundance. Therefore, ASMFC members recommended the preparation of a cooperative Interstate Fishery Management Plan (FMP) for American Shad and River Herring. The ASMFC adopted this recommendation in 1981 and the FMP was completed in 1985. The FMP specified recommended management measures, focused primarily on regulating exploitation and enhancing stock restoration efforts. When the 1985 FMP was approved, the ASMFC did not have authority over individual state fisheries and implementation of the Plan was at the discretion of the states. The ASMFC approved a supplement to the FMP in 1988, which included reports prepared by the Shad and River Herring Stock Assessment Subcommittee, summaries of material presented at the 1987 Anadromous Alosine Research Workshop, and changes to management recommendations and research priorities based on new research findings.

In 1994, American shad stocks were continuing to decline, which led the Shad and River Herring Plan Review Team and Management Board to determine that the 1985 FMP was not adequate for protecting or restoring the remaining shad and river herring stocks. The 1985 FMP did not require any specific management approach or monitoring requirements within the management unit—it only asked that states provide annual summaries of restoration efforts and ocean fishery activity. To address the shortcomings of the 1985 FMP, the ASMFC implemented Amendment 1 to the Interstate FMP for Shad and River Herring. The 1993 Atlantic Coastal Fisheries Cooperative Management Act helped in this effort by requiring states to adopt management guidelines in this and other approved Commission Plans. Amendment 1 was approved in 1999 (ASMFC 1999).

The goal of Amendment 1 was to protect, enhance, and restore East Coast migratory spawning stock of American shad, hickory, shad, and river herring (alewife and blueback herring collectively) in order to achieve stock restoration and maintain sustainable levels of spawning stock biomass. To meet this goal, the Amendment identified several objectives. The objectives listed below pertain to American shad:

1. Prevent overfishing of American shad stocks by constraining fishing mortality below F30.
2. Develop definitions of stock restoration, determine appropriate mortality rates, and specify rebuilding schedules for American shad populations within the management unit.
3. Promote improvements in degraded or historic alosine habitat throughout the species' range.
4. Establish criteria, standards, and procedures for plan implementation as well as determination of states' compliance with management plan provisions.

Amendment 1 established a five-year phase-out of the ocean-intercept fishery for American shad by January 1, 2005 and required fishing mortality targets for specific in-river fisheries (Connecticut River, Hudson River, Delaware River, Upper Chesapeake Bay, Edisto River, Santee River, and Altamaha River). It also required states to implement an aggregate 10-fish daily creel limit in recreational fisheries for American shad and hickory shad in all rivers except the Santee River, where an aggregate limit 20-fish (American and hickory shad) per day creel limit was enacted.

In addition to establishing fishing regulations, Amendment 1 established monitoring requirements for American shad, including juvenile abundance and adult spawning stock surveys and in-river creel surveys. The specific monitoring requirements, both fishery-dependent and independent, were modified through a Technical Addendum in 2000 and an Addendum in 2002. The measures required by Amendment 1 went into effect on January 1, 2003.

1.3.2 Amendment 3

Following several years of management under Amendment 1, the 2007 American shad stock assessment found most American shad stocks remained at all-time lows and did not appear to be recovering to acceptable levels. In response, the Management Board initiated Amendment 3 to the Shad and River Herring FMP. Similar to management and monitoring requirements developed for river herring under Amendment 2 in 2009, Amendment 3 sought to strengthen the requirements for fishery-dependent and -independent monitoring programs as well as fishery regulations for American shad. The Amendment also established a new management goal recognizing the need to account for impacts to the stocks beyond fishing: "Protect, enhance, and restore Atlantic coast migratory stocks and critical habitat of American shad, in order to achieve levels of spawning stock biomass that are sustainable, can produce a harvestable surplus, and are robust enough to withstand unforeseen threats."

To increase available data for evaluating the effectiveness of management efforts, Amendment 3 established river-specific fishery-dependent (including commercial and recreational) and independent (including juvenile abundance, adult stock structure and abundance, and stocking success) annual monitoring requirements. In addition, the Amendment requires American shad bycatch and discard monitoring in inland and coastal fisheries, and recommends increased coordination of data collection on American shad among states with shared water bodies, as well as between freshwater and marine management agencies.

Amendment 3 also required significantly more restrictive management measures for all participating states and jurisdictions. Specifically, beginning January 1, 2013 the Amendment prohibited commercial and recreational harvest of shad in state waters, unless a state or jurisdiction has a sustainable fishery management plan (SFMP) reviewed by the Technical Committee and approved by the Board. The Amendment defines a sustainable fishery as a commercial and/or recreational fishery that will not diminish the potential future stock reproduction and recruitment. SFMPs must include a definition of sustainability, benchmark goals (if different from or in addition to those identified in 2007 Stock Assessment) and a proposed timeframe to achieve stated objectives, in addition to a description of how the fishery will be conducted and annually monitored to show that the sustainability target(s) are being achieved. SFMPs must be updated every five years. Catch-and-release only fisheries are allowed in any river system without an SFMP.

As of February 2019, SFMPs for American shad have been updated and approved by the Board for Massachusetts, Connecticut, the Delaware River Basin Fish Cooperative (on behalf of New York, Delaware, New Jersey, and Pennsylvania), the Potomac River Fisheries Commission, North Carolina, South Carolina, Georgia, and Florida. Per Amendment 3 all states and jurisdictions are also required to identify significant local threats to American shad critical habitat and develop plans for mitigation and restoration. All states and jurisdictions' habitat plans have been accepted and approved.

1.4 Stock Assessment History

1.4.1 1988 Stock Assessment

The ASMFC Shad and River Herring TC conducted its first coastwide assessment in 1988 (Gibson et al. 1988) on 12 Atlantic coast rivers. The Shepherd stock-recruitment model was used to estimate maximum sustainable yield (MSY) and maximum sustainable fishing rate (F_{MSY}). The status of American shad stocks was evaluated by comparing fishing mortality rates (F) in assessed rivers to F_{MSY}.

1.4.2 1998 Stock Assessment

The second coastwide stock assessment conducted by the ASMFC was completed in 1998 (ASMFC 1998). Generally, assessments were conducted on a river-specific basis, but some grouping of river systems occurred (e.g., Maine rivers were examined collectively, Upper Chesapeake Bay, Albemarle Sound, and Waccamaw and Pee Dee rivers). The Thompson-Bell yield-per-recruit (YPR) model was used to derive the overfishing definition ($F_{30\%}$) for some shad stocks where possible. The assessment examined catch and harvest data, exploitation rates, fish-lift counts, current and historic coastal ($F\mathrm{c}$) and in-river ($F\mathrm{r}$) fishing mortality rates, and other indicators of stock status for American shad from selected stocks or river systems located from Maine to the Altamaha River, Georgia, with special attention on recent (1992 to 1996) stock dynamics. The basis for choosing $F_{30\%}$ as an overfishing definition was not provided.

Trends in total mortality (Z) were examined for the Pawcatuck River, Rhode Island, upper Chesapeake Bay, Maryland, and tributaries of Albemarle Sound, North Carolina, as well as trends in commercial landings for Maine rivers, North Carolina rivers (Albemarle Sound, Neuse, Pamlico, and Cape Fear rivers), and South Carolina rivers (Waccamaw-Pee Dee, Savannah, Edisto, and Santee rivers). Trends in relative adult stock abundance were examined in the Merrimack River (Massachusetts and New Hampshire) based on fishway counts and in Virginia rivers (James, York, and Rappahannock rivers) based on commercial catch-per-unit-effort.

The 1998 assessment concluded that there was evidence of recent (1992-1996) and persistent stock declines in the Hudson River, New York and York River, Virginia and that stock abundance increased in the Pawcatuck River and Connecticut River in the most recent years examined. The assessment concluded that the drop in commercial landings in the Edisto River was largely due to a reduction in fishing effort and did not reflect stock abundance. In addition, the assessment reported that there was no evidence of recent stock declines for the Merrimack River, Delaware River, Upper Chesapeake Bay tributaries, Rappahannock River, James River, Santee River and the Altamaha River. Stock declines inferred from declining trends from river-specific commercial landings were evident for the Neuse River, Pamlico River, Cape Fear River, Waccamaw-Pee Dee River, Savannah River, Albemarle Sound tributaries, and rivers in the state of Maine.

Where estimation of recent F rates (1992-1996) was possible, all were below $F_{30\%}$. The assessment also concluded that there was no evidence that the ocean-intercept fishery had an adverse impact on American shad abundance along the Atlantic coast and that there was no evidence of recent (1990-1996) recruitment failure for Maine rivers, Pawcatuck River, Connecticut River, Hudson River, Delaware River, Upper Chesapeake Bay tributaries, Altamaha River and Virginia rivers.

1.4.3 2007 Stock Assessment

The most recent coastwide stock assessment occurred in 2007 (ASMFC 2007b) and included data through 2005. The assessment was conducted on river-specific stocks given variation in life history and factors influencing survival and abundance (e.g., dams, water quality, and fisheries). In total, 31 river systems had data available to be assessed.

Three primary uncertainties were noted during this stock assessment: (1) reliability of age data, particularly scale-based ages, (2) components contributing to total mortality and changes in these components through time and space, and (3) lack of ocean catch data, particularly by stock of origin.

The bulk of assessment results were drawn from abundance trend analyses (juvenile and spawning adults), total mortality estimators (i.e., catch curves with linear regression), and per-recruit reference points. Reference points were defined in terms of total mortality (*Z*) due to uncertainty in components of mortality contributing to declines in age structure data analyzed with total mortality estimators. The threshold mortality level recommended ($Z_{30\%}$) was total mortality that resulted in 30% of spawning stock biomass per-recruit (SBPR) under baseline, life-history-based estimates of natural mortality. Regional life history data and attributes were used to inform regional reference points, given noted latitudinal differences in life history of American shad. The Peer Review Panel noted limited justification for selecting this threshold level and requested more justification be provided in future assessments. The Peer Review Panel and SAS also noted uncertainty with total mortality estimators can be high, but ultimately felt this approach was appropriate given data limitations.

Abundance trend analyses and total mortality estimates were provided for 23 and 16 of the 31 assessed river systems, respectively. Total mortality estimates generally exceeded $Z_{30\%}$ thresholds for most years in rivers where data were suitable for total morality and SBPR estimates. Stock status determinations were generally based on trend analyses and indicated 8 stocks were declining, 2 stocks were increasing, and 11 stocks were stable. Unknown status determinations were made for the remaining systems with available data due to conflicting trends. Further, a qualitative determination was made that all stocks are highly depressed from historical abundance levels and, from a coastwide perspective, stocks do not appear to be recovering. The assessment identified fishing mortality and habitat changes (damming, degraded water quality) as the key components contributing to these abundance conditions, noting that their relative contributions have changed through space and time. The Peer Review Panel and SAS provided several research recommendations for future data collection and stock assessment. Responses by the current SAS and TC are provided in *Research Recommendation* subsections within section 3 (system-specific) and section 5 (coastwide perspective).

2 METHODS

2.1 Assessment Approach

Consistent with past stock assessments of American shad, the current management framework, and stock structure definition, the American shad coastwide metapopulation was assessed on a system-specific basis. American shad spawn in rivers along the entire Atlantic Coast and there are gradual (latitudinal) differences among river systems in life history attributes. Of greater consequence are system-specific factors such as the presence of dams (with and without fish passage), water quality problems, and estuarine and in-river fisheries. All of these factors lead to system-specific variation in patterns of abundance and in restoration potential. Analyses of mixed-stocks are provided for data sets that could not be assigned to a unique stock to provide context and insight on potential impacts to stocks external to watershed systems, but status of stocks should be considered at the system level.

Waterbodies were assigned to systems based on TC knowledge and the information available on stock structure (Table 1-Table 3). Data sets representative of systems were collated and reviewed by system to identify appropriate analyses. Five categories of analyses were applied: analyses of trends in abundance and biological characteristics (mean length, mean length-at-age) for systems with abundance indices and biological sampling, total mortality estimators for systems with age composition data, per-recruit analyses for regions with life history information, population models for systems with total catch time series and active fisheries, and habitat change mapping with simulated spawner potential impacts for systems with expert opinion on change of available habitat over time and life history information. The SAS conducted most analyses, which were reviewed and approved by the TC, but the TC provided some additional analyses for the assessment. Some American shad systems were identified that had no data to support analyses. These systems are identified in Table 1-Table 3, but not included in the system-specific assessment sections to follow. Stock status for these systems remains unknown.

The following information in Section 2 provides details on data selection and analyses applied during this assessment. Details on specific data sets and results of analyses are provided in Sections 3 and 4.

2.2 Life History Inputs

The SAS used regional life history parameters in this assessment based on the best available information to define regions where intra-region life history parameters are expected to be more similar than inter-region life history parameters. This included regional growth from hierarchical models, regional maturity, regional length-weight relationships, and regional natural mortality estimates. The differences in life history parameters were intuitive given knowledge of regional effects (e.g., higher natural mortality and weight-at-length in semelparous stocks). See section 1.1 for details on life history inputs.

2.3 Abundance Trends

2.3.1 Abundance Data Selection

The TC provided all abundance data sets that have encountered American shad (Table 13-Table 20). Data sets were generally from three sources (fishery-independent surveys, fishery-dependent catch monitoring, or fishway counts) and three life stages (age-0 YOY, juvenile fish older than age-0, and mature spawning adults).

The SAS identified four criteria for accepting candidate data sets: (1) the TC members' recommendation that the data set accurately represents interannual abundance changes for the stock(s) which it samples, (2) a minimum time series length of 10 years for adult indices and 5 years for YOY indices, (3) an average of at least 5% positive annual observations over the time series being considered, and (4) an average of at least 2 annual positive observations over the time series being considered. The SAS recognized some of these criteria are not very stringent, but felt that they were appropriate given the data limitations, the short time frame many monitoring programs encounter American shad (e.g., spring spawning runs), and the understanding that many stocks have experienced very low abundance levels during the time series.

The SAS applied regression models to data sets with complementary data that could explain variation in catchability to develop standardized indices or used nominal indices for data sets without supporting catchability data in analyses. See fishery-dependent and fishery-independent data source subsections in sections 3 and 4 for details on system-specific and mixed-stock data sets, respectively.

2.3.2 Autoregressive Integrated Moving Average Analysis

Trawl surveys for American shad can be quite variable, making inferences about population trends uncertain. Observed time series of relative abundance indices represent true changes in abundance, within survey sampling error, and varying catchability over time (Pennington 1986). Autoregressive Integrated Moving Average (ARIMA) models provide a means to filter measurement error from process variability (Box and Jenkins 1976; Helser and Hayes 1995), and hence allow a population to be more closely tracked than the raw data (Pennington 1986). ARIMA models provide time series estimates of abundance where the variance of the fitted estimates is less than the variance of the observed time series (Pennington 1986).

2.3.2.1 ARIMA Methods

The trawl surveys used in this analysis are shown in Table 18. ARIMA models were only fit to indices with contiguous time series data (ARIMA model requirement) and at least 10 years of data except for three surveys: NEAMAP Trawl Survey; nine years and NEFSC Bottom Trawl Survey Fall and Spring; eight and nine years, respectively. These surveys were included based on the following rationale: NEAMAP Trawl Survey originally met the 10-year requirement, but due to sampling issues, some years were excluded; NEFSC Spring and Fall Bottom Trawl Surveys had a vessel change in 2009 and no calibration factor is available to continue the original time series. ARIMA models were fit to ln transformed index values in most surveys but were fit to ln+0.1 transformed index values for surveys with index values of zero catch in one or more years.

ARIMA models were implemented using the fishmethods package in R (Nelson 2019; RCT 2019) and generally followed the approach of Helser and Hayes (1995) who extended Pennington's (1986) approach of a priori specification of an ARIMA model in which the population's size follows a random walk process (ASMFC 2017b). Helser and Hayes (1995) used bootstrap methods to infer population status relative to an index-based reference point. They used a two-tiered approach for this evaluation, whereby they specified the probability of being above or below a reference point and the associated statistical level of confidence (i.e., 80%) in this specification. Their approach takes into account the uncertainty in both the value of the fitted survey index for a given year and the reference point to which the population level is compared (Helser and Hayes 1995). In lieu of Helser and Hayes (1995) probabilistic approach, this report used methods described in ASMFC 2017b Section 6.9.2 that follows an approach used in Shertzer et al. (2008), NEFSC (2013) and ASMFC (2016b) that does not require the subjective determination of an associated level of statistical confidence (e.g. 80%). Probabilities greater than or equal to 0.50 were considered credible evidence that an index value was greater than a reference point (ASMFC 2017b; ASMFC 2019). For bootstrapping, 1,000 samples were generated.

2.3.2.2 Reference Point

In 1999, ASMFC adopted Amendment 1 to the Shad and River Herring Interstate Fisheries Management Plan (ASMFC 1999) implementing a five-year phase out of the ocean intercept fishery which resulted in full closure on January 1, 2005. Therefore, the 2005 bootstrapped fitted abundance index value was selected as the reference point. This reference point allows for the evaluation of the status of American shad in response to the management action implemented in 2005. Other index-based reference points were considered during this analysis (e.g. 25 percentile of the time series mean), however, due to the mixed-stock nature of these surveys and the inability to evaluate population status relative to any one specific stock, the SAS determined the use of the 2005 index value as most appropriate. For surveys starting after 2005, the terminal year was compared to the first year of the survey.

2.3.2.3 Sensitivity Analyses

During previous assessments, concerns regarding the influence of the first year of data on ARIMA results have been raised (ASMFC 2012, ASMFC 2017a). Therefore, the sensitivity of the ARIMA results to the data gathered early in the time series were explored following methods in ASMFC 2017a, where a reverse-retrospective approach was taken by sequentially removing the first four years of data, one at time. Furthermore, the mean of the first three years of data as the initial data point for the ARIMA model was explored. While ARIMA models are potentially sensitive to initial data points, the influence of terminal year data on the probability of being above or below a given reference point should also be considered. To assess the sensitivity of the probabilistic results relative to the value of the terminal year, the mean of the final three years as the terminal year index value was used for comparison to the 2005 reference point. Sensitivity analysis that resulted in a survey having less than 10 years of data were excluded.

2.3.3 Mann-Kendall

A total of 195 fishery-independent and fishery-dependent surveys were submitted for consideration in the assessment. After review, 87 data sets were used in the analysis (Table 13-Table 20), consisting of 21 fishery-dependent surveys, 65 fishery-independent surveys, and 1 hierarchical index (see Section 3.6.5.2.3). Fishery-independent surveys included 9 juvenile abundance indices, 7 run counts, and 49 CPUE based surveys. The trends of American shad abundance along the Atlantic coast were analyzed with Mann-Kendall trend analysis. These analyses and accompanying statistics facilitated an objective assessment of trends over time. Results were reported for river-specific data sets and for data sets that contained CPUE for mixed-stock fisheries in the Atlantic Ocean. The term “mixed-stock” includes those shad partaking in the coastal ocean migration as well as those that are caught in estuarine waters before beginning migrations up natal streams. Mann-Kendall trend analysis was used to detect trends in each of the surveys for both the complete time series provided for each survey as well as the period of all years from 2005 forward. The second time period was used to examine possible responses in indices after the closure of the ocean-intercept fishery, as described in section 2.3.2.2. A significance level of 0.05 ($p \leq 0.05$) was used to determine whether a statistically significant trend was present.

Mann-Kendall results are provided in Table 21.

2.3.4 Power Analysis

2.3.4.1 Background of Analysis and Model Description

Power analysis was used to calculate the probability of detecting trends in the abundance indices developed from fishery-independent and fishery-dependent data using the methods of Gerrodette (1987) in R (RCT 2017). By definition, a trend is detected when a regression has a slope significantly different from zero with Type I (conclusion that a trend in abundance is occurring, when in fact it is not) and Type II (conclusion that no trend is occurring, when in fact it is) errors being defined in the usual way. As such, the probabilities of making Type I and Type II errors are labelled α and β, respectively. Power is defined as 1 – β.

Using the approach of Gerrodette (1987), changes in abundance can take place due to constant incremental changes (linear model) or due to a constant rate (exponential model). Linear trends were modeled as $A_i = A_1[1 + r(i - 1)]$ (equation 1 in Gerrodette 1987) where A_i represents the abundance as a function of an index of time (i) and r is a constant increment of change as a fraction of the starting abundance index (A_1). Exponential trends were modeled as $A_i = A_1(1 + r)^{i-1}$ (equation 2 in Gerrodette 1987), with r being the finite fraction rate of change per time unit. For a linear change, $r = R/(n - 1)$ where R is the overall fraction change in abundance. For an exponential change, $r = (R + 1)^{1/(n-1)} - 1$.

In practice, each abundance, A_i, is estimated by the sample abundance estimate, $\widehat{A_\imath}$. For the linear model, $\widehat{A_\imath} = A_i + \varepsilon_i$, while for the exponential model, $\ln \widehat{A_\imath} = \ln A_i + \varepsilon_i$, where the ε_i are normal, independent random variables with mean zero. For the exponential model, note that this implies that the $\widehat{A_\imath}$ are lognormally distributed. Gerrodette (1987) proposes three different assumption about how the coefficient of variation (CV), and hence variance, relates to abundance: $CV(\widehat{A_\imath})$ is proportion to $1/\sqrt{A_i}$, is constant with respect to A_i, or is proportional to $\sqrt{A_i}$.

2.3.4.2 Model Configuration

All fishery-dependent and fishery-independent surveys that were developed into abundance indices and possessed annual estimates of uncertainty in abundance were tested in the power analysis. Variability in abundance as a function of both linear and exponential change was tested using a one-tailed test. Power was calculated for a change (R) of ±50% over a 10-year time period for both a linear and exponential trend. The resulting constant increment of change (r) as a fraction of the starting abundance index for a linear trend was $r = 0.056$. For the exponential model, the finite fraction rate of change per time unit (r) was $r = 0.046$. As an estimate of the variability in annual abundance estimates, for each survey the median CV of the individual time series was calculated as the median proportional standard error

(PSE; $SE(A_i)/A_i$). For the power analysis, it was assumed that the $CV(\widehat{A_i})$ was constant with respect to A_i, using the median proportional standard error as this measure in the model.

As a benchmark, the SAS established a reference point of a power of 0.80 for surveys to detect an increasing trend over a 10-year time period.

Results of power analysis are found in Table 25.

2.4 Mean Length and Length-at-Age Trends

2.4.1 Trends in Mean Length

Length data from coastwide monitoring programs across 27 identified systems were submitted for potential use (Table 13-Table 20). Only data sets containing sex information and a minimum time series of 10 years with at least thirty fish sampled per year were included for analysis, eliminating 58 data sets and leaving 32 data sets included in the analysis. Fork length data were converted to total length when applicable. Mean length was calculated for each year by sex and time series were examined to determine if changes have occurred over time. The Mann-Kendall test for trends in data was used to test if negative or positive trends occurred in the mean length data. A significance level of 0.05 ($p \leq 0.05$) was used to determine whether a statistically significant trend was present.

Changes in mean length over time can be indicative of demographic shifts in a population. For example, the mean length of a female American shad is often greater than that of a male of the same age, therefore a declining trend in mean length in a population could correlate with a smaller proportion of females. One potential cause of demographic shifts is contraction of the population size structure due to decreasing survival (i.e., increasing mortality).

2.4.2 Trends in Mean Length-at-Age

Mean lengths-at-age of American shad were also examined to determine if population demographic changes have occurred over time. The Mann-Kendall test for trends in data was used to test if negative or positive trends occurred in the mean length data for each age. A significance level of 0.05 ($p = 0.05$) was used to determine whether a statistically significant trend was present. Both scale and otolith ages were submitted, but use varied by program and state. The number of paired samples of otolith and scale age from the same individual were limited. Although otoliths have been shown to provide more accurate ages, particularly in older fish, many of the data sets only contained scale-derived ages. There was no consensus on selecting only one ageing structure to be used in the assessment and because of the number of sampling programs that would be excluded for use if scales were not included, the trend analysis was done for each sampling program regardless of which ageing structure was used. Only data sets with at least 30 individual fish aged per year for a minimum of 10 years were included in the analysis.

2.5 Per-Recruit Analysis

2.5.1 Introduction

Biological reference points (BRPs) provide a metric to assess stock status from a biological perspective (Gabriel and Mace 1999), integrating several components of stock dynamics (growth, recruitment and mortality, usually including fishing mortality) into a single index (Gabriel and Mace 1999) that can inform fisheries management objectives. In turn, they provide a gauge as to whether specific management objectives are being achieved; as such, they provide both the link between mortality and biomass estimates available from stock assessments and management objectives (Caddy and Mahon 1995), and a basis for risk analysis of management actions (Punt and Hilburn 1997).

Three common modeling approaches for developing BRPs are spawner-recruit, dynamic pool and production models. The choice of model selection is predicated on life history and availability of catch, relative abundance, stock-recruitment and age-specific mortality, growth and maturity data (Gabriel and Mace 1999). The SAS believes a SBPR is most appropriate for the development of BRPs for American shad stocks based on the following rationale: SBPR's do not require constant recruitment, they do not require a defined stock-recruit relationship, and they require limited data inputs.

A modified Thompson-Bell SBPR model was used to develop instantaneous total mortality (Z) BRPs for American shad. Since there are many competing theories on relative causes of mortality in Atlantic coastal American shad stocks (see Section 1.5 of the 2007 Benchmark Stock Assessment; ASMFC 2007), a benchmark rate for Z was developed in lieu of instantaneous fishing mortality (F). This does not eliminate the issue of partitioning mortality into F and instantaneous natural mortality (M) in the model, but it does avoid the emphasis on F when comparing the results to observed estimates of Z. Furthermore, this reference point is analogous to the SBPR fishing mortality rates (e.g. $F_{30\%}$, $F_{40\%}$) widely used as reference points in fisheries around the world when spawner-recruit relationships are uncertain under assumed constant rates of M (Quinn and Deriso 1999).

SBPR-based reference points are defined based on the level of additional mortality beyond M the stock can experience without reducing the SBPR below a certain percent, say X, of the unexploited SBPR. Historically, values in the range of $F_{20\%}$ to $F_{30\%}$ (i.e., in terms of Z: $Z_{20\%}$ to $Z_{30\%}$) have frequently been used to characterize recruitment overfishing thresholds (Rosenberg et al. 1994), which is consistent with the choice of $Z_{30\%}$ as a management threshold in the previous benchmark stock assessment of American shad (ASMFC 2007b). However, several more contemporary lines of evidence suggest the need to maintain higher levels of SBPR for species such as American shad. First, simulations by Clark (1993) suggests that fishing at a level between 35-45% ($F_{35\%}$-$F_{45\%}$; or in terms of Z: $Z_{35\%}$-$Z_{45\%}$) provides a high percentage of maximum sustainable yield, especially if there is uncertainty in the stock-recruitment relationship, which is the case for many American shad stocks. Second, Clark (2002) went on to suggest that SBPR would need to be even higher for less resilient and/or data-poor stocks but could be lower for resilient and/or data-rich stocks. American shad possess many of the qualities of species traditionally considered to be less resilient and many of the individual stocks found in individual river systems remain data poor. Third, as temporal correlation amongst annual recruitment increases, a temporal correlation in American shad recruitment was expected given their life history (section 1.1), simulations suggest the SBPR required to achieve MSY increases to greater than 40% and that there is a high probability that spawning stock biomass will fall below 20% of unfished levels if SBPR is reduced to 35-45% of unfished levels; only if recruitment variation is uncorrelated (i.e., truly random) does fishing at $Z_{40\%}$ prevent spawning stock biomass from falling below 20% unfished levels (Clark 1993). Fourth, Clark (2002) suggests that if one is unsure of the stock's resilience (i.e., could be very low), even fishing at $Z_{40\%}$ could lead to trouble. Finally, Mace (1994) suggests that the choice of an appropriate SBPR based reference point is highly dependent on the degree of resilience exhibited by individual species, with his simulations suggesting even stocks of average or above-average resilience, of which American shad are not, should have SBPRs maintained in excess of $Z_{35\%}$, with $Z_{40\%}$ being more appropriate.

Consistent with the above contemporary views on appropriate SBPRs, the data-poor characterization for most, if not all, American shad stocks, and the uncertainty related to American shad stock resiliency, the SAS selected $Z_{40\%}$ as the threshold BRP. $Z_{40\%}$ is the total mortality rate that will preserve 40% of the unexploited SBPR. For comparison with SBPR derived $Z_{40\%}$ BRPs, $Z_{40\%}$ BRPs were calculated using a modified Thompson-Bell egg-per-recruit (EPR) model.

2.5.2 Methods

SBPR and EPR models were implemented using the *fishmethods* package in R (Nelson 2019; RCT 2019) and follow methods described in Gabriel et al. 1989. The SBPR models start with recruits at age one. The abundance of age 1 recruits (N_1) is set to a constant value (say 1000) to obtain a per-recruit value. Recruits are decremented annually by M until they reach harvestable ages. Then they are decremented by M and F through the maximum age observed. The SBPR for a given level of F, $SBPR_F$, is given by:

$$SBPR_F = \sum_a N_a m_a w_a$$

where N_a is the number at age a, m_a, is the age-specific maturity probability and w_a is the mean weight at age a. Values of F ranged from 0 to 2.0. The number of fish at age a is given by:

$$N_a = N_a e^{-(cp_aF+dM)},$$

where c is the fraction of fishing mortality within a year before spawning, p is the fraction recruited to the gear at age a and d is the fraction of natural mortality within a year before spawning. EPR models follow the same equations above substituting fecundity-at-age (f_a) for weight-at-age.

2.5.2.1 Model Inputs

It is important to note that data inputs used in all SBPR models have been obtained from fished stocks as well as stocks that have experienced significant habitat alterations relative to historically available habitat. These data may not reflect those characteristics from an unfished or unaltered stock. For example, natural mortality estimates derived from max age may not reflect the true max age of a stock due to anthropogenic influences. Model inputs were derived from regional aggregate biological data.

2.5.2.1.1 Natural Mortality

Natural mortality was calculated following recommendations in Then et al. 2015 as described in Section 1.1.8. The resulting M values by region are: northern iteroparous = 0.47, southern iteroparous = 0.47, and semelparous = 0.65 (Table 26).

2.5.2.1.2 Maturity Schedule

American shad maturity ogives by region are described in Section 1.1.7 and presented in Table 27 and Figure 52.

2.5.2.1.3 Mean Weight-at-Age

Mean lengths-at-age were derived from von Bertalanffy growth equations reported in Section 1.1.5 and converted to mean weights-at-age in kilograms (Table 27,Figure 52) using respective length-weight equations (section 1.1.3.2).

2.5.2.1.4 Fecundity-at-Age

Recent literature by Hyle et al. (2014) raised concerns about the accuracy of historical American shad fecundity estimates. Historical fecundity estimates used a determinate method that estimated annual fecundity as the standing stock of oocytes at a single point of time prior to spawning. However, American shad have asynchronous development of yolked oocyte clutches, which suggests that new oocytes could arise after spawning commences, biasing the results of a determinate fecundity method downward (Hyle et al. 2014). If so, annual fecundity should be a product of batch size and the number of batches—an indeterminate fecundity method (Hyle et al. 2014). Since batch spawning frequency and spawning duration are often unknown, batch size, also termed batch fecundity, is a useful comparative measure of the reproductive potential of fishes exhibiting indeterminate fecundity (Olney and McBride 2003).

Therefore, regional batch fecundity estimates were developed by applying the linear relationships between batch fecundity and body weight for three rivers reported in Olney and McBride (2003) to regional weight at-age-data (Table 27, Figure 52). The three rivers examined by Olney and McBride (2003) opportunely fell within each of the defined regions; Connecticut River (northern iteroparous), York River (southern iteroparous), St. John's River (semelparous) and were used as proxies for each region, respectively.

While using batch fecundity instead of total annual fecundity alleviates the concerns of Hyle et al. (2014), Olney and McBride (2003) did not observe latitudinal variation in batch fecundity that was observed in annual fecundity reported in other studies (Leggett and Carscadden 1978; Limburg et al. 2003). Hyle et al. 2014 suggests that southern populations may spawn for a longer duration than northern populations and release many more batches noting that if indeterminate fecundity is more prevalent in southern populations, the latitudinal gradient may be even greater than previously reported. This latitudinal gradient in number of batches is further supported by McBride et al. 2015 that reported 6.7 mean batches for Connecticut River shad while Hyle et al. 2014 that reported between 11-17 batches for York River shad. Although a latitudinal gradient of increasing batches from north to south is evident, using batch fecundity in lieu of total annual fecundity derived from an indeterminate method only differs in magnitude not direction. Therefore, the resulting $Z_{40\%}$ reference points derived from EPR models will not differ when using either batch or annual fecundity. However, it should be noted that egg per-recruit values at any given increment of Z will be lower following the same latitudinal gradient (e.g., the difference in EPR values derived from batch fecundity versus annual fecundity will increase from north to south).

2.5.2.2 Partial Recruitment

Partial recruitment at age in this analysis is analogous with gear selectivity. However, the necessary data to calculate gear selectivity is unavailable. To address this issue, it is assumed that once fish are mature, they are equally vulnerable to the fishery. Therefore, a maturity ogive is used as a surrogate for the partial recruitment-at-age. While this assumption is likely violated during residence time at sea due to length frequencies observed in the bycatch of ocean fisheries, it is a fair assumption for a typical in-river fishery as described in Section 1.2.2. In-river fisheries typically target gravid females for their roe regardless of age. This assumption does not account for fishery driven selectivity (fishers trying to capture the largest gravid fish to obtain the greatest market value) however, assuming gear selectivity-at-age is less than maturity-at-age, using a maturity ogive as a surrogate for gear selectivity should result in a more precautionary Z_{40} BRP.

The SBPR model requires specification of parameters c, fraction of F within a year occurring prior to spawning, and d, fraction of M within a year occurring prior to spawning. Parameter c was set to 1 which could be considered a proxy for a Type 1 fishery where fishing mortality occurs before spawning. An in-river fishery is considered representative of a Type 1 fishery therefore deemed appropriate for this analysis. Parameter d was also set to 1 under the assumption that M is uniformly distributed over the year (Gabriel et al. 1989). This assumption is unlikely due to spawning stress and potentially increased predation during spawning events. However, model results were insensitive to d (see *Sensitivity Results* below).

Various sensitivity analyses of model inputs were conducted on the southern iteroparous SBPR and EPR to calculate a $Z_{40\%}$ using a variety of data inputs. The data inputs included varying values of the following inputs/model parameters: M, fraction of F occurring before spawning (c), fraction of M occurring before spawning (d), and where available: river specific; mean weight-at-age and maturity ogives. Sensitivity analyses of age variant M are reported in values of $F_{40\%}$ due to the inability to easily convert $F_{40\%}$ to $Z_{40\%}$ when M varies by age. EPR sensitivity analysis was limited to varying values of M due to limited river specific fecundity data.

2.5.3 Results

The $Z_{40\%}$ from SBPR models by region are: northern iteroparous = 1.00, southern iteroparous = 1.07, and semelparous = 1.43 (Table 28, Figure 53). The $Z_{40\%}$ from EPR models by region are: northern Iteroparous = 0.99, southern Iteroparous = 1.04, and semelparous = 1.52 (Table 28, Figure 53). Curves of SBPR at increasing levels of Z showed highest values of SBPR at each Z for the southern iteroparous, followed by the northern iteroparous, and semelparous regions (Figure 53). Curves of EPR at increasing levels of Z showed highest values of EPR varied between the northern iteroparous and southern iteroparous regions depending on the level of Z followed by lowest values of EPR for the semelparous region (Figure 53).

Influences on SBPR, EPR and $F_{40\%}$ varied with the value of M. Curves of SBPR and EPR at increasing levels of F showed that highest values of SBPR and EPR were produced at the lowest age invariant M values (Figure 54).

For a constant, age invariant M, $F_{40\%}$ increased with increasing values of M. $F_{40\%}$ values based on SBPR ranged from $F_{40\%} = 0.43$ when $M = 0.3$ to $F_{40\%} = 0.93$ when $M = 0.7$ (Table 29). $F_{40\%}$ values based on EPR were similar and ranged 0.42 to 0.88. For age variant values of M, $F_{40\%}$ values were lower than age invariant M for either SBPR or EPR. For age variant M, the $F_{40\%} = 0.35$ (SBPR) and $F_{40\%} = 0.34$ (EPR) (Table 29).

The response of SBPR and $Z_{40\%}$ decreased with increasing values of c (the fraction of F occurring prior to spawning) while holding d (fraction of M occurring prior to spawning) = 1 (Table 30, Figure 55). When $c = 0$ (no F occurring prior to spawning) the resulting $Z_{40\%} = 1.83$, $c = 0.5$ (50% of F occurring prior to spawning) $Z_{40\%} = 1.29$, and $c = 1$ (100% F occurring prior to spawning) $Z_{40\%} = 1.07$.

For model parameter d, the response of SBPR and $Z_{40\%}$ varied while holding $c = 1$ (Table 30, Figure 56). When values of d increased values of SBPR decreased, however; $Z_{40\%}$ remained unchanged at $Z_{40\%} = 1.07$ (Figure 56).

For river-specific sensitivity analyses, M was held constant at $M = 0.47$ while varying river-specific data inputs (maturity-at-age and weight-at-age) for the following southern iteroparous rivers: Hudson R., Delaware R., Nanticoke R., Upper Chesapeake, Potomac R., Rappahannock R., York R., James R., Albemarle Sound, and the Tar-Pamlico River complex. SBPR $Z_{40\%}$ BRPs varied but generally followed the expected pattern of lower $Z_{40\%}$ in northern rivers and higher $Z_{40\%}$ in southern rivers, ranging from $Z_{40\%} = 0.93$ for the Hudson River to $Z_{40\%} = 1.09$ for the Tar-Pamlico River complex (Table 31, Figure 57). Curves of SBPR did not follow the expected pattern from south to north. SBPR values were generally lower in the south and higher in the north. These results are confounding; however, they potentially illustrate the effects of anthropogenic impacts on river-specific stocks. For example, maturity-at-age and weight-at-age can be affected by a fishery that targets the largest fish. As such, anthropogenic effects should be kept in mind when considering the results of this analysis. Ideal data inputs would be from observations taken during a time with no anthropogenic impacts. Unfortunately, no data exists for any east coast American shad stock under such conditions.

2.5.4 Discussion

Models and analyses in this section were developed to provide a relatively simplistic approach to assess the current status of American shad stocks considering the limited data availability. One limitation to this approach is the reliance on data inputs derived from anthropogenically altered stocks. Undoubtedly, the effects of habitat alteration/degradation and fishing have impacted American shad stocks across their entire range resulting in the inability to accurately characterize biological metrics from an unaltered stock. For example, M was calculated based on maximum age observed by region and the sensitivity analysis showed that models were highly sensitive to M. Therefore, underestimating maximum age results in an underestimation of virgin spawning stock biomass which in turn, results in inflated reference points. Nonetheless, the $Z_{40\%}$ BRPs from this analysis are the best available given the limited data for these stocks. $Z_{40\%}$ reference points from this analysis also provide additional metrics for Atlantic coastal states to consider when developing management plans.

It is also important to note that fisheries-type reference points are appropriate when stock abundance is sufficient to support fisheries; however, for populations under restoration, rebuilding, with low freshwater productivity, or affected by other sources of anthropogenic mortality (e.g. turbine mortality), reference points may need to be adjusted to compensate for those additional factors. More specifically, for populations with low freshwater productivity, a $Z_{40\%}$ criterion will not ensure population recovery to historic levels, as it does not explicitly account for this reduced production (ASMFC 2007b).

2.5.4.1.1 Previous Assessments

BRPs resulting from this analysis differ from those reported in the previous two American shad assessments (ASMFC 1998; ASMFC 2007b). In ASMFC (1998), the BRP was defined as $F_{30\%}$ and resulted in higher comparable $Z_{40\%}$ reference points than reported in this analysis. This is primarily due to the selection of M which was much higher for older ages in the 1998 assessment based on the hypothesis of high post spawning mortality. In ASMFC (2007), the BRP was defined as $Z_{30\%}$, and counterintuitively resulted in lower comparable $Z_{40\%}$ reference points. In the 2007 assessment, M was calculated based on the maximum age using methods described in Hoenig 1983. In this analysis, M was calculated based on maximum age using methods described in more recent literature from Then et al. 2015 which results in higher values of M at any given maximum age compared to the Hoenig 1983 method. These inconsistencies in BRPs illustrate the challenges as well as the importance of selecting appropriate model inputs.

2.6 Total Mortality Estimators

2.6.1 Background of Analysis and Model Description

One of the objectives of Amendment 3 to the FMP for Shad and River Herring (ASMFC 2010) is to maintain total mortality of stocks at or below stock assessment benchmarks. To this end, there are numerous stock-specific monitoring efforts sampling annual age compositions and some annual compliance reports provide estimates of instantaneous total mortality rates (Z) of spawning adults, but currently no stocks are managed (through SFMPs) based on total mortality reference points. For the current assessment, available age composition data was analyzed with catch curve analysis to develop a standardized approach for generating total mortality estimates to compare against per-recruit reference points.

Three methods were used during the analysis, Chapman-Robson estimators (Chapman and Robson 1960), weighted linear regressions (Maceina and Bettoli 1998), and generalized linear mixed models (GLMM, Millar 2015). The analyses calculated total instantaneous mortality rates and standard errors. Methods were applied using the agesurv function in the R package fishmethods (version 1.11-0, Nelson 2019; R Core Team 2019).

The Chapman-Robson estimator estimates mortality from natural log transformed data assuming the lifetime of the cohort follows a geometric distribution. Corrections are applied for back-transforming from the natural log scale and for over-dispersion in the data (Smith et al. 2012). The Chapman-Robson estimator has consistently proven robust to assumption violations and has often resulted in superior performance when applied in simulation analyses (Dunn et al. 2002; Smith et al. 2012; Nelson 2019). Weighted linear regression is applied to natural log transformed data and estimates total mortality as the negative of the slope coefficient. Weightings are set as the predicted natural log scale age compositions from unweighted linear regression initially applied to the data set. Weighted linear regression has been shown to perform about as well as the Chapman-Robson estimator under some configurations (Smith et al. 2012). A more recent development in total mortality estimation is the application of Poisson generalized linear mixed models (GLMMs) with a random intercept and log-link function to the untransformed age composition data.

Common assumptions among these methods are equal probability across individuals of being captured (i.e., constant gear selectivity and availability, sampled at random), constant mortality across ages included in the data set, no ageing error, and, if applicable, constant sampling effort through time when applied to longitudinal, or true, cohorts. Constant recruitment is another assumption shared by the Chapman-Robson estimator and weighted linear regression when applied to synthetic, or cross-sectional, cohorts. The random intercept of Poisson GLMMs is intended to account for year class variability, relaxing the assumption of constant recruitment.

2.6.2 Model Configuration

Age composition data were generated by year, monitoring program, system, sex, and age structure according to the respective monitoring program sampling design. Data from monitoring programs that randomly sampled total catch or collected ages from all catch (i.e., census) were tabulated into raw frequencies. Data from monitoring programs that sampled ages by length bin were calculated by applying annual length compositions to age-length keys. These expanded age composition data were then rescaled according to the number of actual ages observed for age-length keys and rounded to the nearest integer. Estimates were not developed from repeat spawn data given concerns with the reliability of these data expressed by peer reviewers of the most recent river herring assessment (ASMFC 2012) and through analyses within this assessment (see Section 1.1.4.3).

2.6.2.1 Data Set Filtering

Two criteria were used to filter data sets for the analysis. A minimum of three age classes greater than or equal to age of full recruitment (see below) and at least 30 individuals across these age classes had to be observed for age. One concern noted for the first criterion of at least three age classes was that this may systematically filter out data sets from periods of higher mortality. However, this criterion is necessary to estimate variance of the regression slope, is consistent with the most recent river herring assessment (ASMFC 2012), avoids drastic swings due to deriving mortality estimates from two noisy data points, and maintains consistency to evaluate changes in mortality over time. The threshold for number of observed fish was based on the general rule of thumb for sufficient sample size necessary to estimate the parameters of a distribution under the central limit theorem. Published simulation analyses typically used greater bounds on the minimum sample size for simulated data sets, but the selected threshold for this analysis is a pragmatic decision given the relatively small sample sizes of available data. Small sample sizes and the limited scope of these monitoring programs also resulted in some occurrences where typically abundant age classes are absent from the data set and imputation of these occurrences by setting them equal to one (zero on the log scale) was explored. Ultimately, these occurrences were assumed to be due to one or more sources of error (e.g., sampling error, year class variation) and not reflective of true mortality. Therefore, imputation was not applied to the data. After the initial filtering, any monitoring programs with fewer than three consecutive years of data for a given sex and age structure were also dropped from the analysis.

2.6.2.2 Age at Full Recruitment

Selectivity of monitoring program gears was assumed constant over time and age composition data were aggregated across years to identify the age at which maximum catch has occurred, or peak age. Age of full recruitment, the youngest age to include in data sets to satisfy the constant selectivity assumption, was then defined based on peak age with two alternative methods commonly applied in the literature, age of full recruitment equal to peak age and age of full recruitment equal to peak age plus one. Females from the same monitoring programs were often found to have greater peak ages than males. In addition, some fisheries target females while males are bycatch. Therefore, data were analyzed by sex only to avoid masking sex-specific trends in mortality and biasing estimates due to sex-aggregate peak ages shifting over time. Smith et al. (2012) recommended varying age of full recruitment definitions by method, with peak age being the recommendation for weighted linear regression and peak age plus one being the recommendation for the Chapman-Robson estimator. Millar (2015) also found that Poisson GLMMs performed better with age of full recruitment equal to peak age plus one.

An apparent mismatch between selectivity assumptions in this analysis and the assumption that maturity is what controls availability and therefore is equal to selectivity of monitoring programs fishing fully selective gear was identified when peak ages for all data sets were determined to be less than age of full maturity. This increases uncertainty in this analysis and was explored in preliminary analysis by dividing observed age composition data by maturity-at-age (see Section 1.1.7). The mortality estimators were then applied to these adjusted age composition data and compared to estimates generated from the unadjusted observed data. This adjustment increases the abundance of partially mature ages and returns a higher total mortality estimate relative to estimates from the unadjusted observed data. Therefore, estimates from unadjusted observed data should be considered more liberal than a scenario where selectivity is equal to the maturity estimated with the mortality-based methodology applied in this assessment.

2.6.2.3 Other Considerations

It is important to keep in mind that mortality estimates only pertain to life stages fully selected in rivers (i.e., spawning adults) and contain no information on the mortality levels of juvenile fish, which could be unsustainable even if mortality of spawning adults is sustainable. Total mortality estimates were not split into fishing and natural mortality components due to uncertainty in other non-riverine fishing components of mortality (i.e., bycatch mortality, barrier mortality, water quality mortality) noted in past American shad and river herring assessments (ASMFC 2007b; ASMFC 2012). Estimates were also not developed for semelparous stocks as it is unclear if age composition data can be interpreted and treated the same as for iteroparous stocks. Semelparous cohorts of spawning fish with different ages of maturity from the same year class are subject to varying mortality since all mature fish in a given year return to the river, spawn, and die. If fisheries intercept returning fish before spawning occurs and/or mortality in marine environments is different, information on fishing mortality is lost, whereas in iteroparous stocks only one cohort exists after age of full selectivity and mortality information can be derived from repeated observations of abundance from this fully selected cohort over time. Final estimates for comparison against per-recruit reference points are provided as running three-year averages to smooth variability of annual estimates from a combination of factors explored through preliminary analysis (e.g., sampling error, recruitment variation).

2.6.3 Model Results

For this analysis, 18 different age composition data sets from 12 different systems collected age data in a manner suitable for the development of unbiased age composition estimates. As such, final *Z* estimates are available from the systems found in Table 32 and are available in some systems from as early as 1983 through 2017. System specific results are found in Section 3 and in Table 33.

2.6.3.1 Age at Full Recruitment and Estimation Method

Peak ages were well defined in most data sets with steep inclines prior to and steep declines following these ages. Peak ages varied by sex and system but were generally greater for females (Table 32).

Defining the age of full recruitment equal to peak age plus one reduced the number of data sets retained for analysis by over 50%, reducing the utility of this analysis. Additionally, the Poisson GLMMs with recommended age of full recruitment (peak age plus one) suffered from poor convergence across many data sets during this analysis, likely due to many data sets including only three data points, further constraining utility of this method. As such, the age of full recruitment equal to peak age was selected as the preferred age of full recruitment definition. To maintain consistency with Smith et al. (2012) recommendations, weighted linear regression was selected as the preferred method for final estimates. However, total mortality estimates tended to be sensitive to the age of full recruitment definition and method, so estimates from weighted linear regressions with age of full recruitment equal to peak age plus one (Figure 58-Figure 63) and the other candidate methods with age of full recruitment equal to peak age (Figure 64-Figure 69) are provided as sensitivity analyses. Estimates with age of full recruitment equal to peak age plus one were generally greater than estimates with age of full recruitment equal to peak age. No right truncation of data was found to result in the best performance in terms of bias (Smith et al. 2012), so no right truncation was applied to the data.

2.6.3.2 Otolith vs. Scale-Derived Ages

An ongoing evaluation during this assessment was of differences in ages assigned to fish based on age structure and implications of these differences on assessment results. Overlapping total mortality estimates by age structure were limited and variable (Figure 70), but do support the use of both age structures if ageing error analyses indicate reasonable levels of consistency in interpretation between age structures (see results for the Delaware and Potomac Systems in Section 3 for additional details). Given estimates can be sensitive to different interpretations between age structures, that the degree of past interpretation differences among systems is unknown, and the general understanding that otolith-derived ages are more robust (Section 1.1.4), age data are not aggregated across age structures for this analysis and otolith-based estimates are provided as preferred estimates. If otolith age data are not available for status determination, scale-based estimates are provided for final estimates as the best available information.

2.6.3.3 Cross-Sectional vs Longitudinal Analysis

Although the methods explored have been shown to be robust to variation in year class variability to varying degrees, early analysis of data sets showed clear influence of variation in year class strength while sampling effort was relatively constant through time. To explore the effect of this recruitment variability on total mortality estimates, Z was calculated for longitudinal (i.e., year class) cohorts and compared to synthetic cohorts by matching estimates of longitudinal cohorts to synthetic cohorts seven years after the longitudinal cohorts were spawned, as this is the approximate midpoint of the longitudinal cohorts age structure used in the analysis. Since estimates from longitudinal cohorts are not biased by varying year class strength and assumed to not be biased by time-varying sampling effort, any differences between estimates from the two cohort types are roughly interpreted as bias in synthetic cohort estimates due to year class variation. Estimates varied, but with no clear trend and were generally of similar magnitude (Figure 71-Figure 76).

2.7 Population Models

2.7.1 Delay-Difference Model

2.7.1.1 Background and Description

The delay-difference model is a variation of a biomass dynamic model that includes biological parameters, can be fitted directly to time series data, and accounts for changes in growth and recruitment over time (Hilborn et al. 1992). Biomass of age structured populations are predicted directly from previous years' biomass and parameters for survival, growth, and recruitment (Deriso 1980; Schnute 1985, 1987; Fournier and Doonan 1987). A primary benefit of this approach is that simulation of age structure is not required.

The delay-difference model from the DLMtool package (Carruthers and Hordyk 2019) in R was used to calculate total allowable catch (TAC), where TAC = U_{MSY} * Biomass in the terminal year. The model is conditioned on effort and estimates of catch, with effort calculated as the ratio of total catch and a relative abundance index over time. The model is observation error only and does not estimate recruitment deviations.

2.7.1.2 Model Configuration

Inputs into the model consisted of time series total annual catch and relative total abundance, estimates of life history parameters: length at 50% maturity, maximum age, natural mortality, von Bertalanffy growth parameters (K, L_∞, t_0), and weight-length relationship alpha and beta parameters. The model requires a complete time series of effort, limiting selection of abundance indices to those fishery-dependent and fishery-independent surveys that had an uninterrupted time series. Models were run for 100 simulations to obtain stable predictions of performance.

The SAS determined that use of regional life history parameter estimates was the most appropriate approach to account for limited observations of age classes in some systems. For each river, either the northern iteroparous, southern iteroparous, or semelparous parameters were applied to the model, with the only river-specific inputs consisting of time series of total catch and relative abundance index.

2.7.2 Habitat Assessment and Simulation Modeling

2.7.2.1 Introduction

Since the late 1800s, a suite of factors has caused precipitous American shad population declines range wide (Limburg and Waldman 2009; Hasselman and Limburg 2012). Most notably, the construction of dams has greatly reduced access to spawning and nursery grounds thereby limiting the scope for population growth (Rulifson 1994; Limburg et al. 2003). Even when fish passage opportunities are available, obstruction of migration at dams restricts access to spawning habitat (e.g., Grote et al. 2014). Although some fishways have been constructed at some of the numerous dams these fish encounter during migration, many, if not most, are largely or wholly ineffective (Haro and Castro-Santos 2012).

Dams are also known to cause acute mortality during both downstream and upstream migrations (O'Leary and Kynard 1986; Kynard and O'Leary 1993) and contribute to latent (Nieland et al. 2015) or delayed mortality (Budy et al. 2002; Schaller et al. 2014; Stich et al. 2015). Dams may also influence population dynamics through delay during both upstream and downstream migrations, resulting in elevated adult mortality due to exposure to predators and energetic costs (Castro-Santos and Letcher 2010). Together these influences impact not only the distribution of American shad, but also the life history and distribution (Stich et al., 2019)

To estimate the opportunity cost realized by this species as a result of dam construction, this assessment sought to estimate habitat historically exploited in Atlantic coastal rivers. This was accomplished by characterizing 21,113 dams and 485,618 river reaches and identifying potential spawning habitat based on criteria of i) river width and ii) distance from seawater intrusion and slope (to exclude natural barriers to migration). The areas of potential spawning habitat were aggregated to estimate historic habitat available prior to the construction of impoundments for each coastal river. Each river was then modeled by developing a life history-based population model using latitudinal appropriate life history parameters developed for regional metapopulations (e.g., clines in size-at-age, maturity rates, and iteroparity). In aggregate this approach will allow a direct comparison of the theoretical stock potential lost coastwide to the construction of dams. Results of this analysis are presented in Section 4.4.2.

2.7.2.2 Characterization of Habitat through the Native Range

American shad habitat was estimated based on available knowledge of habitat extent, area, and accessibility. These data were collected for the entire current and historic geographic extent of American shad, spanning eastern United States and Canada using a two-step approach. First, the United States National Hydrography Data set (USGS 2019) and Canadian National Hydrographic Network (Natural Resources Canada 2019) were used to determine the potential freshwater networks available for migration, spawning, and rearing. These data are organized as a series of flowline segments, representing interconnected stream and river reach segments (Figure 77). To simplify this analysis, it was assumed initially that American shad would not migrate to reach segments that have a mean channel width of less than 15 meters, in accordance with pre-existing habitat suitability models (Stier and Crance 1985; Harris and Hightower 2012). Secondly, an a priori assessment of historic habitat extent of American shad was validated with the help of local experts from each state or province in the study region. Historic extents are largely based on the presence of natural barriers (e.g. steep rapids, waterfalls) and/or environmental conditions (e.g. temperature, salinity, reach segment width) that are unsuitable for American shad spawning.

Empirically determined stream discharge-width relationships were used to calculate potential habitat area from the flowline data (e.g., Leopold and Maddock 1953). This approach allows for the estimation of horizontal surface area at any reach segment based on drainage area, geographic location, and nearby stream gage data. The enhanced unit runoff method (EROM, McKay et al. 2012) was used to estimate mean annual discharge, then estimate mean reach segment width using the power law equation:

$$w=kQb,$$

where Q is discharge, w is channel width, k is a derived width coefficient, and b is a derived exponent. Values for k and b vary by region but are typically close to 10 and 0.5, respectively (Bray 1982; Sweet and Geratz 2003; Dudley 2004; Mohamoud and Parmar 2006; Bent and Waite 2013). Horizontal surface area is then calculated as

$$A=0.8*wl,$$

where l is segment reach length. It was assumed that fluctuations in discharge cause 20% of this area to be periodically dry along the shorelines and therefore inadequate for migration and spawning (sensu NOAA 2009). Lake and pond areas in the assessment were excluded because American shad avoid lacustrine habitat (Stier and Crance 1985).

Cumulative habitat areas segmented by the presence of dams were calculated by combining the habitat flowline data with a congruent dam geodatabase compiled from multiple sources (Martin and Apse 2011; Martin 2013, 2019; Natural Resources Canada 2019). Habitat area was summed for all reach segments upstream of each dam point, in addition to each coastal outlet point of streams and rivers. These point data were also vetted by local experts. Sums are taken iteratively by starting at the reach segment where the point is located, then adding upstream neighbor reaches until upstream dam points or headwater points are found. This search is recursive to avoid summing overestimations due to downstream flow bifurcations. Finally, individual streams and rivers were tagged with common names used by the ASMFC. Data are shown for the three regional metapopulations (Figure 78-Figure 80).

In the end this analysis produced a range wide assessment of putative American shad habitat as influenced by each impoundment found within the identified area. Current unobstructed habitat as a proportion of total historical habitat extent is provided at the system-specific level in Section 3.

2.7.2.3 Population Simulation

In order to assess the theoretical impact of impoundments on American shad range wide, the SAS simulated the population potential for each identified system. This approach allowed the comparisons of three broad scale scenarios i) historical or “intact” rivers, ii) worst case scenario with current dams and “no passage”, and iii) dams with imposed realistic up and downstream passage to best reflect the “status quo” (Figure 81).

This model effort is based on Stich et al. (2019) which applied a stochastic life-history based simulation model to assess the theoretical effects of dam passage and migratory delay on abundance and spatial distribution of spawning adults over time. This general model structure was simplified to facilitate the incorporation of geographically appropriate life history parameters for regional metapopulations. Because these fish are iteroparous in the northern extent of their range, downstream migration of both juveniles and adults is important for population dynamics.

Each river was identified as being in the northern iteroparous, southern iteroparous, or semelparous metapopulation and assigned life history parameters appropriate to these metapopulations. An age-structured starting population was initiated and region-specific *M* and *Tmax* were assigned. Habitat area from the work above was used. For each of the three scenarios, the appropriate dam passage probabilities were assigned. For the intact scenario, the dams exerted no influence on passage, while for the no passage scenario, dams had 0% passage. For the status quo, passage was assigned based on available data where possible (Table 34). For upstream passage a high passage rate of 50% was assigned.

For downstream adult passage the SAS similarly applied a conservatively high passage rate of 80% based on limited available data (Table 35).

For downstream passage of juveniles, the SAS similarly selected a high survival rate (90%) to provide a conservative assessment of dam impact (Table 36).

Note that for the status quo scenario, these three passage rates are fixed across all dams. The SAS acknowledges that dam passage is variable among dams, years, and even within seasons. Therefore, relatively optimist views of the status quo were assigned. Note that upstream passage values restricted the number of adults reaching spawning areas while downstream passage rates were applied as mortality risk for those fish passing a given dam.

Thus the available habitat for returning adults could be calculated based on upstream passage probabilities, allowing the development of a river- and scenario-specific life history-based population model. The spawning pool was generated from the population using regional maturity schedules, number of females (random draw from a defined sex ratio of 50:50) and an assigned fecundity from mass-fecundity relationships based on Olney and McBride (2003). Based on the habitat for each river, or each river unit (if segmented by a dam or dams), the SAS applied carrying capacity using a Beverton-Holt recruitment curve with density dependence using parameters tuned to impose *K* of about 100 adult fish/ acre. This was then applied to generate hatch-to-outmigrant survival.

Adults incurred post-spawn mortality appropriate to the projected degree of iteroparity as derived from Leggett and Carscadden (1978) and applied by Bailey and Zydlewski (2013). Both juvenile and adults then suffered dam passage influence based on proportional distribution as appropriate to each scenario.

Individuals at sea were subject to regionally specific *M* and were assigned a length-at-age from regional von Bertalanffy parameters with associated uncertainties. Mass was assigned from regional length-weight relationships.

2.7.3 Other Population Models

Several systems had data sets to support various types of population models including tag-recapture models, biomass dynamics models (other than delay-difference models), and statistical catch-at-age models. These systems include the Upper Chesapeake Bay, Potomac, Albemarle Sound, and Altamaha. The configurations of these models are highly unique and details are provided in the respective system-specific *Methods* sections.

2.8 Stock Status Determination Framework

The SAS considered the status of stocks from two perspectives: abundance and mortality. There were two categories of analyses for the SAS to make stock status determination: total mortality estimators compared to per-recruit reference points and population models compared to per-recruit reference points or TAC reference points.

Abundance trend data were of varying time series and none are believed to contain information on the historical productivity potential to compare to current conditions. Therefore, abundance trends were assessed relative to reference points to investigate abundance changes since the beginning of the respective monitoring program (i.e., start year abundance) or the implementation of a significant coastwide management change (i.e., 2005 abundance when the ocean intercept fishery was closed), not to make conclusions on abundance status. For example, increasing trends in abundance do not necessarily represent favorable abundance levels in the terminal year of this assessment. The SAS does not recommend using fishery landings alone (i.e., without effort) to make conclusions about abundance trends or status, but when long time series of landings were available in conjunction with recent abundance trends these data were used to make qualitative abundance status determinations (see Sections 3.5.9 and 4.5).

Total mortality estimators and per-recruit reference points have been studied extensively in published literature and robust guidance is available for using these analyses to determine mortality status. Time series of mortality estimates varied and some did not include recent years. Therefore, the SAS made an objective decision that mortality status could only be made for systems with estimates in the last three years of the assessment time series (i.e., terminal three-year average estimate). If estimates did not meet this criterion, the most recent three-year average estimate is provided, but mortality status is unknown. Mortality status was defined as sustainable if mortality was less than or equal to the reference point or unsustainable if mortality was greater than the reference point. The mortality status from total mortality estimators only pertains to mortality of spawning adult fish and is independent from abundance status. A sustainable mortality designation only indicates that recent mortality of spawning adults results in SBPR that would achieve desired abundance levels if maintained for a long period of time, any underlying stock-recruit relationship is not degraded, and unknown pre-recruit mortality is maintained at sustainable levels. If the stock is maintained at a sustainable mortality level and meets the other conditions noted, it will asymptote to desired abundance, with the length of time necessary to reach desired abundance dependent on the current stock abundance levels. That is, a stock with more depleted abundance at the time sustainable mortality levels start will take longer to reach desired abundance levels. If conditions occur that degrade the underlying stock-recruit relationship (e.g., a large scale change in suitable nursery habitat) or that result in unsustainable mortality of pre-recruits (i.e., increased juvenile mortality in ocean bycatch fisheries), stock abundance may never reach desired abundance levels even when spawning adults are maintained at sustainable mortality levels. Trends in mean length can indicate trends in mortality, trends in recruitment, or a combination of both, so system-specific results of mean length trend analysis and YOY index trend analysis, if available, are summarized in *Stock Status and Conclusions* subsections of Section 3 for additional context on potential mortality changes.

Status determination for systems with population models applied are dependent on objectives of two types of models: delay-difference models used to estimate mortality status and statistical catch-at-age models used to estimate both abundance and mortality status relative to internally estimated per-recruit reference points. Delay-difference models provide TAC estimates, but the SAS was not comfortable setting catch recommendations using the median value of TAC from 100 model simulations. Instead the median TAC values are compared to the average catch of the final three years to assess the mortality status and the 25th and 75th percentiles are compared to the average catch of the final three years to characterize uncertainty of stock status.

Additionally, a unique tag-recapture population model was used for the Altamaha system (Section 3.22.6.2), but to estimate trends in exploitation and not stock status.

3 SYSTEM STOCKS

3.1 Merrymeeting Bay

3.1.1 Habitat Description

The Merrymeeting Bay Complex is a unique tidal fresh water ecosystem. It is one of only a few enclosed tidal freshwater deltas in the world. Two of Maines's three largest rivers, the Kennebec with a drainage area of 14,775 km^2, and the Androscoggin with a drainage area of 8,5000 km2 , and four smaller rivers, the Eastern, Cathance, Abadagasett and Muddy which drain 520 km2 in total, converge to create the Merrymeeting Bay Complex. Approximately 40-percent of Maine's freshwater river flow enters the bay before flowing down the remaining 17-miles of the Kennebec River to the Gulf of Maine. The Merrymeeting Bay Complex is approximately 39 km2 and over 101 km2 including the tidal area of the Kennebec River before it enters the Gulf of Maine.

Physical characteristics and habitat types vary widely throughout the bay. Sediments in sections of the larger freshwater tidal rivers are comprised of ledge, cobble and sand. The smaller rivers have considerably more slit and clay compared to the larger rivers. Submerged aquatic vegetation is present at locations throughout the bay and provides habitat for all 12 species of anadromous fish found in Maine. The aquatic plants communities are unique because of the tidal amplitude experienced throughout the area and need for both aquatic plants and some animals to spend considerable amounts of time out of water. The tidal amplitude within the bay varies by location but ranges from 1.6 m to 2.7 m throughout the year.

Each of the six rivers that empty into the estuary; the Kennebec, Androscoggin, Cathance, Abadagasett, Muddy and Eastern, were thought to have had a spawning population of American shad. Using historical landings data recorded by county and historical accounts of fishing activities, Taylor (1951) attempted to assess why shad numbers were stable in the Eastern River and declining in others. Taylor concluded that the free-flowing Eastern River had maintained a healthy spawning population of shad for two reasons, the absence of dams and lack of industrial pollution.

The construction of dams confined American shad to the tidal portions of the Androscoggin and Kennebec rivers in 1807 and 1837 respectively, effectively reducing the amount of available spawning habitat. The remaining four river systems were never dammed and continued to provide access to some spawning habitat. For a short time, American shad continued to reproduce in the seven-mile stretch of river below Brunswick, supporting significant commercial fisheries up until the late 1920's. By the early 1930s, severe water pollution from upstream industries and municipalities had virtually eliminated the remaining American shad populations and those of many other fish species.

The removal of Edwards Dam in 1999 provided 18-miles of spawning habitat from Augusta to Waterville on the Kennebec River. The construction of a fishway at the Brunswick dam, located at head of tide, was designed to pass American shad above Brunswick on the Androscoggin River. However, the fishway constructed in 1982 is largely ineffective and does not pass many shad upstream compared to those observed that remain below the dam throughout the season.

Results from sampling efforts indicated that American shad are still utilizing spawning and nursery habitat within the Merrymeeting Bay Complex. Through the sampling period 1979-2018 the overall highest average catch per unit effort (CPUE) for juvenile American shad was in the Abadagasett River (12.39 shad per haul), followed by the upper Kennebec River (8.78). Merrymeeting Bay (5.95), the Cathance (3.77), Eastern (3.28), and the lower Kennebec rivers (3.47) all have lower but consistent CPUE values. The Androscoggin River consistently has low catches of shad or years where sampling efforts capture no shad.

There was a significant increase in the numbers of juvenile shad captured during the survey period 1999 to 2014. This corresponds with the introduction of hatchery reared larvae and restoration efforts which supported natural reproduction. Since 2014 the numbers of shad captured in the survey have dropped but remain higher than those observed prior to 1999. The strength of these data in identifying successful spawning areas is limited because sampling is performed after the annual shad spawning window and juvenile shad may have dispersed from their natal location by passive larval drift. These data may provide some insight into habitat use by juvenile shad.

3.1.1.1 Barriers

There are main stem barriers on the two largest rivers that create sections of the Merrymeeting Bay Complex. The Kennebec River is the largest river flowing into and creating sections of Merrymeeting Bay. The Kennebec and Androscoggin River were dammed at the head of tide in 1837 and 1807, respectively. This prevented upstream passage of American shad and limited spawning and rearing habitats to the tidal freshwater sections of river below these barriers. The remaining tidal rivers were never dammed and remain barrier free and still provide historic spawning and rearing habitat.

American shad restoration in Merrymeeting Bay and lower sections of the Kennebec River began with the 1999 removal of Edwards dam at the head-of-tide in Augusta. Prior to this date Edwards dam provided poor upstream passage and precipitated the drastic decline of American shad documented in the river below the dam. A remnant American shad population survived downstream of the dam, but the size of this population is unknown.

After the construction of Edwards dam, poor or nonexistent upstream and downstream passage on the Kennebec River and its tributaries precluded American shad from the majority of its native habitat within the watershed. The removal of Edwards dam opened up the river to the next dam located in Waterville, located at rkm 101. There is a fish lift located at the dam, but there is no upstream passage other than a trap and truck operation that transports American shad upstream. Once shad were trucked upstream, turbine mortality contributed to post spawn and juvenile mortality of American shad at Lockwood. Mortality of adult and juvenile American shad occurs at all hydropower projects which post spawn and juvenile shad must pass through as they migrate downstream. The efficiency of downstream passage for these life stages is unknown for all locations.

In 1980 the USFWS developed conceptual drawings for a vertical slot fishway for the Brunswick Hydropower Project, (FERC 4784) which is located at the head-of-tide on the Androscoggin River. The fishway was designed to pass 85,000 American shad and 1,000,000 alewives annually. The upstream passage facility was one of the first vertical slot fishways designed to pass American shad in Maine. The fishway design originated from a scaled down version of a fishway located on the Columbia River. Redevelopment of the Brunswick Hydropower Project and construction of the fishway was completed in 1982. The completed fishway is 570 feet long and consists of 42 individual pools with a one-foot drop between each pool. Downstream passage consists of an 18-inch pipe located between two turbine intakes. When the FERC issued a license for the Brunswick Project in 1979, it did not require efficiency studies for the upstream and downstream passage facilities.

Two additional hydropower dams exist on the lower main stem of the Androscoggin River. There is suitable American shad spawning and juvenile habitat within these river reaches, but few American shad pass through the Brunswick fishway and even fewer are observed passing the fish passage facilities above Brunswick.

Pejepscot dam (FERC 4784) is located 7.3 rkm above the Brunswick dam. A fish lift was constructed at the dam and was operational in 1987. Few American shad are observed using this fish lift, mainly because so few shad are passed above Brunswick during most years. In 2019, Brookfield White Pine Hydro LLC initiated a radio telemetry project designed to assess shad passage at the Pejepscot dam. The results of the study are not available at this time.

Worumbo dam (FERC 3428) is located 12.7 rkm above the Brunswick dam. A fish lift was constructed in 1988 and is capable of passing American shad upstream, though few shad are observed passing through this facility.

3.1.1.2 Water Quality

After dams confined American shad to the tidal portion of the rivers within Merrymeeting Bay, severe water pollution virtually eliminated the remaining American shad population. For a short time, the American shad that continued to reproduce in the 9.6 rkm stretch of river below Brunswick and the 26 rkm of the Kennebec flowing into Merrymeeting Bay supported significant commercial fisheries up until the late 1920s. By the early 1930s, severe water pollution from upstream industries and municipalities had caused declines in American shad and many other fish species. Water pollution abatement efforts that began in the early 1970s resulted in the dramatic improvement of water quality in the Androscoggin River.

The enactment of the Clean Water Act helped to recover and maintain water quality on some of the nation’s worst polluted rivers. The river once supported a large number of industrial activities including pulp and paper making which was a major contributor to poor water quality. Many of the pulp and paper making facilities have closed and the ones that currently exist operate under stricter water quality standards. The river now supports native fish species and recreational activities including fishing and swimming. The Androscoggin now maintains a Class B rating along most the river corridor and has improved significantly over the past 47 years. However, there are fish consumption advisories that suggest limiting the amount of fish consumed from these rivers.

3.1.1.3 Invasive Species

White catfish (*Ameiurus catus*), carp (*Cyprinus carpio*), and Northern pike (*Esox lucius*) populations are increasing in the rivers creating Merrymeeting Bay where American shad spawn and where juvenile shad congregate. The effect of these invasive species on shad populations is not known, however white catfish are known to eat fish eggs and juveniles of native species. Carp continue to impact the growth of submerged aquatic vegetation and increase turbidity throughout the area. These impacts have not been quantified but are believed to negatively impact juvenile American shad habitat in the riverine sections of Merrymeeting Bay and the Bay itself.

3.1.2 Fishery and Management History

The six rivers which create sections of Merrymeeting Bay each have a unique fishing history. Although fisheries management was similar among all the rivers there were differences in how these fisheries operated. Weirs and drift gill nets were the predominant types of commercial gear used to harvest American shad. Stationary weirs in the Bay had the greatest chance of catching large numbers of American shad. These weirs were large and needed constant maintenance to keep them fishing. Drift gill nets provided an opportunity for fishermen to move between systems and concentrate on aggregations of American shad while they spawned.

All the historical commercial fisheries information comes from archived records and personal accounts of these activities when they occurred or recalled in later years. The Department closed the commercial fishery in 1998 and established a 2-fish recreational limit the same year. Commercial fishing ended in the 1940s when there were simply no enough American shad available to make commercial fishing worth the effort. Today, recreational angling still occurs at the head of tide on the Androscoggin River and Cobbossee stream that enters the lower Kennebec River below the head of tide. These recreational fisheries are the direct result of restoration effort that started in in 1985 to recover American shad in Maine.

Kennebec River, Richmond

Although the Edwards dam had a fishway, its effectiveness was poor. The decline, and eventual disappearance, of shad from the lower Kennebec appears to have been a gradual process. The total catch figures, both for the Merrymeeting Bay Complex and the entire Kennebec River, did not reflect the decline that was occurring. However, Atkins cites the catch of a single weir in this district that apparently did show a decline in catch associated with the closing of the Edwards dam: “Mr. Brown’s weir produced in the ten years ending in 1835 an average of 5,961 shad yearly. In the twelve years from 1837 to 1848 the average catch was 3,120 per year, a little more than half the former yield” (Atkins 1889).

In 1860, fishermen in Augusta noted declining shad numbers. Seines fished in the area in 1822 caught as many as 700 shad per day. About 1857, one seine harvested 3,000 shad and 20,000 alewives during the season. In 1867, the shad fishery was a total failure (Atkins 1868).

The most productive shad weirs were those of the Merrymeeting Bay and its vicinity. Of the 140,000 shad taken in the Kennebec in 1880, 108,000 were taken in the Merrymeeting Bay district, 5,800 above Richmond, 16,744 between the bay and Bath, and only 10,00 below Bath, including the Sasanoa or eastward arm, between Woolwich and Arrowsic. In the bay district, 44 weirs averaged 2,048; below Bath 29 weirs averaged 345 shad. All included in the above statement are breeding shad, called by the fishermen “river shad” or “spawn shad.” (Atkins 1889)

During 1851 and 1852, seine weirs began to replace the less effective shallow water weirs. These seine weirs could be fished at locations where traditional weirs were impractical.

Recreational angling occurs for American shad at Cobbossee Stream which enters the tidal section of the Kennebec River. Angling pressure at this location is covered by the MRIP survey and captures American shad effort at this location.

Androscoggin River, Brunswick

Harvest records indicate that commercial fishermen regularly fished the first 8 km of the Androscoggin River, from Brunswick down to Merrymeeting Bay starting in 1887 continuing until the late 1950s. The falls at Lewiston were a natural barrier to upstream migration and shad were never documented above the falls. There is access to fish for American shad and the head of tide on the Androscoggin River. There are anglers that do fish for American shad but the success rate for the fishery at this location is unknown.

Cathance River, Bowdoinham
There was a commercial fishery for shad in the upper and middle sections of the river, approximately 2.0 km above Bowdoinham to the bay. The last good catch of shad occurred in the spring of 1918, after that, the fishery collapsed. In the 1980s one fisherman put a drift gill net into the river to show how the fishery historically harvested shad (Squiers, pers. comm.). To his surprise, he caught six shad the first night he fished. He fished the river for four more years. His catch never exceeded 13 fish in one night. Once the nets fell into disrepair, the fisherman did not feel it was worth the cost to replace the nets.

Abagadasett River, Bowdoinham
This is a small tidal river approximately 25.7 km long. Although there is no direct historical reference to the river, it is believed to have contained shad. Maine's juvenile index survey conducted in the Abagadasett the past 20 years indicates the presence of juvenile American shad at this location.

Eastern River, Dresden
The Eastern River is a 22.5 km long tidal river that enters the Kennebec River on the eastern side of Swans Island. Historically the river was one of the most productive rivers in the Merrymeeting Bay area. Historical accounts provide evidence of how important the Eastern River was, and may still be, to reestablishing Maine's American shad runs. "In the Eastern River thirty years ago, there were eight or nine weirs, each of which took 6,000 to 8,000 shad per year and about the same amount was taken by seines and drift nets, indicating a catch of 100,000 shad annually" (Stevenson 1898).

Muddy River, Dresden
The 7.5 km Muddy River is the least studied regarding the presences of American shad. There are no direct references to the Muddy River being a significant site for the commercial harvest of American shad.

3.1.3 Anthropogenic Sources of Mortality and Productivity

Historically, dams on the Androscoggin River, including the Edwards dam removed in 1999, were documented to delay and prevent upstream and downstream passage of American shad that would have inhabited Merrymeeting Bay. The Edwards Dam is no longer an issue but limited American shad recruitment from 1837 to 1999. Significant efforts have been made to assess upstream passage at the dam in Brunswick, located at the head of tide. Few efforts to assess upstream passage have occurred at the dams above Brunswick due to low abundance of shad within these river reaches.

Analysis of survey data indicates that the Brunswick dam is a major impediment to passing prespaa\wn American shad upstream. The dam is the single largest obstacle that limits recovery of this river specific shad population. Tagging and video observations document shad making serval attempts to ascend the fishway without ever reaching the impoundment above Brunswick.

Downstream passage through the Brunswick dam is poorly designed and is assumed to contribute to increased juvenile mortality at this site. An 18-inch diameter pipe located between turbines 1 and 2 is the extent of dedicated downstream passage for this location. Adult and juvenile shad must pass in front of the turbine intakes to reach the downstream passage pipe. Juvenile shad do pass downstream through the upstream fishway and can pass over the dam during periods when river flows exceed station capacity. Juvenile shad do pass through the turbines when the hydropower station is in operation. Downstream survival of American shad passing through the three turbines is unknown, but fisheries staff do observe significant mortality of juvenile alewife during some years, especially when river flows are below station capacity.

Restoration activities on the Androscoggin River involved developing fish passage facilities, stocking shad larvae, and transferring pre-spawn adults from other river systems. Maine released larvae from the Waldoboro Shad Hatchery into the Androscoggin from 1999 through 2008 (Table 38). Larval shad were marked with OTC to differentiate and assess the hatchery contribution to the restoration effort.

During the period when hatchery reared American shad larvae were released into the river the Waldoboro Shad Hatchery used OTC to mark larvae otoliths to differentiate hatchery reared fish from wild reproduction. Starting in 2000, field staff began collecting adult shad that died in fish passage facilities for OTC mark analysis. Fisheries staff also collected dead adult fish from Androscoggin River to look for OTC marks from shad returning to the river (Brown and Ryder 2001). Adult shad were not intentionally killed for this study due to concerns for population size and restoration efforts. Juvenile shad for this study were collected from fish passage operations on the Androscoggin River and from the biweekly juvenile seine survey in the Merrymeeting Bay Complex. The Merrymeeting Bay Seine Survey supplied the majority of the study fish, which were systematically sampled throughout the July – September sample period. Lab personnel removed the otoliths, cleaned them in distilled water and mounted them in a thermoplastic resin. The otoliths were ground using 9, 3, and 1 micro lapping film. Otoliths were ground to the mid-sagittal plane on one side, flipped over, and ground to mid-sagittal plane on the opposite side. A drop of Type FF (low fluorescing) immersion oil was placed on each otolith and covered with a glass cover slip. A compound microscope was equipped with fluorescent light and a FITC filter set to illuminate the OTC ring if it was present. Any OTC marked otoliths exhibited a glowing ring representing the day that the larvae were marked at the hatchery. The proportion of marked fish indicated the percent contribution of hatchery fish within the sample. Hatchery contributions, based on assessment of juvenile American shad sampled in the Merrymeeting Bay Seine Survey, were as high as 10-percent.

Results from annual analyses of stocked versus wild juveniles indicated that 5.3 to 62.5 percent of the juveniles emigrating from the Androscoggin River system were hatchery reared (Table 39). Samples collected in Merrymeeting Bay range from 2 to 10 percent. The State of Maine released a statewide average of approximately four million larvae each year. The results from this study indicated that a substantial population of wild adult shad is present in the rivers flowing into the Merrymeeting Bay Complex, but the originations of both marked and unmarked shad are unknown.

On the Kennebec River a larval stocking effort commenced in 1992 to supplement the existing remnant stock that was able to reproduce below the Edwards dam. Larval stocking occurred during the period 1992-2008 using adult broodstock from several in-state and out of state sources to produce the hatchery reared larvae. Natural reproduction in the newly restored river section from the Edwards dam to the existing Lockwood dam now provides the basis for population growth. There was no effort to recover marked Juvenile shad in the Merrymeeting JAI survey. This is because it would be impossible to differentiate marked shad from the Androscoggin releases vs the Kennebec River releases.

Throughout the Merrymeeting Bay Complex water quality has played an important role in fish abundance. The two major industrial rivers that create sections of Merrymeeting Bay each have a legacy of industrial pollution contributed to by pulp and paper making, tanneries, electronics manufacturing and other industries. The Clean Water Act of 1972 helped reduce the effects from these industries on water quality, so the direct impacts are no longer observed (fish kills, low dissolved oxygen). However, fish consumption advisories are still in place for Merrymeeting Bay and the lower Androscoggin and Kennebec rivers. The long-term effects from the contaminants which warrant the fish consumption advisories on American shad are unknown.

3.1.4 Fishery-Dependent Data Sources

Fishery-dependent data is limited to historical catches in the Androscoggin River below the existing Brunswick dam. Harvest records indicate that commercial fishermen regularly fished the first 8 km of the Androscoggin River, from Brunswick down to Merrymeeting Bay starting in 1887 and continuing until the late 1950s. By the 1950s pollution and the lack of fish passage reduced shad populations to the point that commercial fishing was no longer economically viable (Table 40).

3.1.5 Fishery-Independent Data Sources

3.1.5.1 Adult Fishery-Independent Data Sources

3.1.5.1.1 Brunswick Fishway Count

Department fisheries staff have monitored the Brunswick fishway since it opened in 1982. Run counts and species information are collected each year to track run trends, collect biological samples and facilitate the states anadromous fish trap and tuck operations.

Prior to the restoration effort directed at reestablishing American shad above Brunswick there were no American shad that passed upstream through the fishway. As the restoration project progressed and shad numbers increased in the river below Brunswick a small proportion of these fish located and successfully used the upstream passage. The numbers of shad counted passing at the fishway appear to be heavily influenced by flows, turbine operation, water temperature and attraction flow from the fishway more than population size estimated below the dam. Trap count numbers, though available for the period 1982-2019, do not reflect the population size returning to the Androscoggin River and should not be used to quantify or estimate population size for this assessment (Table 41).

Limited amounts biological data have been collected during the period 1982-2019. Most data collected is associated with specific studies investigating upstream passage and collecting hatchery broodstock at the Brunswick fishway. There are limited age, sex and length data available for some years, but systematic sampling of shad caught at the trap at Brunswick does not occur. These data are not collected to reduce handling stress and/or mortality of shad native to the Androscoggin River (Table 42).

Environmental data including river flow, water temperature, turbine operation, run timing and daily observations of shad in the fishway are available and may provide some benefit for a broader perspective on shad behavior and run timing.

3.1.5.2 Young-of-Year Fishery-Independent Data Sources

3.1.5.2.1 Merrymeeting Bay Seine Survey

ME DMR initiated sampling of age-0 American shad in 1979 at 14 sites in the Merrymeeting Bay Complex. There are four sites on the lower tidal Kennebec River, three on the lower Androscoggin River, four on Merrymeeting Bay, and one each on the Eastern, Cathance, and Abagadasett rivers. Eight sites were added to the Kennebec River above the former Edwards dam in 2000. Site 8A was abandoned because a recent bridge construction project altered the river at that sampling site.

Field crews sample sites once every two weeks between July 1 and October 1 each year. Collections are made with a beach seine within three hours of low water. From 1979 through 1982, the net was 9 m long, 1.8 m deep, and constructed with 3.2 mm stretched nylon mesh. Starting in 1983, the seine was constructed of 6.4 mm stretch nylon mesh and measured 17 m long, and 1.8 m deep with a 1.8 m x 1.8 m bag at its center. Although a bag was added, and the method of seining was modified, the area sampled remained the same.

During sampling, field staff holds one end of the seine stationary at the land-water interface and the boat operator tows the other end perpendicular to shore. When the net is fully extended, the distal end is towed in an arc upriver and pulled ashore. The net samples an area of approximately 220 square meters. Field personnel sort and process all samples at the sample location. Field staff count and measure all alosines. Fifty individuals of each species, other than alosines, are measured. Dividing the number of individuals caught by the number of seine hauls gives the catch-per-unit-effort (CPUE) index. The State does not collect juvenile index data from other river systems where shad spawning exists.

ME DMR staff believes that age-0 shad move freely among sites in the lower Kennebec, Androscoggin, Eastern, Cathance, and Abagadasett rivers, and Merrymeeting Bay. For this reason, data from these sites were combined and single arithmetic and geometric mean calculated each yea. Separate means were calculated for the sites above the site of the former Edwards dam on the upper Kennebec River.

The annual geometric means for collections of age-0 American shad in the Merrymeeting Bay Complex were relatively high in the 1980s, low during the 1990s and increased until 2010 (Table 43, Figure 83). Since 2010 the geometric mean has decreased within Merrymeeting Bay except for the years 2013, 2014 and 2017. The geometric means of the catch per haul at the upper Kennebec sites were high for the period 2004 through 2008. For the period 2009 to 2017 the JAI index decreased significantly. Since 2012 the number of sampling trips had also declined to fewer than thirty-two seine hauls per season, partly due to low water levels and the ability of sample crews to access sample locations on the river.

To assess the effects of dam removal, larval stocking, and assumed increase in population size based on trap counts, comparisons were made to better understand these relationships. The relationship between the relative abundance of age zero American shad lagged by five and six years was calculated for the period 1984 to 2018. The numbers of larvae stocked were also compered to changes in the Merrymeeting Bay JAI Index for the period 1992 through 2008 as well as the contribution of larval stocking to the number of the zero aged American shad captured during the JAI survey. The number of OTC marked hatchery larvae stocked in the Kennebec River was compared to the percent of OTC marked juveniles recovered during the JAI survey. Results indicated that there was a positive relationship between the number of larvae stocked and the number of juveniles captured during the survey.

3.1.6 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Please refer to section 2 for a description of the methods.

3.1.7 Results

3.1.7.1 Abundance Trends

3.1.7.1.1 Power Analysis

The only abundance index for American shad in this system containing estimates of PSE was the Merrymeeting Bay Seine Survey. This survey exhibited a moderate median PSE (0.189). Given this median PSE the power analysis suggests the survey would be able to detect a 50% decrease in abundance (power > 0.80) in 10 years, though it would not be able to detect a 50% increase over the same period (Table 38). Currently, there is no SFMP for this system so this survey is not used for sustainability targets and monitoring.

3.1.7.1.2 Mann-Kendall Analysis

Data was provided for the Merrymeeting Bay Seine Survey for the period between 1979 and 2017. A plot of the index showed lower levels through 2001, followed by an increase through 2007 and gradual decline afterwards, but remaining well above the early part of the time series

(Figure 83). Mann-Kendall trend analysis found a significant increasing trend for the full time series, but failed to detect a trend for the period from 2005 forward (Table 21).

3.1.7.2 Habitat Assessment Results

Current unobstructed American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Merrymeeting Bay system, habitat estimates were based on combined information from the Androscoggin, Kennebec, and Cathance Rivers. Current unobstructed habitat area for the Merrymeeting Bay system represents 50.02% of the historical habitat extent (21.37 of 42.71 square kilometers).

3.1.8 Stock Status and Conclusions

Mortality

Juvenile and adult mortality status is unknown due to lack of data to make this determination.

There were no mean length data available for trend analysis.

Abundance

Abundance status is unknown. There have been no trends in YOY abundance since 2005. There were no adult abundance data available.

3.1.9 Research Recommendations

There were no river specific recommendations for the Androscoggin River in the 2007 assessment other than increased biological sampling at the Brunswick fishway. The annual goal of collecting a 300 fish sample was not achieved due to the low numbers of shad that are captured in the trap. The trap returns are still considered to be too low to overcome the risks of collecting these data.

Progress has been made on statewide research recommendations to develop species-specific estimates of upstream passage and to improve upstream and downstream passage at barriers on the Androscoggin River. The federal fisheries agencies have required an upstream fish passage efficiency study at the Pejepscot dam, above Brunswick, as part of the FERC relicensing process. Fish passage construction, as part of the FERC relicensing process at the Lower Barker Hydropower Project, is underway and is expected to result in construction of a fishway at Lower Barker, the first dam on the Little Androscoggin River, a major tributary to the lower Androscoggin River.

3.2 Merrimack

3.2.1 Habitat Description

3.2.1.1 System Description

The Merrimack River flows for 204 km from tributaries in New Hampshire to the Atlantic Ocean. The lower 78 km of the river are in Massachusetts and the first dam is the Essex Dam, located at 42º 41’ 57.942” N and 71º 09’ 57.086” W at 48 rkm in Lawrence, Massachusetts. The drainage area of the Merrimack River is 12,970 km2. A USGS streamflow gauge station has been maintained since 1923 in Lowell at drainage area 12,005 km2 (#01100000) at approximately 66 rkm. Mean monthly discharge for the time series at this station during the spring are: 19,400 cfs – April; 11,700 cfs – May; 6,700 cfs – June; and 3,740 cfs – July (http://waterdata.usgs.gov/ma/nwis/).

Historically, the shad spawned in the Merrimack River as far in the watershed as Lake Winnipesaukee in central NH and its tributaries. Prior to dam construction, the shad run in the Merrimack River supported important fisheries that landed several hundred thousand shad annually (Stolte 1981). By the late 19th century, Goode (1884) considered the Merrimack River shad run to be insignificant due to passage barriers. Anadromous fish are managed by the Merrimack River Anadromous Fish Restoration Program that is comprised of USFWS, NOAA Fisheries, US Forest Service, MA DMF, MassWildlife, and NH Dept. of Fish and Game representatives. Fishways are present on the first three dams in the Merrimack River. The lowermost dam, the Essex Dam, was first built in 1848 and presently has a spillway width of 920 ft and height of 31 ft. Several fish passage facilities have been operated at the dam since construction. Since 1983 passage has been provided by a fish lift. The fish lift is operated by the dam owner, Consolidated Hydro, Incorporated Energy (FERC Project No. 2800).

The next dam upstream is the Pawtucket Dam in Lowell MA at 70 rkm. The Pawtucket Dam was built in 1830, enlarged in 1876, and presently has a spillway width of 1086 ft and height of 15 feet. A vertical-slot fishway and fish lift became operational in 1986 at the Pawtucket Dam. The fishways are operated by the Lowell Hydroelectric Project (FERC Project No. 2790). The third dam upstream is the Amoskeag Dam in Manchester, NH, at 119 rkm, that has a pool and weir fishway where shad counts are monitored by the New Hampshire Department of Fish and Game. The next two dams in NH (Hooksett and Garvins) presently have no fish passage facilities.

3.2.1.2 Shad Spawning/Nursery Habitat

There is a large amount of existing and potential shad nursery habitat in the Merrimack River. Currently, upstream passage in the Merrimack River is blocked at the Hooksett Dam at 132 rkm. The Merrimack River Shad Restoration Plan (MRTC 2010) estimated that there was approximately 5,687 acres of potential main stem nursery habitat downstream of the Hooksett Dam. The plan also identified 700 acres of potential nursery habitat available in tributaries to the Merrimack River downstream of the Hooksett Dam. Restoring passage at Hooksett and Garvins would provide another 3,802 acres of habitat currently unavailable to spawning shad.

The Technical Committee for the Anadromous Fishery Management of the Merrimack River first introduced a strategic plan for restoration in the Merrimack River that contained an interim objective of annually passing 35,000 shad at the Essex Dam fish lift (USFWS 1997). The 1997 plan recognized that variable river discharge can alter both fish lift operations and attraction flows to the fish lift entrance which can influence the passage efficiency of shad present below the dam annually. The shad restoration plan for the Merrimack River was updated in 2010 (MRTC 2010) and contains shad restoration targets based on habitat units.

3.2.1.3 Essex Dam Lift Operations

The Essex Dam fish lift begins operating each year between April 15th and May 1st depending on flow conditions. The lift is typically operated from 0800 to 1600 with lifts occurring each hour. The lift frequency and range of time can be extended if large numbers of shad are present. The lift operation ceases when the shad run is complete, usually in the latter half of July. The installation of flash boards on the dam crest is critical to attract shad to the fish lift entrance and prevent them from aggregating at the base of the dam. During 2005 and 2006, high flows prevented the installation of flash boards until June. In 2010 the flash boards were replaced with an inflatable flashboard system. Data on the number of lifts each year are not available for every year in the time series. When available the tally of lifts and count of days that the lift operated can be used to standardize shad counts relative to operations.

3.2.1.4 Passage Efficiency

Existing fish passage limitations, including passage efficiency, have been reviewed and summarized in the Merrimack River Shad Restoration Plan (MRTC 2010). Downstream passage assessments are recommended by the Plan (MRTC 2010), along with specific recommendations to improve fish passage efficiency throughout the watershed. Presently, downstream passage efficiency studies are underway at the five main stem dams. Upstream passage efficiency at the Essex Dam in Lawrence has not been assessed, although specific efforts to improve passage have been implemented recently through the Technical Committee that should increase passage efficiency.

Upstream passage efficiency at the Pawtucket Dam in Lowell is low. Data collected between 1989 and 2009 indicates that on average only 29% of fish that pass through the Essex Dam fish lift eventually ascend the lift at the Pawtucket Dam. Sprankle (2005) conducted telemetry studies to assess passage efficiency at the Lowell Dam. Sprankle (2005) found that 66% of the shad radio tagged at the Essex Dam arrived at the pool downstream of the Lowell Dam and 55% entered the dam tailrace. Only 4% of the shad entering the tailrace passed the Lowell Dam fish lift. No ripe shad have been caught below the Essex Dam during electrofishing monitoring, indicating that no spawning habitat occurs below the dam and all shad are seeking to move upstream.

3.2.2 Fishery and Management History

3.2.2.1 Coordination within the Merrimack River Watershed

The MA DMF accepts the restoration goals of the cooperative Merrimack River Anadromous Fish Restoration Program as specified in the updated shad restoration plan (MRTC 2010). Based on upstream habitat units and the assumed production metric of 100 shad per acre of habitat, the MRTC (2010) goal for passage is 744,083 shad at the Essex Dam and 651,173 shad at the Pawtucket Dam. The plan provides detailed recommendations for achieving shad restoration goals through fish passage improvements and stocking measures with long-term monitoring and program evaluation.

Additionally, the state of New Hampshire also accepts the restoration goals of the cooperative Merrimack River Anadromous Fish Restoration Program as documented in their American Shad Fishing/Recovery Plan submitted to the ASMFC Shad and River Herring Technical Committee in 2012 (NHFG 2011). New Hampshire presently has closed both the recreational and commercial shad fisheries to harvest while allowing catch-and-release for sportfishing in the Merrimack River. Discussions were held with NH Fish and Game staff over the need to coordinate further on this SFMP update; however, given that their fishery is closed to harvest, no further action was taken.

3.2.2.2 Shad Fisheries

Commercial fisheries for shad are presently closed in Massachusetts with no change proposed. Recreational fisheries are presently open to catch-and-release only with the exception of harvest allowed in the Merrimack River with a three fish per day bag limit.

3.2.2.3 Sustainability Fisheries Management Plan

No stock abundance indices are available for Merrimack River shad other than the ongoing fish lift monitoring at the Essex Dam. This long-term census data is proposed as the basis for establishing sustainable fishery benchmarks. The Essex Dam fish lift count series has 36 years of census (Table 44) and CPUE data of the annual spawning run. Biological data on shad size, age, and sex composition has also been collected since the 1990s. Over time, these data can be evaluated for stock thresholds related to size, age, total instantaneous mortality (Z) and repeat spawning ratio. Because the time series for age and mortality estimates and repeat spawning percentage is brief, the present SFMP plan depends on the distribution of long-term fish lift data. The fish lift count data, age structure data, mortality estimates, and repeat spawner percentages are reported annually in the MA River Herring and American Shad ASMFC Compliance Report.

3.2.2.4 SFMP Performance

The SFMP for the Merrimack River was prepared and approved in 2012 using fish lift count data from 1983-2011 as a basis for the benchmark. Shad counts at the fish lift increased substantially during 2012-2017; averaging 17,694 shad/year in the last five years of the 2012 SFMP versus

59,019 shad/year in the most recent five years. Under this condition of rising spawning run counts, the benchmark was exceeded by a large margin in each year during 2012-2017.

3.2.2.5 Fish Lift Count Benchmark

With the addition of 2012-2017 shad count data, the benchmark (25th percentile of the 1983-2017 Essex Dam fish lift count data series) increases from 174 to 210 shad/lift day (Figure 84 and Table 45-Table 46). This benchmark will serve as a spawning run threshold for management action. Three consecutive years below this benchmark will trigger consultation between *MassWildlife* and MA DMF to discuss reducing harvest. This benchmark value will not vary annually, and will be updated with the next SFMP review.

3.2.2.6 SFMP Control Rules

Three consecutive years below the fish lift count 25th percentile benchmark at the Essex Dam on the Merrimack River will trigger consultation between *MassWildlife* and MA DMF to discuss reducing recreational harvest. These interim values will be revised when this plan is updated in the future. The Z_{30} shad mortality warning threshold has been exceeded each year since 2012. There is some concern related to the recent rise in shad mortality in the Merrimack River, although this is tempered by the expectation that recent improved recruitment is an influence on the higher mortality. This exceedance will receive annual attention and be documented in the annual compliance report and be used to supplement management decisions and actions if the fish lift benchmark is exceeded. A summary of SFMP metrics and thresholds is provided in Table 45.

3.2.2.7 Potential Future Benchmarks

There is potential to modify the shad count index at the Essex Dam fish lift by standardizing the fish counts to environmental data such as discharge and water temperature, and operational data, and to model the results to improve the quality of this spawning run index of abundance. Discussions were held with the partners of the Merrimack River Anadromous Fish Restoration Program on this topic. For the 2018 SFMP it was agreed that much work was needed to bring environmental and operational data into the fish lift data file were an index modeling exercise could be attempted. This investigation is recommended for a future SFMP update.

3.2.3 Fishery-Dependent Data Sources

No Merrimack River-specific shad landings data or other fishery-dependent information is available. Harvest in MA has been restricted to hook and line since 1987. Communications with local fishing clubs and bait and tackle shops indicate a small sport fishery persists with relatively low participation and low retention of shad.

3.2.4 Fishery-Independent Data Sources

3.2.4.1 Adult Fishery-Independent Data Sources

3.2.4.1.1 Essex Dam Fish Lift Counts

Massachusetts is required by ASMFC to conduct fishery-independent monitoring of American shad in the Merrimack River including the annual spawning stock survey (i.e. Essex Dam Fish Lift Counts) and representative subsampling of spawning adult shad to describe size, age, and sex composition of spawning stock (Table 47 and Figure 85 – Figure 88). From this information, estimates of mortality, survival and repeat spawning are made. Merrimack River shad have been aged since 1991: using scales until switching to otoliths in 2009, while maintaining the use of scales to estimate the rate of repeat spawning.

Long-term fishery-independent indices for shad have been developed from the Essex Dam Fish Lift Counts on the Merrimack River. Cooperative monitoring efforts have been ongoing in the Merrimack River since 1969 involving the USFWS, MA DMF and *MassWildlife*. The Merrimack River shad run is considered to be of sufficient size to support out-of-basin transfers for restoration efforts. The monitoring efforts include annual spawning stock surveys at the fish lifts, biological sampling, and determination of age structure and population mortality and survival estimates. *MassWildlife* is responsible for reporting shad monitoring at the two fish lifts in MA. The most recent performance report for the Essex Dam (covering March 1, 2017 through February 28, 2018) was prepared by *MassWildlife* (Slater 2018a).

From 2007 to 2017, approximately 700-1700 adult shad were collected annually at the Essex Dam for hatchery propagation and restoration efforts in the Merrimack River, Charles River and Maine rivers. American shad fish passage from the Essex Dam Fish Lift Counts from 1983–2017 are presented in Figure 84. High water levels in 2005 and 2006 caused the closure of the fish lifts which severely limited counts and collections. The series mean count, excluding 2005/2006, is 29,350 shad, the median is 20,796 and the 25th percentile is 12,359. The lift counts can be standardized by the number of days when the lift was operating each season. The lift day index has a series mean of 422 shad/lift day, a median of 313 shad/lift day and 25th percentile of 210 shad/lift day. The 25th percentile of the shad/lift day data series was adopted as a threshold for lower run sizes in the 2012 SFMP.

Ongoing shad scale ageing will provide data on the ratio of repeat spawners in the spawning run. Repeat spawning ratio data are available for the Merrimack River from 2004-2017 (Table 48). The time series is too brief to allow the setting of a repeat spawning ratio benchmark or to discern any trends. This data collection will continue and be reported in the River Herring and American Shad ASMFC Compliance Report annually and considered further with the next SFMP review.

3.2.5 Methods

Mann-Kendall analysis was used to evaluate trends in abundance, mean length, and mean length-at-age. Total mortality estimators were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Please refer to section 2 for a description of the methods.

3.2.6 Results

3.2.6.1 Abundance Trends

3.2.6.1.1 Mann-Kendall Analysis

Run count data was provided from the Essex Dam Fish Lift Counts on the Merrimack River for the period between 1983 and 2017 (Table 46, Figure 89; Shad per Lift Day). A plot of the index showed a general increase over time with peaks in the mid-1980s, 1990s, 2001, and 2015, with immediate declines after each peak (Figure 89). Mann-Kendall trend analysis found a significant increasing trend for both the full time series and for the period from 2005 forward.

3.2.6.2 Mean Length Trends

Length data from fish sampled at the Essex Dam Fish Lift was submitted for 2005-2017. A plot of mean length versus year shows a steady decrease in mean length of both male and female American shad since 2005 with a slight increase from 2016 to 2017 (Figure 90). Mann-Kendall trend analysis confirmed the decrease, finding a significant decreasing trend in mean length over time for both sexes (Table 22). One additional data program was submitted, but excluded from analysis because the time series was too short.

3.2.6.3 Mean Length-at-Age Trends

Mean length-at-age data using otoliths were provided from the Essex Dam Fish Lift Counts. Fish aged ranged between ages 4 and 9 for females and ages 3 and 10 for males. Mann-Kendall Trend analysis failed to detect any change in mean length-at-age over time in the program (Table 49).

3.2.6.4 Total Mortality Estimates

Age composition data tabulated from scales and otoliths collected randomly during the Essex Dam Fish Lift Counts were used for mortality estimates. Scale-derived data met all criteria (see Section 2.6) for 3 years between 2005 and 2007 for both sexes. Otolith-derived data met all criteria for 9 and 10 years between 2008 and 2017 for females and males, respectively (Table 32). Sex-specific estimates between age structures did not overlap during any years but were generally of similar magnitude (Figure 70). Mortality of both sexes varied without trend (Table 33, Figure 91 and Figure 92). The female estimate in 2016 (2.47) was more than double the time series mean and about 46% greater than the next highest mortality estimate (1.69 in 2008) and is believed to be biased by an exceptionally large year class in 2010 (M. Bailey, USFWS, personal communication). There were no female data available for 2017 precluding estimation of a three-year average for females in 2017.

3.2.6.5 Habitat Assessment Results

Current unobstructed American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Merrimack River, current unobstructed habitat area represents 17.83% of the historical habitat extent (7.21 of 40.45 square kilometers).

3.2.7 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. The adult mortality status is also unknown as there was no estimate of female total mortality in 2017. The most recent three-year average female total mortality was 1.25 in 2016 which is above the $Z_{40\%}$ threshold (1.00).

There was a declining trend in female mean length detected since 2005, but no YOY recruitment data to compare to mean length trend analysis.

Abundance

Abundance status is unknown. There were no YOY abundance data available. There was an increasing trend in adult abundance detected since 2005.

3.3 Pawcatuck

3.3.1 Habitat Description

The Pawcatuck Watershed, also known as the Wood-Pawcatuck Watershed, encompasses a 308-square mile (197,000 acres) area across southwestern Rhode Island and southeastern Connecticut (Desbonnet 1999; Erkan 2002). Approximately 80 percent of the watershed is located in Rhode Island (Erkan 2002). One of the major rivers within the watershed is the Pawcatuck River, which originates in southern Rhode Island and generally flows southeast and south where it serves as a natural border between southern Connecticut and Rhode Island before emptying into Little Narragansett Bay. The Pawcatuck River is approximately 48 km long. The lower 2.5 km are tidal, with a small, breached dam located at river kilometer (rkm) 2 of the Pawcatuck River (measuring from its confluence with the Pawcatuck River Estuary; Erkan 2002).

The Pawcatuck River supports spawning runs of several anadromous fish species, including American shad. The annual runs once supported lucrative in-river fisheries on which Native Americans and colonists relied (URI EDC 2006). The importance of these fisheries to residents was reflected in historic legislation aimed at protecting fish passage (Clark 1984; Buckley and Nixon 2001). For example, laws passed in 1735 and 1767 prohibited the construction of obstacles on the Pawcatuck River that would hinder the passage of fish (Clark 1984). The favor shown towards the river fisheries eventually waned as people placed more value on rivers as a source of waterpower for the growing textile industry (Buckley and Nixon 2001). By 1896, upstream shad passage along the Pawcatuck River was completely blocked by dams (Mansueti and Kolb 1953). The construction of the dams was accompanied by decreased water quality (O'Brien and Stolgitis 1977). As the number of textile factories increased, more wastewater was discharged into the river. The growing number of mills also drew more people into the area, which led to an increase in the municipal waste discharged into the river. Anadromous fish runs disappeared from most rivers and the small populations that remained were heavily fished. A few remnant runs of American shad persisted and one still exists in the Runnins River (Erkan 2002). The Pawcatuck River's native population of American shad was extirpated for about one hundred years (O'Brien 1979).

There are currently 20 dams throughout the Pawcatuck watershed, many of which were built over a hundred years ago and are no longer functional (Desbonnet 1999). Six dams are on the main stem of the Pawcatuck River (Figure 93). The White Rock Dam and Bradford Dam were removed in 2015 and 2018 respectively. These were thought to be major impediments to shad movement upstream. Currently, it is thought that American shad returning to the Pawcatuck River spawn in the 11-kilometer river section between Potter Hill dam and the former Bradford dam (Edwards, pers. comm.; D. Erkan, pers. comm.). It is not known if American shad spawn in the 11-km stretch below the Potter Hill Dam.

3.3.2 Fishery and Management History

Currently there is a moratorium on American shad harvest in Rhode Island fresh and marine waters. A small non-directed recreational catch-and-release fishery exists in the freshwater portions of the Pawcatuck River. A complete closure of the commercial fishery in Rhode Island marine waters was enacted in 2005 [RIMF Reg. Part 7.17 2006a].

3.3.3 Anthropogenic Sources of Mortality and Productivity

Currently there is a moratorium on American shad harvest in Rhode Island fresh and marine waters. A small non-directed recreational catch-and-release fishery exists in the freshwater portions of the Pawcatuck River. A complete closure of the commercial fishery in Rhode Island marine waters was enacted in 2005, and bycatch mortality since this closure is largely unknown.

Initial efforts to restore American shad to the Pawcatuck River began in 1972 (Phillips 1972; Guthrie 1973, 1974). Eggs were collected from ripe females taken from the Connecticut River, fertilized, and then transplanted into the Pawcatuck River (Phillips 1972; Guthrie 1973, 1974). The stocking of fertilized eggs was deemed unsuccessful and so the RIDFW began stocking fingerlings and spawning adults in 1975 (Guthrie 1975; O'Brien 1977–1981). Stocking of fingerlings ended in 1980 and stocking of adults ended in 1985 (Guthrie 1975; O'Brien 1977–1986). Stocking programs resumed again in the 2000s in conjunction with USFWS and the USFWS North Attleboro Fish Hatchery. Adult broodstock and fry originating from the Connecticut River were transplanted into the Pawcatuck River. This program continues to run based on the availability of fish from the Connecticut River (Table 50).

3.3.4 Fishery-Dependent Data Sources

No fishery-dependent data are available for the Pawcatuck.

3.3.5 Fishery-Independent Data Sources

Data collected from RIDFW's fishery-independent surveys were not available in electronic format for years prior to 1998. Most of the original data records are no longer available either. Data observed in these earlier years were obtained from performance reports that are submitted to the USFWS on an annual basis as cited throughout this report. The degree of detail available varies among years. All fishery-independent survey data are being moved into an electronic database to facilitate its access and use in the future.

3.3.5.1 Adult Fishery-Independent Data Sources

3.3.5.1.1 Potter Hill Fishway Count

The RIDFW began monitoring adult returns of American shad to the Pawcatuck River in 1973 (Guthrie 1973). The Potter Hill Fishway Count is conducted at a modified fishway at the Potter Hill Dam—the first intact dam on the Pawcatuck River (Erkan 2002) via fish trap (Table 51, Figure 94). No returns were documented until 1979.

Survey Methods

The Potter Hill Fishway trap is built to retain larger fish, such as shad and salmonids, while allowing smaller species, such as river herring to pass through. RIDFW staff checks the Potter Hill fishway trap daily while the trap is set, from early April until mid or late July. Staff count, sample, and release American shad that have ascended the fishway. A subsample of trapped fish are sexed, weighed, measured, and scale samples are taken for aging. Fish are released alive. Physical data is recorded, including water temperature and water depth. Scale samples are used for Rhode Island's aging and repeat spawning data.

Trends

Counts at Potter Hill remain low (Figure 94), as do numbers of repeat spawners caught at the Potter Hill trap. Removal of the White Rock dam in 2015, completion of the Bradford rock ramp in 2018, and minor modifications to the entrance and baffle boards of Potter Hill fishway have been completed, allowing for better access to spawning sites.

3.3.5.2 Young-of-Year Fishery-Independent Data Sources

3.3.5.2.1 Pawcatuck River Seine Survey

In 1986, the RIDFW initiated a beach seine survey (Pawcatuck River Seine Survey) to monitor the annual abundance of juvenile American shad in the tidal portion of the Pawcatuck River (O'Brien 1986). However, no data were available for this assessment.

Survey Methods

Five stations are sampled weekly from August to November (Figure 95). A 150-foot center bag beach seine with an 8-foot drop and quarter inch square delta mesh is deployed by boat. The net is pulled ashore for contents to be examined. All American shad are enumerated. In recent years, length measurements were taken. Water temperature, salinity, and dissolved oxygen are also recorded. In 1992, station 3 was temporarily moved 100 yards downriver to avoid debris.

3.3.6 Methods

Mann-Kendall analysis was used to evaluate trends in abundance. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Details for these methods are provided in Section 2.

3.3.7 Results

3.3.7.1 Abundance Trends

3.3.7.1.1 Mann-Kendall Analysis

Potter Hill Fishway Counts on the Pawcatuck River were available for analysis for the period between 1980 and 2017 (Table 51). A plot of the run counts versus year showed that there was an initial increase from 1980 through the mid-1980s, a steep decline followed by inter-annual fluctuation with count at some of the lowest levels of the time series after 2003 (Figure 94). Mann-Kendall trend analysis found a negative trend over the entire time series, but also found an increasing trend in the final years of the time series after 2005 (Table 21).

3.3.7.2 Habitat Assessment Results

Current unobstructed American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Pawcatuck system, current unobstructed habitat area represents 19.21% of the historical habitat extent (0.34 of 1.75 square kilometers).

3.3.8 Stock Status and Conclusions

Mortality

Juvenile and adult mortality status is unknown due to lack of data to make this determination.

There were no mean length data available for trend analysis.

Abundance

Abundance status is unknown. There were no YOY abundance data available. There was an increasing trend in adult abundance detected since 2005.

3.4 Connecticut

3.4.1 Habitat Description

3.4.1.1 Main Stem

The Connecticut River, the largest river in New England, flows approximately 410 miles from its source in New Hampshire, just south of the Canadian border, into Long Island Sound (Garabedian et al. 1998; USEPA 2000). The basin is shared by four states (Vermont, New Hampshire, Massachusetts and Connecticut). The river drainage encompasses 11,250 square miles within New Hampshire, Vermont, Massachusetts, and Connecticut. The Connecticut River flow is heavily regulated; there are at least 125 reservoirs within the basin used for power generation and 16 flood control reservoirs (Garabedian et al. 1998). The Connecticut River Atlantic Salmon Commission's "Connecticut River American Shad Management Plan (2017)" identifies 7,998 hectares of main stem and 811 ha of tributary habitat for shad in the basin. Minimum adult return production targets are defined for the river mouth and subsequent dam segmented river reaches and tributaries. Other major systems in Connecticut include the Housatonic and Thames Rivers, which together drain 3,420 square miles (Garabedian et al. 1998).

Historical documents describe the great abundance of alosines in the Connecticut River basin during the 1700s. There was a large amount of commercial fishing and alosines were harvested for export. American Shad were known to migrate as far as Bellows Falls, Vermont (natural barrier) on the main stem at rkm 280. Native Americans and early settlers fished natural falls and rapids (South Hadley Falls, MA; Turners Falls, MA; Bellows Falls, VT/Walpole, NH) during spring months, before dam construction eliminated fish access to the upper basin. Early in the Connecticut River's history in the upstream basin states, the construction of dams for navigation and mechanical hydropower significantly impacted anadromous fish stocks. Industrialization during the 18th and 19th centuries exacerbated water quality problems due to stagnation and the creation of faunal barriers (USEPA 2000). The construction of a dam at Turner Falls, Massachusetts in 1798, 198 km upstream from the mouth of the Connecticut River, marked the beginning of a long-term decline in anadromous fish runs in New England (Buchsbaum et al. 2005). By the early to mid-1800s, American shad were practically eliminated from the Massachusetts portions of the Connecticut River (Commonwealth of Massachusetts 2004). By 1870, American shad, anadromous species were all declining throughout southern New England, including the Connecticut River basin (Buchsbaum et al. 2005; USEPA 2000).

One of the first multi-state and federal restoration programs for Atlantic salmon and American shad was initiated in the 1860s in the Connecticut River, including early culture work with shad by Seth Greene. Those efforts, particularly those dealing with salmon eventually dissolved by the 1880s. A second modern federal and state cooperative anadromous fish restoration compact was signed in 1967 creating the Policy and Technical Committees for the Connecticut River Anadromous Fish Program. This effort evolved in 1983 with a Congressional Act creating the Connecticut River Atlantic Salmon Commission (CRASC) that assumed the role of the existing Policy Committee. The Connecticut River Policy Committee and CRASC has worked continuously since 1967, to restore American Shad to its historic range and also to achieve other anadromous fish management goals (Gephard and McMenemy 2004). The CRASC Commissioners include the four basin State Agency Fish and Wildlife Directors, the USFWS Northeast Regional Director, NOAA Fisheries Northeast Administrator and four Public Members appointed by each basin State Governors. A Technical Committee provides support to the CRASC. The CRASC has an updated Connecticut River American Shad Management Plan (2017) that identifies goals and objectives. In February 2020, CRASC adopted a Fish Passage Performance Addendum to the Plan that established passage performance criteria (CRASC 2020). The Federal Energy Regulatory Commission (FERC) recognizes this CRASC document as a Comprehensive Plan for use in FERC proceedings.

3.4.1.2 Tributaries

The Connecticut River has 148 tributaries with 15 major tributaries. The Connecticut tributaries within the state of Connecticut include-Black Hall River (Old Lyme), Falls River (Essex), Deep River (Deep River), Salmon River (East Haddam), Mattabesset River (Middletown), Hockanum River (Hartford), Park River (Hartford, CT), Farmington River (Windsor, CT), Scantic River (South Windsor, CT).

3.4.1.3 Barriers

Additional information on FERC regulated dams in the Connecticut River Basin will be included in section 4 of this assessment.

There are over 3,000 dams in the entire Connecticut River watershed, and it is likely that dams have been constructed on all of the rivers that were believed to have had historic shad runs. Small tributary dam construction began in the late 17th century and most dam construction in the state occurred primarily in the 19th century for industrial purposes. Dams constructed during the 20th century were likely build for hydropower purposes (Kennedy et al. 2018). As cities developed, dams were constructed for reservoirs. In the 1940s The US Army Corps of Engineers constructed flood risk management projects and these efforts continued into the 1960s. Effects of these dams on the Connecticut River diadromous species have been well documented.

Three of the major FERC regulated projects in the Connecticut River include Northfield Mountain (P-2485), a pumped- storage facility and the most recent of the FERC Hydropower projects that began operation in 1972, Holyoke Dam (P-2004), and Turners Falls Dam (P-1889). Turners Falls (rkm 198) was the first main stem dam of the Connecticut River watershed and construction was completed in 1798.

The Connecticut River was the first river in the country to be improved by canals, with the construction of locks at South Hadley Falls in 1795, which enabled river traffic to move past the falls at South Hadley. American shad and Atlantic salmon stocks began to show signs of depletion after the construction of Turners Falls Dam in 1798. A timber dam constructed at South Hadley falls was completed in 1849, although a smaller version of a dam was built during construction of the canals and was maintained and enlarged 3 to 4 times with a wing dam in place until the construction of the timber dam (Leffel, 1874). The dams caused immediate declines to anadromous fish populations.

The Holyoke Dam at Hadley Falls, MA (rkm 139), the first high head dam in the Connecticut River, was completed in 1849, but fish passage was not implemented until 1955 (Henry 1976, Moffit et al 1982). Between 1849 and 1955, there was no known American shad habitat access above the Holyoke Dam. The first type of fish passage at Holyoke was attempted in 1873 and was unsuccessful at passing shad. In 1893, a fish ladder was built and was ineffective in passing shad. In 1900 the present form of the dam was constructed and in 1940 a second attempt was made to construct a fishway, which was also unsuccessful. In 1949 the Holyoke Water Power Company was granted a license to construct a new power plant. A stipulation was for the power company to build fish passage. The finished product was completed in 1952, but was ineffective and replaced by a fish elevator in 1955 (Henry 1976). Daily counts of American shad lifted have been made annually from 1955 to 2017 (Watson 1968; Moffit et al. 1982; Leggett et al. 2004; Normandeau Associates 2018). Major technological improvements in the Holyoke lift have been made in 1969, 1975 and 1976, (Henry 1976) which resulted in increased annual passage rates (mean number/lift day) of American shad. After 1976 no further improvements in the fish lift were made until 2005, when a new tailrace lift tower, bucket and hoist, new spillway lift tower, bucket and hoist, redesigned spillway entrance gallery and crowder, a wider exit flume, a new shad trap and truck facility, a new counting room and second counting window were completed, with increased spill at the dam (into spillway reach) and greatly reduced regulated (peaking) of operations turbine (Normandeau Associates 2018). A specially designed bascule gate weir insert had also been developed to rapidly accelerate water velocities to pass shad over the dam in the late 1990s. Additional downstream passage protection had also been installed in the mid-1990s for the adjacent canal system with a full depth louver to guide fish from the canal to the fish bypass, directing fish to the nearby tailrace (Normandeau Associates 2018).

As part of a settlement agreement, Holyoke Gas and Electric (HG&E) was required to incorporate downstream fish passage measures. The new downstream facility was constructed in 2015 and opened for operation as of April 2016. The downstream passage facility above the dam consisted of a new full-depth vertical bar rack (2 inch clear) and surface and submerged bypasses. Downstream of the dam, water from above was deflected over the spillway lift entrance to a plunge pool by an apron flow deflector (Normandeau Associates 2018).

The Enfield Dam (rkm 110) construction was completed around 1829 in order to divert water to the Windsor Locks canal so boats could avoid the rapids. The dam was a wooden crib structure nearly 1,500 feet in length and at one time had a fish ladder in its center that was believed to be ineffective (similar to other early attempts at fish ladders). The low-head dam was often submerged during high flows in the spring and became an obstruction to fish migration only during low flows. The dam fell into disrepair in the late 1970s and is now barely distinguishable by some limited near-river bed partial wood crib fragments, spikes and rocks. The Enfield Dam is no longer an impediment to anadromous fish migration (Leggett et al. 2004).

3.4.1.4 Water Quality

The Connecticut River, once famously referred to as “New England’s most beautifully landscaped sewer,” has had a long history of poor water quality due to heavy industrial expansion of textiles, heavy metal processing, logging and sewage. Natural disasters such as hurricanes, droughts and flooding events have also had impacts on the water quality of the river. Concentrations of dissolved oxygen in the Connecticut River below the Holyoke Dam were measured close to zero during the mid-1960s and early 1970s. Connecticut has been progressive in the development of water quality management following some of the dismal times of heavily polluted waters. Connecticut’s Clean Water Act (1967) was developed 5 years ahead of the Federal Clean Water Act of 1972.

Legislative interest in water pollution dates back as far as 1887 when the Connecticut General Assembly authorized the formation of a sewer study commission to investigate sewage disposal. The commission report in 1889 recommended the State find ways to stop further pollution. A Legislative study commission was created in 1913 to investigate factory wastes and, again, in 1921 to investigate solutions to eliminate pollution. In 1925 laws were enacted to create a State Water Commission, but the commission had few resources and a lack of direct regulatory authority. The State and Federal Clean Water Acts resulted in several downward trends in pollutants and increasing trends in dissolved oxygen. Downward trends in sulfate concentrations likely are attributable to reductions in sulfur dioxide emissions mandated by the Clean Air Act of 1970. Water quality challenges for the Connecticut River still remain and include: reducing nitrogen loads from point and nonpoint sources, reducing bacteria and other contaminant concentrations in storm water runoff, and separating storm water and sanitary sewers at some locations to prevent combined sewer overflows (Mullaney, J.R. 2004). Microplastics and pharmaceutical residuals are recent pollution issues in water bodies, and while they are known to be a threat to the marine and aquatic life that consume them, their impact on fish health is largely unknown. Both the federal government and the state of Connecticut have passed legislation to phase out the use of plastic microbeads from cosmetic products.

3.4.2 Fishery and Management History

3.4.2.1 Commercial Fishery

The commercial shad fishery in the Connecticut River began during colonial times, but little is known of the fishery prior to 1880 (McDonald 1887). Since the 18th century, haul seines, pound nets and drift gill nets were the principal commercial gear types used to harvest American shad in the Connecticut River (Walburg and Nichols 1967). Just prior to World War II, commercial fishermen began to shift from haul seines and pound nets to drift gill nets that required less labor to operate (Fredin 1954). By 1965 all commercial fishermen in the river were using drift gill nets that were typically 180-275m long and 30-50 meshes deep with 14cm stretch mesh. This larger mesh tends to select for the female (roe) shad that were worth substantially more than male shad at the market.

There is a long history of fishing regulations in Connecticut with one of the most significant being the establishment of “rest days” in 1922, prohibiting all commercial fishing except for dip nets. The numbers of rest days per year have varied over time from three to zero. During WWII, fishing was encouraged by removal of the rest days. Two rest days per year have been in effect since 1948.

Under the commercial shad fishing license the following are prohibited: use of gill nets constructed of single or multiple strand monofilament from sunrise to sunset, monofilament twine thickness greater than 0.28 mm (#69), commercial fishing for shad from sundown Friday to sundown Sunday except by the use of a scoop net, the use of nets with mesh size less than five inches stretched mesh, fishing in other than the main body of the Connecticut River (no coves), and the use of pound nets or other fixed or staked nets to take shad. A daily record detailing catch, effort and landings is required in a report that must be submitted by July 15th of the fishing year.

3.4.2.2 Recreational Fishery

The Connecticut River was once the most popular site for American shad recreational fishing and some believe this was the birthplace of the sport. Numbers of fishermen, effort, catch, and harvest have all varied greatly over time but, similar to commercial fishing, recreational fishing for American shad exhibits a general decrease in participation with time. Anecdotal and limited creel information gathered in the last ten years indicates that few Connecticut fishermen have targeted American shad in the traditional shad fishing areas from Hartford to the Connecticut-Massachusetts state line, and the trend is not expected to change.

Angling for American shad is the only legal method of recreational take and may occur during the open season from April 1 through June 30 in rivers and streams open to fishing all year; otherwise, the open season runs from the 3rd Saturday in April through June 30. There is a daily possession limit of six American and hickory shad in the aggregate, per person, in both the Inland and Marine Districts. Fishing licenses are required for anyone 16 years of age or older fishing in the Inland District. Licenses are issued on a calendar basis and expire on December 31. Under the Connecticut River SFMP, the recreational shad fisheries in all other systems within Connecticut are catch-and-release only. There have been no other changes to recreational catch limits of American shad fishing since 1999, when the existing six fish recreational creel limit was modified to include hickory shad as an aggregate creel limit for the two species.

3.4.2.3 Sustainable Fishery Management Plan (SFMP)

The State of Connecticut has had an approved SFMP in place for Connecticut River commercial and recreational fisheries since 2012. The shad stock is managed by 3 metrics that are monitored and evaluated annually. The metrics are Holyoke fish lift passage for adults, juvenile abundance, and adult escapement. A stoplight style approach is used to express the level of perceived risk to maintaining a Sustainable Fishery in the Connecticut River system. Risk is assessed via a combination of two stock status (response) indicators and a fishing rate (stressor) indicator recognizing that factors other than in-river fishing (ocean environment, stream flow, temperature, dam & fish passage operations, etc.) significantly influence adult run size and recruitment.

The first response metric is Passage, or the number of adult fish lifted at the first main stem dam in Holyoke, MA. Annual fish passage counts of American shad are used as a proxy for total run size (i.e., adult stock). The trigger for Passage is 140,000 fish. Recruitment (JAI) at this value has varied independent of adult stock size, indicating sufficient stock reproductive capacity to support future stock reproduction and recruitment.

The second metric is Recruitment Failure, defined in Amendment 3 as three consecutive years of recruitment in the lower quartile of the time series. The time series of American shad JAI provided by the Connecticut Department of Energy and Environmental Protection's (CT DEEP) Connecticut River Juvenile Shad Seine Survey will be used as the basis for the Recruitment metric. This metric will provide an early warning of a population decline due to inadequate stock reproduction.

The third metric, Escapement, is a measure of fishing pressure on the stock expressed as the proportion of the total run "escaping" the fishery to spawn. A very conservative trigger of 90% escapement was chosen to facilitate timely review of potential implications for future stock production in the event of increasing fishery removals. Recent escapement has been in excess of 90%, but lower escapement rates were common through much of the time series with no evident diminishment in subsequent recruitment. Median Escapement between 1990 and 2016 was 96% with a range of 90%-98%. All commercial fishing and virtually all sport fishing takes place below the Holyoke dam.

The sustainability metrics have remained above target levels, with the exception of the initial year of the plan's implementation. In 2013, the JAI fell below the three year average. Since then, all targets have remained above the thresholds.

3.4.3 Fishery-Dependent Data Sources

3.4.3.1 Commercial Fishery

3.4.3.1.1 Landings

In order to participate in the commercial fishery, Connecticut requires purchase of an annual commercial shad license for the Connecticut River. The shad fishery is managed through area, gear, and season restriction as well as rest days. The American shad gill net season runs from April 1 through June 15. In the inland district (north of Interstate 95 bridge), American shad may be taken only in the main body of the Connecticut River from the I-95 Bridge to the William H. Putnam Memorial Bridge on Route 3 in Glastonbury/Wethersfield (rkm 75). Directed fisheries for American shad are only allowed in the Connecticut River since the implementation of the SFMP. The commercial shad license fee was doubled in 2009 to $200 and is the most expensive open access commercial fishing license available in Connecticut.

American shad is the only alosine species harvested by directed fisheries in Connecticut waters. The commercial fishery is exclusively a drift gill net fishery. Commercial shad fisheries have been in existence for centuries, and the state of Connecticut has landings data dating back to 1880. The National Marine Fisheries Service has reported landings from Connecticut that date to 1887. More detailed landings reports of American shad abundance (numbers and pounds) have been collected annually from 1974 to 2008. After 2008, the CT DEEP Fisheries Commercial Fisheries Statistics Project changed the mandatory shad report form and no longer required numbers of shad reported, only pounds landed. The detailed individual catch records prior to 1990 have not been incorporated into the CT DEEP commercial statistics database and are only available in summary form at this time

There is thought to be some level of underreporting of overall landings and male discards. Both Leggett (1976) and Crecco et al. (1986) reported that in-river commercial fishermen might have underreported their landings by 35 to 67 percent annually from 1966 to 1983 based on the ratio of tag returns to reported commercial landings. The fishery has had little technological changes since the adoption of outboard- powered vessels, with the exception of the change to drift gill nets from all other gear types (haul seine, fixed gill nets, traps, and pound nets).

The number of commercial American shad fishing licenses sold, and associated effort has been systematically declining since the number of licenses peaked during and after World War II. Commercial license sales have declined to low levels and are expected to stay low or further decrease as fishermen retire and are not replaced. Numbers of boats commercial shad fishing on an annual basis has reached all-time lows and landings have remained below 70,000 lbs since 2004.

No poaching or illegal catch of American shad is thought to occur in this fishery. The fishery is somewhat self-regulating in that drift gill nets are selective in nature and licensed commercial fishermen are not likely to allow unlicensed fishers to displace them from preferred fishing reaches. American shad are likely occasionally caught in the commercial trawl fishery, but landings records in recent history show zero reporting of catches.

3.4.3.1.2 Biological Samples

Scale samples and biological information were collected for shad at local seafood markets during the 1970s and 1980s. The commercial fishery catches were qualified by sampling at commercial markets using only fishermen's catches who were known not to cull their catch for male shad. Markets and catches were sampled one or two days per week depending upon availability and catch size. As the commercial fishery experienced declines in participants, CT DEEP staff was no longer able to gain access to commercial markets. This data was not included in this assessment because it is only in summarized form at this time.

In more recent years, CT DEEP staff collected biological samples to characterize the fishery with drift gill nets and mesh sizes similar to the commercial fishery and in a similar fashion to that used by commercial operators. Gill nets were fished during daylight hours to avoid interfering with commercial efforts; research nets were shorter in length and drift times were shorter than those employed by commercial netters. Staffing shortages have prevented the continuation of this effort.

3.4.3.1.3 Catch Rates

An index of adult abundance was developed from commercial catch (in pounds) in the Connecticut River from 1995-2017. Nearly all reported trips were positive for American shad and occurred between April and June. Catch was originally separated by sex but was combined in this analysis. River discharge data (mean cfs per day) from the USGS gage at Thompsonville, CT was included in the analysis. While this gage is approximately 80 km north of where the commercial shad fishery occurs, it has the longest time series of discharge data. Water temperature data was also available from this gage and two others closer to the shad fishing grounds; however, data collection either did not start until later in the time series or was collected very sporadically, which would have resulted in many records being dropped due to missing data. Included records had to have complete observations for hours the nets were fished, day of year, and discharge. While this did result in a number of trips being removed from the data set, there was still an average of 169 trips reported per year (ranging from 111-239). As some records reported numbers of fish that were converted to partial pounds harvested, pounds were rounded as necessary. The data were fit using a negative binomial GAM that included year, discharge, a smoother for day of year, and an effort offset (hours net was fished).

Commercial shad CPUE in the Connecticut River was low in the late 1990s and generally increased through 2001 (Table 52, Figure 98). While somewhat variable, CPUE generally declined after 2001, bottoming out from 2008-2011 to levels similar to those observed in the late 1990s. Since 2011, a general increase to approximately the time series average CPUE was observed though the 2017 terminal year is still well below the peak CPUE observed in 2001.

3.4.3.2 Recreational Fishery

Recreational American shad landings in numbers have estimated annually from 1980 to 1996 and periodically thereafter by a roving creel census (Savoy 1998). The last year of the Connecticut River recreational creel survey was 2010. Creel data collection techniques have varied slightly with time, but basically have followed a modified “bus stop” technique. Sampling intensity has varied over time, becoming generally less intensive as the fishery got smaller and anglers switched their angling preferences to other species. Two weekdays, the weekend, and all holidays were sampled in early years compared to one weekday and one weekend day in recent years. Holidays have always been sampled given the larger number of people expected to be fishing. No biological sampling of the recreational harvest has been conducted since 1978 and detailed catch data is unavailable in electronic form and has not been included in this stock assessment.

Prior to 1993, there was a thriving recreational fishery for American shad in the Connecticut River from Enfield, Connecticut (rkm 110) to the Holyoke Dam (rkm 139). These sport landings would comprise up to 82 percent of annual total in-river landings. Recreational shad landings began to fall dramatically after 1994 to a point where harvest estimates from creel surveys were unreliable and imprecise as reflected by high (>80%) proportional standard errors (PSE) about the mean harvest estimates. All American shad caught in the recreational fishery were assumed dead although most are released and some survive the catch-and-release. Hook and release mortality is a function of age, sex, and physiological condition of the fish, as well as external factors including water temperature, length of time “played” by the angler, skill of the angler in handling and releasing the fish, and hook type and location.

Recreational landings of Connecticut River shad varied greatly from 1981 to 2010. Both commercial and recreational in-river landings remained relatively high from 1981 to about 1992 with peak total landings (commercial and recreational) of 159,000 fish occurring in 1986.

3.4.4 Fishery-Independent Data Sources

3.4.4.1 Adult Fishery-Independent Data Sources

3.4.4.1.1 Holyoke Dam Fish Lift Counts

The Holyoke Dam and fish lift are located at river kilometer 139. All of the commercial fishing (by statute confined to below river kilometer 75) and most of the recreational fishing has already taken place. The percentage of the population that continues upstream of the Holyoke lift likely varies. Prior to the 2005 lift improvements, CT DEEP had developed a method to estimate the population based on the daily lift rate (Crecco and Savoy 1985). Since the 2005 lift improvements, which increased the hopper size of the elevator, the developed method is no longer used. The effect of the implementation of a downstream passage system in 2015 should allow for better survival of adult and juvenile shad migrating downstream. It is worth noting that the Connecticut River stock of American shad persisted and produced sustainable runs from time of restricted access upstream from the Holyoke Dam in 1849 until effective fish passage began in 1975. This suggests that spawning occurs downstream of the dam.

Information on the number of fish lifted daily, the number of lift days (days the lift is in operation) and the daily sex ratio at Holyoke are obtained annually from HG&E staff. The annual sex ratios are extrapolated by weighting the daily sex ratios by the number of fish lifted that day. Batches of shad that are lifted are trapped and randomly selected for biological sampling. A portion of the shad used for biological sampling are sacrificed. The data recorded includes length, weight, and sex, and a scale sample is collected.

The most recent methods for obtaining diadromous species counts at the Holyoke lift, as described by HG&E in their annual report for 2017, are detailed as follows:

Monitoring methods were consistent with previous years and with the updated monitoring plan. A copy of the Holyoke Fish Lift Study Plan and Procedures (Procedures) was maintained on site and followed throughout the season. In order to ensure consistency among annually changing monitoring staff, training, coordination, and daily oversight were provided by experienced fisheries technicians. The hours of operation and frequency of lifting were specified in the Procedures. Fish lift monitoring personnel counted the number of each species that passed the Project and tabulated the data hourly. Additionally, a relative index of fullness of the fish lift hoppers as described in the Updated Plan was used to qualify the amount of fish lifted in each operation on a scale of 0 - 5. In the fullness index, 0 = no fish lifted and 5 is representative of a heavy run period. The Procedures included a protocol to extend fish passage operations on peak passage days. If hopper fullness was assigned an index value of 5 for either lift in the last operations of the day, lift frequency was increased as appropriate, and lifting continued with both lifts for an additional hour. Otherwise, if each of the following three criteria were met, operations were continued for an additional hour:

1. American shad in the last scheduled hourly counts totaled 750 or more; and

2. Fish lift hopper fullness was assigned an index value of 4 for either lift in the last operations; and

3. Fish lift frequency was at least once every 20 min. At the end of any additional hour of lifting, the assessment was repeated. Exceptions to extensions of operations were made under extenuating circumstances, such as poor visibility exacerbated by low ambient light in the evening and when determined to be unsafe to continue operations (at the discretion of the fish lift operator). Resident species were also enumerated and passed upstream and passage counts were tabulated hourly. Following the spring (and early summer) fish passage season, nominally April 1 – July 15, fish lift operations continued four times per day, Monday through Friday through November 15, with exceptions, for shortnose sturgeon passage.

Counts are provided in Table 53 and Figure 96.

3.4.4.2 Young-of-Year Fishery-Independent Data Sources

3.4.4.2.1 Connecticut River Juvenile Shad Seine Survey

Survey Design and Methods

A long and consistent (1978-present) time series of juvenile abundance indices (geometric mean catch per seine haul) has been established in the Connecticut River, below the Holyoke Dam. Juvenile American shad are collected weekly from mid-July through mid-October at seven fixed stations located from Holyoke, Massachusetts to Essex, Connecticut. Seine haul locations and techniques have remained similar to those employed in past Connecticut River American shad investigations (Marcy 1976; Crecco et al. 1981). Sites were previously chosen based on location, physical conditions, and accessibility. One seine haul per station was made during daylight hours with an 18.2m nylon bag seine (4.6 mm mesh, 2.4 m deep, and 2.4 m bag) and 0.5m lead ropes. Each haul is completed using a boat to set the net approximately 30 m upstream and offshore of the site. Using the lead ropes, the seine is then towed in a downstream arc to the shore and beached.

Biological and Environmental Sampling

With small sample sizes (less than 500 fish), all clupeids (*Alosa sapidissima, Alosa aestivalis, Alosa pseudoharengus,* and *Brevoortia tyrannus*) are returned to the laboratory. With large sample sizes, clupeids are sub-sampled volumetrically and unnecessary fish returned to the water. Water temperature, weather conditions, time, and tidal stage (when appropriate) are recorded for each station.

In the laboratory, juvenile clupeids are identified to species by the criteria of Lippson and Moran (1974) and counted. Up to 40 juvenile shad per haul are measured (TL mm). Individual seine collections containing greater than 40 shad are randomly sub-sampled for length measurements. All other clupeids were only counted. The annual relative abundance of juvenile American shad is calculated as the geometric and arithmetic mean catch per seine haul from all stations and all dates sampled each year. Water temperature, weather conditions, time, and tidal stage (when appropriate) were recorded for each station. Daily flow is available for the entire time series from the USGS gage at Thompsonville, CT.

Evaluation of Survey Data

This survey provides a relative abundance index for YOY American shad in the lower Connecticut River (below Holyoke). Overall, the proportion of positive hauls in all years of the survey is 68.1%, with percent positive hauls declining with each ensuing month of sampling. Percent positive tows are also different among sampling stations. Hauls at six of the stations are at 54% or higher percent positive throughout the time series, but the outlier is Enfield at only 39% of all historic hauls capturing shad. The historic, nominal index is an annual geometric mean catch per haul, which includes all stations and years. A standardized index using generalized linear modeling was investigated to account for covariates that may influence catch rates. The factors explored in the analysis were ordinal day, flow, site name, sample time, and water temperature. As described in the section above, these last three variables were not consistently sampled over time. Any model including time and water temperature would require the data set to begin in 1985. Site name is a more complicated variable as not all sites began in 1978. Holyoke, which has some of the biggest hauls in the time series, is not sampled until 1981, while Essex was sampled from 1980-83 and then 1985 to present. As Essex has fewer catches and is often below the salt front during sampling, it was removed from the model data set. After consideration of percent zeros per sampling station, Enfield was removed from the data set as well. A correlation analysis on all factors found ordinal day and water temperature to be highly correlated, as were sample time and site name. This latter relationship is due to the direction of sampling. Generally, the northernmost sites are sampled first and sampling effort moves southward toward Long Island Sound as the day progresses. Both the inconsistent variable collection and high correlations among variables required both a decision for the year to start the model data set as well as which variables to leave out. In the end, the SAS believed the early 1980s were important to the time series and any index should include Holyoke. The base model included year, ordinal day, site name, and flow. Nested submodels were compared using AIC. Based on dispersion, AIC, and percent deviance explained, the final standardized model selected was a negative binomial GLM with catch predicted as a linear function of year, ordinal day, and site name. This final standardized model was then compared with the nominal index for similarity in trend as well as CVs. Both are similar in trend with the major differences in the mid-1980s and 2001-2003. The CVs are similar between the two indices. Because it accounts for some of the variability associated with significant covariates, the SAS decided that the standardized index provides the best representation of the relative abundance of YOY American shad from 1981-2017.

Abundance Index Trends

There is an increasing trend in the time series (slope = 1.8755; $R^2 = 0.1085$), with the most pronounced increase in abundance from 1981 to 1994 (Table 54, Figure 97). The index is variable but stable from 1995 to 2010. The period from 2011 to 2014 has some of the lowest values in the time series; however, this is followed two years later with the largest peak in the time series in 2016. Other peak catch years are 2010, 2002, and 1994.

3.4.5 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance, mean length, and mean length-at-age. Total mortality estimators and delay-difference models were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Please refer to section 2 for a description of the methods.

3.4.6 Results

3.4.6.1 Abundance Trends

3.4.6.1.1 Power Analysis

Two abundance indices for American shad were developed for this system that contained estimates of PSE, the Connecticut River fishery-dependent commercial CPUE index (median PSE = 0.061) and the Connecticut River Juvenile Shad Seine Survey (median PSE = 0.211). Currently, only the seine survey is used for sustainability targets and monitoring in the SFMP. Both of these surveys exhibited sufficient power to detect a 50% decrease in American shad abundance in 10 years, though only the commercial CPUE index exhibit sufficient power to detect a 50% increase in American shad abundance over the same time span (Table 25).

3.4.6.1.2 Mann-Kendall Analysis

Connecticut River [Run Counts]

Run counts at the Holyoke Dam Fish Lift on the Connecticut River steadily increased after 1975, peaking in 1992, before declining and remaining relatively low through 2010, and finally increasing afterwards (Figure 96). Mann-Kendall analysis did not detect any trend over the full time series, but did find an increasing trend in the period after 2005.

Connecticut River [JAI]

Geometric mean CPUE from the Connecticut River Juvenile Shad Seine Survey shows a considerable amount of inter-annual variation, with no apparent trend (Figure 97). A time series peak CPUE occurred in 2016, but returned to average levels in 2017. Mann-Kendall trend analysis did not detect any trend for either time period examined.

Connecticut River [FD]

American shad abundance indices developed from commercial CPUE surveys conducted by Connecticut Department of Environmental Protection in the Connecticut River were available for years between 1995 and 2017. Plots of the data showed an increase from 1995 through 2001, followed by a general decline through 2010, then subsequent return to average levels over the entire time series (Figure 98). Mann-Kendall analysis did not detect any trend for either time period examined.

3.4.6.2 Mean Length Trends

3.4.6.2.1 Connecticut River

The State of Connecticut conducts biological sampling of American shad from fishery-dependent and fishery-independent collections in the Connecticut River. Lengths from a fishery-dependent commercial fishery monitoring program are available for most years between 1995 and 2012. A plot of mean lengths showed a decrease in mean length of both sexes from 1995-1998 followed by an overall increase through 2003 before decreasing again (Figure 99). No significant trends in mean length over time were found for either sex in the Mann-Kendall trend analyses. Similarly, a plot of fishery-independent sampling at the Holyoke Dam Fish Lift between 2000 and 2017 showed a decline early in the time series until 2004, a short decline through 2006 and has remained low since then (Figure 100). No significant trends in mean length over time were found in the Mann-Kendall trend analyses.

3.4.6.3 Mean Length-at-Age Trends

Mean length-at-age data using scales were provided from two sampling programs: commercial fishery monitoring and Holyoke Dam Fish Lift sampling. Fish aged ranged between ages 3 and 7 for both sexes. Mann-Kendall Trend analysis failed to detect any change in mean length-at-age over time in the commercial fishery monitoring, but did detect a decrease in mean length-at-age in age 6 females and males in the Holyoke Dam Fish Lift sampling (Table 55).

3.4.6.4 Total Mortality Estimates

The SAS used age composition data tabulated from scales collected randomly or by census during Holyoke Dam Fish Lift sampling for mortality estimates. Data met all criteria (see Section 2.6) for 7 and 16 years between 2000 and 2017 for females and males, respectively (Table 32). Mortality of both sexes decreased from the highest levels observed in the early 2000s, increased in the late 2000s, and have varied without trend since (Table 33 and Figure 101).The three year average female estimate in 2017 (1.40) was above the threshold ($Z_{40\%}$ = 1.00) and the average standard error for this estimate was 0.59.

3.4.6.5 Delay-Difference Model

Two abundance indices for American shad were developed for this system that were identified as suitable for use in the delay-difference model: the fishery-dependent Connecticut River Commercial CPUE index and the Holyoke Dam Fish Lift Counts. The delay-difference model was run using northern iteroparous life history parameters and each of the indices individually.

Total adult run counts at the Holyoke Dam Fish Lift on the Connecticut River were available for 1990 through 2017. Estimated biomass declined through the 1990s, remaining relatively low through 2010, and finally increasing afterwards (Figure 102). The ratio of estimated biomass to initial biomass followed the same trend as the biomass. The index and effort showed opposing trends throughout the time series alternating widely between 1990 and 2010, with the index increasing after 2010 and effort dropping to low levels. Observed and estimated catch from the model simulations show that total catches have decreased across the time series, despite the index increase increasing over the final seven years. Median TAC over 100 simulations was estimated to be 78,037.1 lbs, with overfishing unlikely to occur within the confidence intervals at catch levels equal to the mean of the final 3 years of the time series.

Total commercial fishery catch and abundance indices developed from Connecticut River Commercial CPUE data reported to CT DEEP in the Connecticut River were available for years between 1990 and 2017. Estimated biomass remained relatively constant throughout the time series (Figure 103). The ratio of estimated biomass to initial biomass indicated an initial decrease between 1990 and 1995, then remains at an average level through 2017. The index fluctuated throughout the time series, with a period of increase in 2003, followed by sharp decline through 2011, and ending the time series with increased levels from 2012 through 2017. Effort displayed a drastic declining trend throughout the time series. Observed and estimated catch from the model simulations show that total catches have decreased across the time series, despite the index increase increasing over the final seven years. Median TAC over 100 simulations was estimated to be 150,454.8 lbs, 70% higher than the average catch over the final 10 years of the time series.

3.4.6.6 Habitat Assessment Results

Current unobstructed American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Connecticut system, current unobstructed habitat area represents 45.19% of the historical habitat extent (31.05 of 68.71 square kilometers).

3.4.7 Stock Status and Conclusions

Mortality[2]

Juvenile mortality status is unknown due to lack of data to make this determination. Adult mortality status is also unknown due to conflicting results of the total mortality estimators and delay-difference models. Total mortality estimators indicate unsustainable mortality levels, as the three-year average female total mortality in 2017 was 1.4 which is above the $Z_{40\%}$ threshold (1.00). Conversely, the delay-difference models indicate sustainable mortality levels as the three-year average catch in 2017 was less than the median TAC estimates.

There were no trends detected in female mean length from two data sets (1995-2012, 1997-2017) nor YOY abundance (1978-2017, 2005-2017).

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[2] This status determination changed following the Peer Review Workshop. See the addendum (Section 9) for final status determination.

Abundance
Abundance status is unknown. There have been no trends in YOY abundance since 2005. There have been conflicting trends in adult abundance since 2005, with an increasing trend detected from the Holyoke Fish Lift and no trend detected from Commercial CPUE, further confounding assessment of abundance conditions in recent years.

3.5 Hudson River

3.5.1 Habitat Description

The Hudson River flows from Lake Tear of the Clouds in the Adirondacks to the Battery in New York City. It is tidal to the Federal Dam in Troy, 246 km from the Battery (Figure 104). The location of the salt front varies, depending on freshwater inputs from Hudson River tributaries and tidal flow, and generally fluctuates from Tappan Zee (km 45) to Newburgh (km 95). The river includes two major estuarine bays: Haverstraw Bay (km 55) and Tappan Zee Bay (km 45). These bays are mainly shallow water less than four meters deep where the river extends up to five and a half kilometers from shore to shore. The river also includes a narrow and deep section, the Hudson Highlands, where the river is less than one kilometer wide and over 60 meters deep (Stanne et al. 2007).

American shad predominantly spawn in the sandy, gravelly shoals and shallow water areas in the upper half of the Hudson River Estuary, from Kingston (km 144) to Troy (km 246). The nursery area includes this area and extends south to Newburgh Bay (km 90), encompassing the freshwater portion of the Estuary (Hattala and Kahnle 2007).

3.5.2 Fishery and Management History

3.5.2.1 Commercial Fishery

Fisheries targeting spring runs of anadromous species have likely existed in the Hudson River since humans first settled in the Hudson Valley roughly six millennia ago (Limburg et al. 2006). Most of these fisheries were likely subsistence fisheries or small-scale commercial efforts until the rise of the Industrial Revolution in the mid-19th century and the population boom that followed (Limburg et al. 2006). By the turn of the 20th century, shad were the second highest commercially harvested species on the Atlantic coast following Atlantic cod (USCFF 1884), with harvest in the Hudson River as one of the most valuable on the Atlantic seaboard (Stevenson 1899). The first written record of commercial shad landings in the Hudson River was in 1880 and records are sporadic through 1915 (Figure 105, Table 56). Gaps in landings during this time period are likely due to poor record keeping rather than a pause in the fishery considering the very large catches reported through 1910. From 1915 through the period prior to WWII, landings are low for reasons that are unclear. However, if fishing occurred at low levels during the time period, this abatement would have allowed the stock to grow to the substantial size necessary to sustain the huge harvest that occurred from the late 1930s through the early 1950s (Hattala and Kahnle 2007). Landings dramatically decrease after the 1950s, as do the number of nets licensed, until the early 1980s when a resurgence in the fishery occurred. This small fishery continued through 2010 when New York State placed a moratorium on the commercial and recreational fisheries due to continued recruitment failure observed in fishery-independent juvenile sampling.

The historic commercial shad fishery in the Hudson River operated from mid-March through mid-June, targeting the Hudson River spawning stock. The fishery took place throughout most of the tidal Hudson, beginning near the mouth of the river and ending near the town of Castleton at km 220 (Cheney 1895, Talbot 1954, Hattala and Kahnle 2007). Based on landings, gill nets were the predominant gear type in Hudson fishery with smaller historical landings reported for other miscellaneous gear types such as seines, trap nets, and fyke nets (Talbot 1954, Hattala and Kahnle 2007).

In the lower 70 km from the Battery to Peekskill, fixed gill nets were the primary gears used in both New York and New Jersey sections of river. The New Jersey fishery operated on the western shore in the deep, fast moving section of river south of the George Washington Bridge (km 19) north to the state line near Piermont, NY. Nets were fixed to long poles driven into the substrate and usually fished on flood tides, with nets picked at slack water due to the fast-moving ebb current in this section of river (Talbot 1954). Few NY fishermen were located on the eastern shore of this lowest section of river. Most NY fishermen operated fixed gill nets in the wide, shallow areas in NY waters from Piermont (km 41) to Peekskill (km 70). Water movement is generally slower in this reach and fishing took place during all tide stages (Talbot 1954). By the 1930s each fisher used a particular location in this lower section of river based on an assigned areas system initiated by the US Army Corps of Engineers (USACE), designed to avoid collision of commercial shipping traffic with fixed fishing gear (Talbot 1954). It then evolved to lessen the turf wars that often erupted among the several hundred fishers in this area during the period from 1930 to 1955 (T. DeGroat and R. Gabrielson, commercial shad fishers, personal communication). From Peekskill north to Castleton, drift gill nets were primarily used. Historically, from 1930 to 1960, much of the same competitive conflicts between fishers occurred in the drift fishery but to a much lesser extent than in the fixed gear fishery (F. Parslow, Jr., commercial shad fisher, personal communication). Improvements in technology, such as monofilament netting and depth sounders, likely had significant impacts on catch rates in the drift net fishery over time, although likely impacted both fishing methods.

3.5.2.2 Recreational Fishery

There is little mention of a recreational fishery for American shad in the Hudson River prior to the 1970s (Zeisel 1988). The Clean Water Act in 1972 paved the way for much improved sewage treatment and water quality throughout the river, but none more significant than in the stretch of river found between Castleton, NY and the Federal Dam at Troy (Brosnan et al 2006). Soon after, a sport fishery developed for American shad that were aggregated below the Federal Dam (Limburg et al. 2006). This fishery remained very popular until the 2010 moratorium on all shad fisheries in the river.

The NYDEC contracted with Normandeau Associates, Inc. to conduct creel surveys on the Hudson in 2001 and 2005. Catch in 2001 was 19,766 American shad with a 6.5% retention rate (Table 57). Catch dropped in 2005 to 6,582 American shad, although the retention rate was higher at 7.7%. Catch rates were dramatically different in the two years. In 2001, boat and shore catch per unit effort (CPUE) were 1.5 fish per hour. In 2005, the rates were much lower at 0.58 fish per hour for boat and shore fishers.

No known recreational data for American shad exists in New York ocean waters. Recreational catches of American shad reported from ocean waters along Long Island are suspect because hickory shad are frequently caught in the fall and misidentification is likely (Hattala and Kahnle 2007).

3.5.2.3 Management History

During the 19th century, regulating the shad fishery within New York waters was the sole responsibility of the state. An anecdotal article in Harper's Weekly (1872) suggested a serious decline of the Hudson River American shad occurred in the 1860s. Following this "collapse" (referred to parenthetically as no written records exist to document this event), in 1868 the New York State legislature implemented fishing net restrictions, an escapement period and a season to control fishing on the Hudson. However, according to US Fish Commission Reports (USCFF 1898), the prevailing intent of the states, including NY, was not to interfere in any business, including fishing. These restrictions generally defined current fishing practices, setting the season to coincide with the period that shad were in the river. It is clear, that although restrictions were implemented, fishing largely continued unabated. Some variant of these 19th century rules existed until the fishery closed in 2010.

Following the mid 1800s perceived collapse, the United States Fish Commission and the NY Board of Fish Commissioners began stocking the Hudson River with American shad fry and fingerlings (Cheney 1900). So began New York's legacy, along with many other east coast states, of shad hatchery production and an attempt to restore stocks perceived to be exhausted. This "exhausted" condition is questionable. From 1880 through 1901, the Hudson stock produced the largest harvest in its recorded history. This suggests the spawning stock was large enough to quickly recover to produce two successive, historically high peaks in harvest within 30 years. The suggested need for hatchery supplementation was a factor of the times. Most other east coast shad stocks, primarily the Susquehanna and other Chesapeake stocks were being severely depleted (Talbot 1954). Leaders of the US Fish Commission only drew on hatchery production rather than fishing curtailment as a solution. Shad stocking continued in New York for nearly 50 years (Talbot 1954), decreasing steadily while focus of fish culture shifted to other warm-water and cold-water species. After 1920, mention of shad hatchery production no longer appeared in New York State Commission reports.

Studies conducted by the US Bureau of Fisheries (USCFF 1939) indicated that:

> "although pollution and obstruction of rivers have doubtless contributed to the failure of reproduction…of many Atlantic coast shad streams, the decline in yield has not been limited to polluted or obstructed streams…some unpolluted rivers (Edisto) have been severely depleted, yet a fine recovery has been observed in the polluted Hudson. This

> recovery is attributed to regulations limiting fishing to four nights a week and closing spawning areas to fishing."

This recovery did not last very long. During the years leading up to, during and after WWII, regulations were greatly relaxed, or abolished altogether. After almost ten years of continuous, unabated fishing at near record levels, the Hudson stock experienced a collapse in the early 1950s from which it never recovered (Walters 1995). The high fishing rate continued to remove fish faster than the stock could replace itself. In hindsight, the greatest downfall of management of the fishery was the disconnect that occurred between fishing and understanding the biology of the stock.

This disconnect between understanding fish stock dynamics and the long prevailing attitude of not interfering in, or restricting, the fishing industry has held firm since the 1800s for American shad. Perceived declines created the hatchery industry that employed commercial fishers to harvest their eggs. Yet most reports of fishery agencies from the late 1880s through the 1930s stated that overfishing was a continuing problem greatly interfering with natural and artificial propagation.

It was late in this period that the ASMFC was created. In 1943, its objective was to assist in continued harvest of US fishery resources to supply troops during WWII; its motto "food will win the war" (ASMFC 1944). Regulatory management of the Atlantic coast shad stocks through ASMFC would wait another 42 years with adoption of an Interstate Fishery Management Plan (ISFMP) for Shad and River Herring in 1985. Although the ISFMP contained many strong recommendations, following the plan was voluntary. This changed in 1993 with the passage of the Atlantic Coastal Fisheries Cooperative Management Act which mandated compliance by federal law. In 1998, Amendment 1 to the ISFMP included the first interstate regulation to close the mixed-stock ocean fisheries for shad by 2005. The closure took a stepped approach over five years which still allowed further erosion of remaining shad stocks. This proved to be too little too late for the Hudson as young-of-year (YOY) production has remained extremely poor since 2002 (see Fishery-independent data below; Hattala and Kahnle 2007).

3.5.2.4 Assessment History

During the 1930s, the U.S. Bureau of Fisheries conducted a variety of studies on Atlantic shad stocks, primarily tracking landings to assess stock condition (USCFF 1939). However, few study details can be found in Commission reports. The reports recognized that exploitation rates were very high in systems experiencing declines (MD, VA and SC stocks), with over-fishing as the primary reason and not the excuse of pollution or major obstructions. Annual harvest from the Hudson exceeded 2.4 million pounds between 1936 until 1948, peaking at 3.8 million pounds in 1944 (Figure 105). Fishing continued to erode the stock following WWII.

In 1949, the Anadromous Fish Act supported initiation of the Shad Project, a program funded to determine the underlying causes of shad stock declines along the Atlantic coast. Talbot (1954) conducted the sampling program in the Hudson in 1950 and 1951. He determined the primary cause of the decline was over-fishing, blamed on the lapse of fishing restrictions during World

War II and the years following. Exploitation was 0.66 and 0.46 based on mark-recapture population estimates from his tagging efforts.

The first ASMFC assessment of the Hudson stock occurred in 1988 (Gibson et al. 1988). This assessment used a Shepherd stock recruitment model to estimate maximum sustained yield (MSY) and maximum sustainable fishing rates (Fmsy) by using long term commercial catch-effort, age composition and mortality data. It is not clear what natural mortality rate (M) was used. Model fit was poor (R^2=0.35); faulting to primarily significant measurement errors of the stock and recruitment estimates or other unknown or poorly understood factors (Gibson et al. 1988). Exploitation rate (µ) was estimated at 0.31 (fishing mortality=0.37) which was below the value of µ MSY of 0.45, recommended in the 1988 report. For a historical perspective, Gibson et al. (1988) adjusted Talbot's rates in the 1950s due to catchability issues associated with Talbot's use of Peterson disc tags in his mark-recapture study. The adjusted rates were µ of 0.38 and 0.27 for 1950 and 1951, well below the recommended 1988 level of 0.45; however, stock levels in the Hudson continued to decline after 1951. This suggests the recommended µ values from the 1988 assessment were too high for stock stability.

Walters (1995) used growth parameters, the natural survival rate and proportion of variation in relative abundance indices due to measurement error to compute maximum likelihood estimates of the recruitment anomaly sequences for several stocks. His analysis included American shad of the Hudson River. Results showed the Hudson stock had been subject to massive recruitment overfishing since the late 1930s.

In 1997, the Hudson River electric generating companies hired consultants to assess the Hudson's shad stock status as part of their environmental impact statement on power plant operation effects on fishes of the Hudson River (CGH&E 1999). The initial assessment looked at 17 years of data from 1980 to 1997. During an intensive review, this short-term series was expanded to encompass all available data for the Hudson since 1915. Deriso et al. (2000) estimated fishing mortality (F) and calculated equilibrium yield, exploring several hypotheses regarding the spawner-recruit (S-R) relationship. M of 0.3 was used, based on maximum age (13) observed in the Hudson stock. A Beverton-Holt S-R was used with assumptions of low, mid and high levels of density dependence occurring in the stock. Equilibrium calculation showed the stock was fully to over-exploited, unless one assumed high-density dependence. Given that the Hudson shad stock was approaching an all-time historic low stock size, the high-density dependence hypothesis was rejected.

The next coastwide, ASMFC Benchmark Stock Assessment was in 1988 (ASMFC 1998). This assessment generated debate on data inputs, methods, and model assumptions. At the forefront of the debate was the appropriate level of M to use for American shad. The resulting approach used a Thompson-Bell yield per-recruit to calculate a F30 which was defined an over-fishing rate. This was compared to an estimate of "current" F.

Although stock specific data were available for the Hudson, all Hudson yield model inputs in ASMFC (1988) were based on a variant of the Connecticut River shad stock, which are different from the biological stock characteristics observed in the Hudson. The greatest debate on inputs occurred on the value of M. For the Hudson stock, the stock assessment used an M of 0.3 for ages one to three and 0.6 for ages four to ten, although the observed maximum age for Hudson shad was 13. These were best estimates based on what was observed in the Connecticut River shad stock. Current *F* was estimated from an exploitation rate calculated from harvest estimates (combination of in-river plus estimated ocean harvest, both adjusted for underreporting) divided by an estimated population size (scaled from the estimated population size of the Connecticut River shad stock using data from the 1950s). Current *F* was calculated at 0.33, the over-fishing definition of F30 was 0.39. The conclusion was that the Hudson shad stock was not over-fished, but fully exploited.

NY disagreed with the methods used in the assessment and wrote a minority opinion stating inputs and methodology overestimated the over-fishing definition and underestimated the fishing rate. To illustrate their response, the authors used the same methodology to estimate F30 but with inputs that were based on Hudson River data. The major difference was reliance on a value of M based on maximum observed age. Sensitivity analyses on selection of M showed model results were very sensitive to M. For age invariant M, F30 increased with increasing M. F30 was higher where M increased with age than when M declined with age. The authors recommended use of either an age invariant M of 0.3 or an age specific M that decreased with age. F30 estimates in the minority opinion equaled 0.27 based on a constant M of 0.3 and 0.25 based on age specific M. Using this definition of over-fishing compared to current *F* (subtracting 0.3 from catch curve Z's estimated from the observed age structure of Hudson fish), the Hudson shad stock was deemed over-fished since the mid-1980s (Hattala and Kahnle 2007).

The last ASMFC benchmark stock assessment of American shad was completed in 2007 (ASMFC 2007b). This assessment developed total mortality benchmarks (Z30) for specific regions or rivers using simple biomass per-recruit models with regional or river-specific biological inputs. The Hudson River was one of the rivers selected for its own model and had a resulting Z30 estimate of 0.54. Nearly all annual total mortality estimates from catch curves on ages and spawn marks from the Hudson spawning stock in 1984 through 2005 were above this Z30.

In the NY state chapter of the 2007 assessment, the authors also estimated empirical spawning stock abundance (ESSA) and biomass (ESSB) indices for the Hudson from 1985 through 2001 using the relative abundance index of female shad in the fixed gear commercial gill net fishery, the age structure of females in fishery-dependent and independent surveys and the observed annual mean weight at age (Hattala and Kahnle 2007). Results showed spawning stock abundance peaked in 1986, declined through 1993, fluctuated without trend through 1999, and then increased in 2000 and 2001 to roughly half of the 1986 peak value. Estimates of female CPUE were deemed unreliable after 2001 due to small sample sizes in the Commercial Gill Net monitoring program. To potentially extend the time series for these indices, the authors evaluated early life stage indices (EGG, YSL, PYSL, YOY - see section 6b for details) as surrogate indices by a simple linear regression of the early life stage index on the spawning stock index for the period 1985 through 2001. The EGG index correlated best, indicating that a positive relationship existed between the observed female spawning stock and the resulting egg production measured in the river. Estimates of ESSA and ESSB for years 2002 through 2005 were the lowest in the time series.

The overall conclusion of the 2007 stock assessment was that the Hudson shad stock had been subjected to excessive mortalities for at least 20 years, continuing over a century of successive periods of overfishing. The continued poor recruitment and decline in spawning stock biomass did not indicate an immediate recovery in the stock was likely. Recommendations were to restrict all fisheries that may encounter Hudson River shad, including commercial and recreational fisheries in the Hudson as well as any other mixed-stock fisheries that persist along the coast.

3.5.3 System-Specific Life History

3.5.3.1 Maximum Age

American shad of the Hudson River Estuary grew to age 10 in the years following WWII after the stock had experienced a major collapse (Talbot 1954). Recent data from the Hudson River stock indicate that female American shad can reach age 13 and males reach age 10. Maximum age that the Hudson shad stock can attain is unknown because age data are not available from times when the stock was not fished.

3.5.3.2 Reproduction

Spawning begins in the Hudson Estuary in late April when water temperatures reach 15° C. It continues through the month of May and generally ceases by early June. Shad spawn in fresh water, over shallow water shoals that occur in the upper half of the Hudson (km 142 to 240).

Post-spawning mortality for Hudson shad appears to be low (Whalon 1999). Extensive radio and sonic tracking of American shad was conducted in the Hudson River Estuary in 1995 and 1996 (Whalon 1999). Over the two years of the study, 110 fish were captured during immigration to the Hudson, marked and released over several weeks during the spawning period. Shad were tracked over periods of 15 to 40 days after release through the entire spawning season. Field efforts ceased when no more fish could be located. Five fish apparently died (repeatedly found in one location) within 12 to 18 hours of release. Mortalities were assumed to be related to tagging stress from the sonic or radio-gullet applied tag. In 1995, approximately 49% of the 55 radio-marked shad released, were found and followed throughout the spawning season. Results in 1996 improved when 77% of radio-marked fish (n=30) and 84% of sonic-marked fish (n=23) were found and tracked throughout the spawning period. The improved 1996 detection rate resulted from more intensive air and boat surveys. The percent fish listed above for fish tracked during spawning season do not include suspected dead fish. For the live tracked fish, all left the river after spawning suggesting a very low rate of in-river post-spawn mortality for the Hudson stock. Residence time for adult shad in the Hudson following tagging was found to be approximately 19.8 days.

Percent of repeat spawning in the Hudson River stock varies among years. Fifty percent of female shad evaluated from the fishery-independent spawning stock survey have repeat spawn marks, with an annual maximum of 69% in 1984. Just over 40% of all males evaluated have repeat spawn marks, and the maximum annual value was 71% in 2012. The maximum spawn marks observed for an individual female is seven and for an individual male is six.

3.5.3.3 Maturity

Deriso et al. (2000) estimated the maturity schedule using a likelihood function on age and repeat spawn data of Hudson River shad (Table 58). This approximates the same results of calculating age at first spawn (age minus the number of repeat marks) from all age data, to arrive at an approximation of percent at age at first spawn.

3.5.3.4 Fecundity

The first estimate of fecundity for Hudson River shad was from samples taken in the 1950s (Lehman 1955), after the stock had collapsed following WWII. Sample size was small, only 22 fish. Piper (2003) completed a study of fecundity of Hudson River American shad. Samples collected in 2000 and 2001 showed a wide range of variability at age within year and differences among years. Overall, the fish collected in 2000 and 2001 had higher fecundity estimates than those collected in 1951 (Table 59). It is not clear why the results of these studies are so different. Sample size may have contributed to the differences. Few samples were collected in 1951, yet fecundity was found to be directly proportional to age (R=0.98), length and weight of the fish. The more recent sample of 105 fish taken in 2000 and 2001 was larger. The relationship between fecundity and age was positive, but not as highly correlated to age (R = 0.69), as the 1951 data.

Of important note, Lehman (1955) recognized that shad are indeterminate spawners or "… have a multi-spawning or continuous period of spawn, rather than a single spawning act." A phenomenon recently confirmed by Hyle et al. (2014) for shad of the Mattaponi River in Virginia. Both Lehman (1955) and Hyle et al. (2014) suggest traditional fecundity estimates may only measure a portion of the total egg production of a female in any given year.

3.5.4 Anthropogenic Sources of Mortality and Productivity

3.5.4.1 Water Quality

The Hudson has a very long history of abuse by pollution. New York City Dept. of Environmental Protection recognized pollution, primarily sewage, as a growing problem as early as 1909. By the 1930s raw sewage from roughly 6 million people was being discharged in the lower Hudson (Brosnan et al. 1999).

New York City was not the only source of sewage. Most major towns and cities along the Hudson added their share. It was so prevalent that the Hudson was often referred to as an open sewer. Biological demand created by the sewage created oxygen blocks that occurred seasonally in some sections of the river. One of the best-known blocks occurred near in the 1960s and 1970s, located near Albany in the northern section of shad spawning and nursery habitat. This block often developed in late spring and remained through the summer months. It essentially cut off the upper 40 kilometers of the Hudson for use as spawning and nursery habitat. A second oxygen block also occurred in the lower river near New York City in late summer. This block could potentially have affected emigrating age zero shad. This summer oxygen-restricted area occurred for decades until 1989 when a major improvement in a sewage treatment plant came on line in upper Manhattan. It took decades but water quality has greatly improved in both areas since the implementation of the Clean Water Act in the 1970s (Brosnan et al. 2006).

There are also persistent chemical pollutants in the Hudson's legacy. The best known and most pervasive chemical is PCB (polychlorinated biphenyl) contamination that remains today. The major source of the chemical is an area approximately 40 kilometers north of the Troy Dam, where General Electric discharged up to 1.3 million pounds of PCB's into the river for over 25 years beginning in the 1940s. The EPA declared 322 kilometers of the Hudson below Hudson Falls and Fort Edward, NY a Superfund site in the 1970s and called for targeted dredging of the 65-km section between Fort Edward and Troy in a 2002 Record of Decision (USEPA 2002). A GE funded dredging project began in 2009 and ended in 2015. Monitoring of PCB levels in the water column, sediments, biota, and floodplain habitats throughout the Hudson River watershed will continue into the foreseeable future.

A host of other environmental contaminants have also been found in Hudson River biota, including PBDEs, PCCDD/Fs and PBDD/Fs in smallmouth bass and striped bass (Skinner 2012); Strontium in several fish species (NYSDEC 2010) and Cadmium and Mercury in blue crabs (Skinner and Kane 2016).

3.5.4.2 Habitat Alteration

The historical upstream limit for anadromous fish in the Hudson River was the natural falls at Fort Edward, NY (Zeisel 1988). Natural falls at the confluence of the Mohawk River and the Hudson prevented fish from moving into the Mohawk System. With the rise in commercial shipping at the beginning of the 19th century, there was a desire to connect the ocean-going ships to Midwestern states. The Erie Canal was completed in 1825, linking the Hudson River near Waterford, NY (roughly 5km north of Troy, NY) to the Great Lakes through a series of locks mostly within the Mohawk River system. Today the Erie Canal consists of 34 locks from Waterford to the Niagara River. In addition, six hydropower facilities are now in operation along the Mohawk corridor.

During the same time period as the Erie Canal construction, there was a push to move timber and other commodities from Canada and northeastern states to New York and then on to Midwestern states. The Champlain Canal was finished in 1823 linking the upper Hudson River to Lake Champlain. The current Champlain Canal consists of eleven locks operated from Waterford, NY to Whitehall in Lake Champlain.

At the downstream end of the Erie and Champlain navigation corridors, a 3-m-high dam was constructed in 1826 at Troy, NY, roughly 56 kilometers from the traditional head of tide at Fort Edward. This dam was made of log cribwork and filled with stone; likely impassable for shad at all but the highest spring floods (Stevenson 1899). In 1915, the US Army Corps of Engineers replaced the old dam with a new concrete structure, which included a lock. In 1921, a hydropower unit was fitted to the dam. Undoubtedly, American shad spawning and nursery habitat was lost after the construction of the Federal Dam at Troy. However, any passage or improved passage of fish above this dam would provide just under nine additional kilometers or 3.5% of habitat before the next lock and dam system (C1) on the upper Hudson River north of Waterford, NY. Movement above the Federal Dam would expose adults and YOY to mortalities associated with both upstream and downstream passage at the hydropower facility, a cost that may outweigh the benefits of a minimal increase in habitat. Furthermore, the huge commercial landings reported in the late 1800s as well as the 1930s and 1940s indicate that spawning and nursery habitats in the 245 river kilometers below the Federal Dam are enough to support large populations of American shad.

Through the middle of the 19th century, the northern third of the estuary below the Federal Dam at Troy, NY was a braided river-channel system dominated by vegetated shallows and intertidal wetlands. Side channels in this section provided important shallow water and intertidal habitats that were isolated from the higher energy regime of the main channel. Unfortunately, these habitats were largely altered by the early twentieth century due to the dredge and fill activities associated with construction and maintenance of the federal navigation channel allowing ocean vessels to reach Albany. Miller et al. (2006) approximates 57% of the braided, intertidal shallow water habitat (1,821 hectares) found north of the City of Hudson (km 190) was lost during this time period.

Another factor that is not well researched or understood is the potential barriers posed by the railroads along both the east and west sides of the Hudson River. Tributaries once flowed freely, with unobstructed hydraulics, from the upland valley to the wide estuary. While these connections still exist, they are much different today than they were historically. Tributaries are forced through bridge and culvert constrictions under the tracks as they make their way to the Hudson River. The impact of this funneling effect on water quality and access from the Hudson into tidal tributary mouths is not well understood.

The Hudson River Estuary Habitat Restoration Plan (Miller 2013) identifies a number of river and tributary restoration activities that will benefit alosines, including barrier mitigation and side channel restoration, the latter of which having the biggest impact for shad. The first of these side channel restoration projects was completed in July 2018 at Gay’s Point (km 196), near Coxsackie, NY (HRNERR 2019). The site originally consisted of an artificially created tidal embayment that was separated from the main river channel by dredge spoils. A channel was excavated through the dredge spoils to reconnect the northern end of the bay to the main-stem Hudson River. Increased tidal flow through the embayment should improve water quality, provide coarser-grained bed materials, and likely improve the quality of nursery habitat for juvenile fishes in this river section.

Hudson River tributaries provide important habitat to both migrating and resident fishes, as well as other wildlife. Barriers to upstream and downstream movement exist in tributaries to the Hudson River, many of them in relatively short distance upstream from the confluence with the Hudson River. While many of these barriers are natural features, such as waterfalls and ledges, there exist numerous anthropogenic barriers, including dams (some opportunistically built on top of existing natural barriers), undersize and improperly positioned culverts, and undersized bridges. Thus, many opportunities exist to remove man-made barriers in order to restore historical upstream and downstream access to important habitats for both diadromous and resident fishes. Based on NOAA's 2009-2014 evaluation of 67 lower Hudson tributaries, the first barrier upstream from the Hudson is man-made on 27 tributaries, while 37 are natural and three are undetermined (Alderson and Rosman 2014). After further assessment to consider where barrier removal is practical and beneficial to alosines, this research estimated that 56 tributary kilometers have the potential to be opened to river herring via the removal of 27 barriers on 14 tributaries. The largest gains in total stream miles can be found on the following five tributaries: Claverack, Croton, Moodna, Rondout, and Sparkill Creeks. Restoration opportunities on these five tributaries could enhance access to alosine habitat for an estimated 35.8 kilometers. Removal of man-made barriers in the Hudson River Estuary is a high priority because of the potential for habitat gains.

3.5.4.3 Invasive Species Introductions

Five piscivores are native to the freshwater, tidal Hudson River (Daniels et al. 2011). Beginning in 1830 through present day, at least 10 additional piscivores have been introduced to the Hudson, including voracious predators such as black bass (introduced in 1830s), Northern pike (1840s), walleye (1890s), and channel catfish (1976) (Daniels et al. 2005). The addition of these piscivores has likely impacted the recruitment of alosines; however, the magnitude and rate of predation by these species on juvenile and adult alosines in the Hudson River has yet to be fully explored.

Water chestnut, an ornamental macrophyte native to Eurasia, was introduced to the Hudson River estuary in the 1930s (Strayer 2006). This plant outcompetes native macrophytes such as water celery, forming expansive, dense mats in most of the shallow water embayments in the tidal freshwater portions of the river. Sedimentation and turbidity within these mats are greatly increased and the dissolved oxygen levels within the mats is much lower than surrounding waters (Strayer 2006), favoring species with wide tolerances for unfavorable environmental conditions (Schmidt and Kiviat 1988). The establishment of these immense water chestnut mats each summer significantly reduces the amount of near-shore nursery habitat available to YOY alosines, cutting off areas that would likely have remained more productive with native macrophyte beds.

The introduction of zebra mussels in the Hudson in 1991, and their subsequent explosive growth in the river, quickly caused pervasive changes in the phytoplankton (80% drop) and micro- and macro-zooplankton (76% and 50% drop respectively) communities (Caraco et al. 1997). Water clarity improved dramatically (up by 45%) and shallow water zoobenthos increased by 10%. Given these massive changes, Strayer et al. (2004) explored potential effects of zebra mussel impact on YOY fish species. Most telling was a decrease in observed growth rates and abundance of YOY fishes, including open-water species such as alewife and blueback herring. A decade later, Strayer et al. (2014), reported on the improvement in zooplankton and macrobenthos inhabiting deep water, indicating that abundance of juvenile alewives increased during the late zebra mussel invasion period while post-yolk sac larval abundance did not. The abundance of post-yolk sac and juvenile American shad and post-yolk sac river herring declined during the early to later zebra mussel invasion period. It is not yet clear how this constraint affects survival and subsequent recruitment.

3.5.4.4 Water Withdrawals

American shad, and other fish, are negatively impacted by water withdrawals on the Hudson River. Shad are killed both on the impingement screens of these sites and as they are entrained in the cooling water of steam electric plants. Steam electric plants alone are permitted to use nearly 5 billion gallons of Hudson River water per day.

A river-wide ichthyoplankton survey occurred annually in the Hudson River Estuary through 2016, conducted by consultants under contract with the Hudson River Generating companies. In order to better define impacts of the once-through cooling systems on fish, estimates of mortality on various ichthyoplankton life stages were calculated using two models, the Empirical Transport Model and the CEMR (Conditional Entrainment Mortality Rate) model. Detailed methodology for both models can be found in CHG&E et al. (1999).

Estimates of mortality are expressed as conditional entrainment mortality rates, or the percent reduction in a year-class which would be due to mortality from entrainment through once-through cooling water systems if no other causes of mortality operated. Loss estimates for the Hudson River Estuary include one major office complex air conditioning unit, two nuclear, one waste-fuel, and five fossil-fuel power plants located throughout the Hudson Valley above New York City. CEMR at these facilities combined has ranged from 16% to as high as 52% during the period 1974 to 1997 (Table 60). An estimated average of 20% was assumed for the period 1952 to 1973 when major power plant once-through cooling systems came on line (CHG&E et al. 1999).

In years since the 1999 study, reduction in year-classes of American shad have probably been reduced due to changes at a variety of locations. Several plants (i.e., Bowline, Danskammer, and Roseton) operated at less than 30% of capacity for most of the period from 2010-2016. Athens Generator uses a dry cooling system requiring no water from the Hudson River for cooling. Water withdrawal at Lafarge Cement Plant in Bethlehem is located in the area of the river most vulnerable for developing shad larvae. Water withdrawal at this site is 25% of what it was in the late 1990s and impingement and entrainment have been effectively eliminated by the use of wedgewire intake screens. The Albany Steam Electric Plant (now called Bethlehem Energy) was repowered and uses a hybrid closed cycle cooling system with a water intake fitted with wedgewire screens. This has nearly eliminated the impingement and entrainment of fish at this location.

Scheduled improvements will also have positive impacts for American shad. Indian Point Energy Center (IPEC) is scheduled to close in 2021 and will vastly reduce the amount of water required at that site. IPEC is currently permitted to use more than 2 billion gallons of water per day. The Empire Plaza operates a once through cooling system at Albany, withdrawing approximately 90 million gallons per day for air conditioning purposes. A recently issued SPDES permit requires the intake to be fitted with a wedgewire screen system which will eliminate impingement and nearly eliminate entrainment at this site.

3.5.5 Fishery-Dependent Data Sources

3.5.5.1 Commercial

3.5.5.1.1 Landings and License Reporting

The best compilation of landings records for Hudson River shad is found in Table 56. Unless noted, all landings represent New York and New Jersey landings in Hudson River counties only. Records listed from 1880 to 1915 are from a variety of sources including the 1895 NY Fish and Game Commission Report, Talbot (1954) and Stevenson (1899). Landings from 1915 through 1949 come from Talbot (1954). Landings from 1950 to 1961 are all NY county landings plus all non-drift gill net NJ landings reported by NOAA Fisheries. New Jersey fishers in the Hudson River used predominantly fixed gill nets (Talbot 1954), while fishers in Delaware River and Bays mostly used drift gill nets (estimated from NOAA Fisheries landings by county in the 1960s). Landings from 1962-1994 come from NOAA Fisheries reports for Hudson River counties in NY and NJ. From 1995 to the present, NYSDEC has summarized in-river landings from mandatory state catch reports for Hudson River commercial fishing licensees. Though historical records of licensed fishermen and amount of nets licensed do exist (see Talbot 1954 or Klauda et al. 1976), record keeping was not consistent over time and there is little information on actual versus presumed use of gear. It wasn’t until 1995 that the true recording of effort data was phased in on reporting forms. Full compliance for reporting of fishing effort was implemented in 2000. Up until the fishery closure in 2010, commercial monitoring data were used to verify and adjust reporting rate for the mandatory reports. A reporting rate of 74% was described in Hattala et al. (1998).

3.5.5.1.2 Commercial Gill Net CPUE

The Hudson River Fisheries Unit monitored the in-river commercial fishery annually from 1980 through 2010. Technicians attempted to be on board fishing vessels on all fishery days. When aboard, they recorded data on numbers of fish caught, gear type and size, and fishing time, location and water temperature. Scale samples, lengths and weights were taken from a sub-sample of each trip’s catch. Net effort was calculated as square yards multiplied by hours fished times 10-3.

Fishing effort declined across the time-series and monitoring trips were very low after 2001. Reduced sample size in the fixed gear fishery occurred because fishers changed fishing patterns as shad became more difficult to catch (presumably due to low numbers) and fishers tried to avoid catching abundant striped bass, which were not allowed to be retained or sold due to regulations stemming from PCB contamination. In the NY Chapter of the 2007 ASMFC Stock Assessment, NY authors found catch rates of both species were positively correlated, indicating gear saturation by striped bass was not a factor in shad catch rates. However, large catches of striped bass often resulted in gear destruction (ripped meshes, large holes) along with an increase in time-consuming labor to remove the bass. To avoid these problems, many fishers either reduced effort or gave up fishing entirely.

1. Commercial Discards: The observed discard of female shad in the Hudson River gill net fishery was relatively low (Table 61). The fishery used mesh sizes that optimized catches of females which were targeted for their roe. For males, the discard rate varied over time, by gear and market demand; however, due to gear selectivity, males made up only a small proportion of the total catch of both gears.

2. Catch Rates: The CPUE of the fixed gear fishery provides the best estimate of relative abundance as it presents the most accurate picture of shad moving into the river to spawn. Fixed gear was always fished in approximately the same locations in the lower Hudson each year, was passive in nature and intercepted fish that moved through the area to get to freshwater spawning areas. The CPUE in the drift fishery was more variable because it was an active gear that could be set directly into a school of fish. Catch rates of the fixed gill net fishery are calculated in two methods: (a) an annual sum of weekly CPUE and (b) a generalized additive model.

    a. Sum of weekly CPUE: Data within week is summarized as total weekly catch divided by total weekly effort (square yards x hours fished x 10-3). Annual CPUEs are then calculated as the sum of the weekly CPUEs (Table 62, Figure 106). This method accounts for any periodicity in density of spawners as well as duration of the run, mimicking area under the curve calculations where sampling occurs in succeeding time periods. Because the fishery is predominantly targeting females, the CPUEs are split by sex. Annual CPUEs after 2001 should be used with caution due to the low number of annual trips. All mesh sizes are included in this analysis.

    b. Generalized additive model (GAM): Generalized linear modeling provides a way to account for covariates that may impact catch rates due to sampling design as well as prevailing environmental conditions. Both generalized additive models and generalized linear models were evaluated for the commercial monitoring data set. To mimic historical CPUE indices, the data set was subset for monitoring trips of fixed gill net fishers in the brackish section of the Hudson River. Data were also subset for 5.5-inch stretch mesh, which was the most consistently sampled mesh across all survey years. As this mesh size generally is selective for females, only female catches were used as the count data for modeling. Due to low sample sizes after 2001, any monitoring trips after 2001 were removed from the data set.

       Initial models included the following covariates: year, Julian day, river kilometer, water temperature, and daily flow. Effort was included as an offset. Additional filtering was also done for these covariates. Data were trimmed to include the most consistently sampled ranges of each variable. The final standardized model was selected through evaluation of AIC, dispersion and percent deviance explained. The best performing model was a negative binomial GAM with female catch predicted as a function of year, Julian day, river kilometer, water temperature and effort as an offset. Table 63 shows the predicted annual catch rates from the model, while Figure 107 shows a comparison of annual GAM female CPUEs with the AUC female CPUEs.

Despite the high annual CVs (0.21-0.34), GAM index is preferred over the area under the curve index (AUC) due to its inclusion of important covariates with catch; however, it should be noted that the AUC method is more highly correlated with other surveys. The commercial monitoring trips used in this analysis took place in the spring in the lower Hudson, where there is high inter- and intra-annual variation with flow and water temperature. The GAM predictions potentially account for some of this variability as well as any bias that may result from the sampling strategy. This method also allows for an easier calculation of error structure around each annual mean.

3. Biological characteristics of the commercial catch: Table 64 lists the mean weights and lengths of the commercial catches by sex, while Table 65 lists the numbers at age by sex. Ages through 1995 are estimated from scales; ages 1995-2001 are estimated from age-length keys. Biological data for years 2002-2009 are not provided as sample coverage was poor and data were likely not representative of the fishery.

3.5.5.1.3 Evaluation of Survey Data

To mimic historical CPUE indices, the data set was subset for monitoring trips of fixed gill net fishermen in the brackish section of the Hudson River. In addition, data were subset for 5.5 inch stretch mesh, which is the most consistently sampled mesh across all survey years. As this mesh size generally is selective for females, only female catches were used as the count data for modeling. Finally, due to low sample sizes after 2001, any monitoring trips after 2001 were removed from the data set.

Generalized linear modeling provides a way to account for covariates that may impact catch rates due to sampling design as well as prevailing environmental conditions. Both generalized additive models and generalized linear models were evaluated for the commercial monitoring data set. Initial models included the following covariates: year, Julian day, river mile, water temperature, and daily flow. Some filtering was also done for these covariates. Data were trimmed to include the most consistently sampled ranges of each variable. The final standardized model was selected through evaluation of AIC, dispersion, and percent deviance explained. The best performing model was a negative binomial GAM with catch predicted as a function of year, Julian day, river mile, and water temperature. Despite the high annual CVs (0.21-0.34), the SAS was more confident using the GAM index over the nominal indices. Because this survey takes place in the spring in the lower Hudson, there is a lot of inter and intra-annual variation with flow and water temperature. The GAM predictions potentially account for some of this variability as well as any bias that may result from the sampling strategy.

Model predictions of mean number of adult, female shad captured per year in commercial nets ranged from 2.53 – 13.27 with a 25th percentile of 3.58, median of 6.08 and a 75th percentile of 8.99 (Table 63, Figure 107). There is a slight increasing trend in the time series (slope = 0.0618; R^2 = 0.0143), but there are noticeable trends across several shorter periods of years. Relative abundance values are low for four of the first five years of the survey, then increase to a peak in 1988. Relative abundance drops to low levels until 1995, which has the highest relative abundance value in the time series. Following this peak, relative abundance remains low until the final two years of the data set where catch rates are on par with the highest values in the time series.

3.5.5.2 Recreational Creel Survey

The magnitude of the recreational fishery is unknown for most years. NYSDEC contracted with Normandeau Associates, Inc. to conduct recreational creel surveys on the Hudson in 2001 and 2005. Table 57 lists the effort and catch rates from these two creel surveys.

3.5.6 Fishery-Independent Data Sources

3.5.6.1 Adult Fishery-Independent Data Sources

3.5.6.1.1 Spawning Stock Survey

Spawning Stock Haul Seine Survey

Since 1984, spawning populations of American shad have been sampled by haul seines, which exhibit relatively low size selectivity in sampling fish when compared to other gear types (Kahnle et al. 1988). The fish sampled in this program best represent the spawning stock, or production portion of the population which has escaped coastal directed, coastal intercept, and in-river commercial fisheries (Hattala and Kahnle 2007).

From 1984-1988, a 305 m haul seine was the primary gear. Beginning in 1988, a 152 m haul seine was used and has continued to be the main gear used in this survey. Sampling is concentrated near known spawning areas and at beaches where adults are susceptible to capture by shore gear. Approximately 75 to 100 haul seine collections are made annually. Collections occur from April through the first week of June at sites located between km 88 and 224.

Captured fish are transferred to a floating live car after which they are identified to species, sexed, measured, weighed and scale samples taken. Water quality data such as temperature, salinity, pH, dissolved oxygen, conductivity and total dissolved solids are taken at each station. In addition, prevailing conditions such as tide, wind speed, wave height, cloud cover and vegetative cover are also recorded at each seine event.

Spawning Stock Electrofishing Survey

In recent years, there has been an increased effort to sample the spawning stock in the known aggregation area below the Federal Dam at Troy. Due to the swift current and bottom obstructions, sampling must be done using an electrofishing boat. Initial comparisons of proportion at lengths and ages by sex indicate biological data for electrofishing and haul seine gears can be combined in size and age analyses; however, these gear evaluations will be bolstered by more years of data. The electrofishing survey catch rates are not considered representative of interannual abundance changes and were not used in the assessment for abundance trend analyses (Table 16).

Size and Age Distribution

Mean lengths and weights of the fishery-independent Spawning Stock Haul Seine Survey samples are found in Table 66. Data are split by sex. Annual age and spawning mark characteristics are in Table 67 and Table 68, respectively. Mortality and survival estimates using scales and spawning marks are listed in Table 69. Age or repeat spawn marks with the highest abundance were the initial values in mortality calculations.

Catch rates

Catch rates from Spawning Stock Haul Seine Survey have not been used in previous assessments to track spawning stock abundance due to a lack of validation with other abundance surveys. It was thought the survey methods were not appropriate for abundance estimation, with the primary objective of the survey to capture and tag striped bass for coastwide mortality studies. However, this survey remains the longest running survey to capture the spawning stock in the Hudson, the gear used is non-size selective and the survey covers a large portion of the spawning reach. Catch rates from this survey were once again evaluated, in hopes that a longer timeframe would benefit validation analyses. Fortunately, generalized linear modeling provides a way to account for covariates that may impact catch rates due to sampling design as well as prevailing environmental conditions. Both generalized additive models and generalized linear models were evaluated for males, females and sexes combined.

During initial covariate exploration, many variables were eliminated due to the brevity of the time series of collection. These include salinity, dissolved oxygen, TDS, pH and vegetative cover, which were not recorded until the 1990s. 'Sampling region' was selected over river kilometer as there are large sections of river kilometers that are not sampled in the time series, creating potential issues with using river kilometer as a continuous variable in the models. Sampling reach was also inconsistent among years as sampling sites have moved northward as the time series progresses. Therefore, the regional variable was split into two factors: 'north' and 'south'. The breakpoint in the river is km 160.

Initial models included the following covariates: year, water temperature, time of day, tide stage, daily flow, region, and Julian day. Some filtering was also done for these covariates. Data were trimmed to include the most consistently sampled ranges of each variable. The final standardized model for each sex was selected through evaluation of AIC, dispersion and percent deviance explained. The preferred model for all sexes combined was a negative binomial GAM with catch predicted as a function of year, tide stage, time of day, region, Julian day and daily flow. The same model was the best fit for male shad. The optimum model for female shad included all the covariates in the sexes combined model except for the flow variable. All indices are shown in Table 70 and Figure 108.

Evaluation of Survey Data

This survey is not designed for relative abundance estimation and its catch rates have not been used in previous assessments to track spawning stock abundance. For much of the time series, the primary objective of the survey has been to capture and tag striped bass and American shad with external tags for coastwide mortality studies. Sampling takes place in known aggregation areas and sites are often resampled within a sampling the day. Within a year, sampling is initially spread out among different freshwater reaches of the Hudson River; however, as the season progresses, sampling efforts often become focused on the specific reaches and sites with the highest catch rates. With the closure of the Hudson River American shad fishery in 2010, shad tagging was eliminated from the survey and more focus went toward tagging striped bass. Beginning in 2017, efforts to target shad increased and external tagging was reinstated to further understand potential sources of mortality outside of the Hudson River.

Another caveat to using this survey as an abundance index is the timeframe. The YOY 3/8" Seine Survey and Commercial Gill Net CPUE both show the early to mid-1980s to be their highest years of relative abundance. Unfortunately, the gear change means that the time series begins in 1988, when the population had already started showing signs of overfishing (Hattala and Kahnle 2007). Therefore, there may be minimal contrast within the time series as the population was likely overfished for most years in the index.

Fortunately, generalized linear modeling provides a way to account for covariates that may impact catch rates due to sampling design as well as prevailing environmental conditions. Both generalized additive models and generalized linear models were evaluated for this data set. During initial covariate exploration, many variables were eliminated due to the brevity of the time series of collection. These include salinity, dissolved oxygen, TDS, pH, and vegetative cover, which were not recorded until the 1990s. 'Sampling region' was selected over river mile as there are big sections of river miles that are not sampled in the time series creating potential issues with using river mile as a continuous variable in the models. Sampling reach was also inconsistent among years as sampling sites have move northward as the time series progresses. Therefore, the regional variable was split into two factors: 'north' and 'south'. The breakpoint in the river is river kilometer 160.

Initial models included the following covariates: year, water temperature, time of day, tide stage, daily flow, region, and Julian day. Some filtering was also done for these covariates. Data were trimmed to include the most consistently sampled ranges of each variable. The final standardized model was selected through evaluation of AIC, dispersion, and percent deviance explained. The best performing model was a negative binomial GAM with catch predicted as a function of year, tide stage, time of day, region, Julian day and daily flow. Despite slightly higher annual CVs, the SAS was more confident using the GAM index over a standard geometric mean as it potentially accounts for some of the biases associated with the sampling strategy.

Model predictions of mean number of adult shad captured per year ranged from 0.3 – 24.2 with a 25th percentile of 0.8, median of 1.28 and a 75th percentile of 2.42 (Figure 108). There is an overall declining trend in the time series (slope = -0.2334; R^2 = 0.1867); however, patterns emerge when breaking the data set into shorter stanzas. Relative abundance values are relatively stable from 1988 through 2005, exceptions being the high catch rates in 1992 and 1993. Excluding those peaks, the predicted catch rates are roughly 4.6 shad per haul across that time frame. From 2006 to 2016, catch rates fall well below the median catch rate. This decline correlates well with the sharp decline and continued low level of abundance observed in the YOY American shad relative abundance index. This index also overlaps in time with the Hudson River Commercial CPUE index; however, the two indices do not track well. The Commercial CPUE index tracks relative catch rates (fixed gill nets) of the female spawning stock in the brackish portion of the Hudson River, well below the known spawning areas. This is contrasted with the Haul Seine index which captures both sexes with a less size selective gear in areas adjacent to known spawning/aggregation areas. The Commercial CPUE sampling strategy likely produces a more reasonable abundance estimate as there is the potential to intercept the entire spawning stock on their way into the river, rather than focusing on aggregation areas. Unfortunately, the Commercial CPUE time series ends in 2001, when commercial fishing effort sharply declined in the river and sample sizes of commercial monitoring trips became very low.

3.5.6.1.2 American Shad Tagging Program

In 1995, New York initiated a three-year, large scale (greater than 1500 shad tagged per year) tagging program within the Hudson River to estimate population size and exploitation rate on the Hudson shad stock. These estimates were never achieved because of the failure to meet many modeling assumptions due to the Hudson River being such an open system. A complete description of methods and results is found in Hattala et al. (1998). Abundance estimates ranged from several hundred thousand to over one million fish, depending on the model used.

Tagging of adult shad continued in the Hudson River during the annual spawning stock survey until the fishery closure in 2010. Due to an increased interest in fisheries that may intercept Hudson River American shad, tagging resumed in 2017. The consistent annual data on released and recaptured tagged fish allowed the calculation of annual survival rates using the software program MARK for most years prior to the closure (White 1998). Only three fish have been recaptured since tagging resumed in 2017; recent data have not been analyzed using MARK.

3.5.6.2 Young-of-Year Fishery-Independent Data Sources

3.5.6.2.1 NYSDEC Hudson River YOY 3/8" Seine Survey

Survey Methods

Since 1980, the NYSDEC has sampled YOY American shad in the Hudson River Estuary. In the first four years of the program, sampling was river-wide (km 0-252); occurring bi-weekly from August through October. The sampling program was altered in 1983 to concentrate in the tidal freshwater mid and upper portions of the Estuary (km 88-225), the major nursery area for young shad. Timing of sampling changed in 1985, with the survey beginning in late June or early July and conducted biweekly through late October each year. By 1989, the fixed stations were settled within these river sections and minimal changes have taken place since. Gear is a 30.5 m by 3.1 m beach seine with 0.64 cm stretch mesh. Sites are sampled during the day at approximately 28 standard sites in the freshwater tidal reaches of the Hudson River.

Biological and Environmental Sampling

Captured fish are transferred to a bucket after which they are enumerated by species and life stage (YOY or older). Water quality data such as temperature, salinity, pH, dissolved oxygen, conductivity and total dissolved solids are taken at each station. In addition, prevailing conditions such as wind speed, wave height, cloud cover and vegetative cover are recorded at each seine event.

Catch rates

This survey provides a relative abundance index for YOY American shad in the freshwater tidal section of the Hudson. The nominal index is an annual geometric mean catch per haul that encompasses the entire time series and incorporates all hauls. An additional standardized index was evaluated using generalized linear modeling to evaluate covariates that may affect species presence and catch rates.

i. Geometric mean index: The traditional catch rate metric for this survey has been the geometric mean (Table 70). A value of one is added to all catches to account for zeros in the calculation. The standard errors of the mean are calculated using a jackknife method provided by Gary Nelson of the MA DMF.

ii. Generalized linear model: For this stock assessment, an additional standardized index was evaluated using generalized linear modeling to evaluate covariates that may affect species presence and catch rates. During initial covariate exploration, many variables were eliminated from the data set due to the brevity of the time series of collection. These included turbidity, salinity, dissolved oxygen, TDS, pH and vegetative cover which were not recorded until the 1990s. Region was also removed as all regions were not consistently sampled in 1987, an important year for the time series. The initial model that was examined included the following covariates: year, water temperature, time of day, tide stage, daily flow and Julian day. Some consideration also went into choosing the start year of the index which was 1983, as it was the year the survey concentrated on the freshwater portion of the river. There is limited sample size data from freshwater reaches in prior years.

    The final standardized model was selected through evaluation of AIC, dispersion and percent deviance explained. The best performing model was a negative binomial GLM with catch predicted as a linear function of year, water temperature, time of day, tide stage and Julian Day. The resulting trends in abundance of the standardized model are very similar to the nominal geometric mean index, with the biggest differences in years 1994, 1996 and 2000-2004 (Figure 109). The annual CVs for the standardized index are consistently lower using this model (Table 71). The GLM index is the preferred NYSDEC YOY index for this assessment.

Evaluation of Survey Data

This survey provides a relative abundance index for YOY American shad in the freshwater tidal section of the Hudson River. The nominal index is an annual geometric mean catch per haul that encompasses the entire time series and incorporates all hauls. An additional standardized index was evaluated using generalized linear modeling to evaluate covariates that may affect species presence or catch rates. During initial covariate exploration, many variables were eliminated from the data set due to the brevity of the time series of collection. These included Secchi readings, salinity, dissolved oxygen, TDS, pH and vegetative cover which were not recorded until at minimum the 1990s. Region was also removed as all regions were not consistently sampled in 1987, an important year for the time series. The initial model examined included the following covariates: year, water temperature, time of day, tide stage, daily flow and Julian day. Some consideration also went into choosing the start year of the index. The start were was determined to be 1983, as it the year the survey concentrated on the freshwater portion of the river. There is limited sample size in freshwater reaches in prior years.

The final standardized model was selected through evaluation of AIC, dispersion, and percent deviance explained. The best performing model was a negative binomial GLM with catch predicted as a linear function of year, water temperature, time of day, tide stage, and Julian Day. The resulting trends in abundance of the standardized model are very similar to the nominal index, with the most deviance between the two occurring after 1995. The annual CVs for the standardized index are consistently lower with the standardized model. The SAS concluded that the standardized index provided the best estimate for YOY relative abundance in the Hudson River.

Model predictions of mean number of YOY shad captured by beach seine ranges from 2.4 – 79.8 with a 25th percentile of 7.2, median of 18.4 and a 75th percentile of 41.0 (Table 71). There is a sharp, declining trend in the time series (slope = -1.599; R^2 = 0.5021), with the most noticeable shift in abundance beginning in 2002 (Figure 109). Catch rates increase from 1983 to 1986, followed by relatively high abundances through 1992. From 1993 through 2001 relative abundance is variable with both high and very low values. In 2002, relative abundance drops to very low levels and remains low through the rest of the time series. The only exception is a moderate increase in relative abundance in 2014; however, values in subsequent years are equivalent to the rest of the time series since 2002.

3.5.6.2.2 Hudson River Utility Surveys

Additional data on year class abundance in the Hudson Estuary are available. From 1974 through 2016, trawl and seine surveys provided shad abundance measures of all early life stages: EGG, yolk-sac larvae (YSL), post-yolk-sac larval (PYSL), and age zero (YOY) fish in a beach seine survey (BSS) (Table 72). These surveys were annually performed by contractors for the Hudson River Generating (HRG) utility companies (ASA 2016). The Long River Survey (LRS) sampled ichthyoplankton river-wide from the G. Washington Bridge (km 19) to Troy (km 246). Gears used were a 1-m epibenthic sled or a 1-m Tucker trawl. Ichthyoplankton were sampled from all strata (shore, shoals, bottom and channel). Each larval index is the density of eggs or fish collected per 1000 m3 of water sampled river-wide. The HRG Utility YOY Seine Survey (Utility YOY Survey) randomly sampled beaches in thirteen river segments spread out over the entire 246 km of river, from July through October. It was designed to sample for young of the year striped bass. The seine used is similar to the NYSDEC YOY 3/8" Seine Survey program, except that the stretch mesh size is slightly larger (0.95 cm rather than 0.64 cm).

All juvenile abundance measures (EGG, YSL, PYSL, Utility YOY, and DEC YOY) contain some degree of uncertainty in measurement accuracy due to life stage habitat preference, sample gear and sample timing. The EGG index may only measure a portion of the total production as the sampling gears can only sample along the spawning shoals and not over them (most areas are too shallow for the sampling vessel). The YSL index has similar problems; fish are still small enough to be on the shoals, limiting the accessibility to sampling gear. Their catchability, along with eggs, is also influenced by existing flow conditions. In addition, the sampling period of one week is likely longer than the life stage cycle, especially in later weeks with warmer water temperatures. By the PYSL stage, larvae can move and may be differently distributed as they begin to choose a preferred location. YOY have the greatest mobility choice. The two YOY beach seine programs are different from each other. The NYSDEC YOY 3/8" Seine Survey samples beaches within the freshwater nursery area (Newburgh, km 88 and north) whereas the Utility YOY Survey had random site design, sampling a variety of habitats, not necessarily where shad could be found. Sampling was highly concentrated in the brackish water portion of the Hudson. The Utility YOY Survey began in August for most years of the survey (1974 through 1997), then changed to a similar timing as the NYSDEC survey until the survey ended in 2016.

Final catch rates for the egg and post-yolk-sac larval surveys are provided in Figure 115 and Figure 116, respectively.

3.5.6.3 Index Validation

The following cross-validation analyses among the different relative abundance indices for Hudson River American shad provide a measure of confidence in using each index of abundance for stock assessment and in management plans.

3.5.6.3.1 Juvenile Indices

A correlation analysis among co-occurring juvenile surveys is a good tool to determine the validity of perceived year class strength, especially if the survey methods and life stage targets differ. Fortunately, there is a large timeframe with competing juvenile surveys in the Hudson River. The timeframe for this correlation analysis begins in 1983, the first comparable year for the NYSDEC YOY survey, and lasts through 2016, which was the last year of the Hudson River Generators’ Utility YOY Survey and Larval Surveys.

Recall that the EGG, YSL, and PYSL indices all are products of a random stratified trawl survey encompassing the tidal reach, whereas the Utility YOY Survey and NYSDEC YOY surveys are beach seine surveys with net meshes specifically targeting the YOY life stage. The two seine surveys also differ in that the Utility YOY Survey is a stratified random survey that encompasses most of the tidal reach, while the NYSDEC YOY survey is a fixed station survey that only samples the freshwater reach.

A correlation matrix of all the available juvenile surveys is found in Table 73. The YSL index generally has the lowest correlation value when compared with the other life stage indices. The lack of correlation is likely due to the sampling issues associated with catching the short-lived YSL life-stage. Encouragingly, there is a high degree of correlation between the two seine surveys, despite the vastly different sampling protocols (0). As important, the PYSL and seine indices are also highly correlated, with the highest correlation between the PYSL index and NYSDEC DEC GLM index (0). These correlations provide confidence in the NYSDEC YOY seine survey's ability to detect relative abundances of YOY shad, indicating this survey will play an important role in monitoring the progress toward recovery of the stock.

3.5.6.3.2 Juvenile and Adult Indices

In the previous assessment, Hattala and Kahnle (2007) evaluated potential use of early life stage indices (EGG, YSL, PYSL, NYSDEC YOY) as surrogate adult indices by a simple linear regression of the early life stage index on the empirical spawning stock indices for five- to seven-year-old females during the period 1985 through 2001. Neither index was lagged; therefore, the relationship tested was whether adult female spawning stock indices could predict early life stages within the same year. They found the EGG index had the most significant correlations with both empirical spawning stock indices.

Table 74 shows an updated correlation matrix including female spawning stock abundances calculated by Hattala and Kahnle (2007) as well as those using the fishery-dependent catches using GAM models. All indices represent catch rates of five- to seven-year-old females only. As seen in the table, the EGG vs Area Under the Curve (AUC) ESSB remains the index with strongest correlation among the other adult indices. Despite the high correlation with the AUC indices, the GAM indices do not have a very strong correlation with the EGG index. Looking at 0, the lack of correlation is likely driven by differences in the 1986 and 1995 values, with the AUC values much more closely tracking those from the EGG index. Any future fishery-independent gill net survey on the Hudson spawning stock should take careful consideration of the methods for annual index calculation, especially in the brackish section of river. The AUC method is likely the best option in this part of the river.

A second method of validating juvenile with adult indices is to use the juvenile indices to predict future spawning stock abundance. In the 2007 Assessment, Hattala and Kahnle (2007) showed the PYSL index to be highly correlated with their fishery-dependent index made up of five to seven-year old's (R = 0.92). However, the relationship did not hold up after 1984, concurrent with the spike in total mortality observed in adult cohorts from the 1985 year class and later. A similarly strong relationship was found with the PYSL versus the FD GAM index (R = 0.87).

The same methods used by Hattala and Kahnle (2007) were used to compare the fishery-independent spawning stock abundance index with the PYSL index and NYSDEC GLM YOY index. Annual index-at-age for the Hudson River Spawning Stock Haul Seine Survey was calculated as the annual index for a given year, multiplied by the proportions at age for that particular year. Because maturity is variable, multi-year indices were also calculated by adding the following year's index value at the subsequent age. For example, the 1988 four-year-old index is summed with the 1989 five-year-old index to make a four and five-year-old index that would be compared with the 1984 juvenile index value. All adult indices were lagged to match their respective cohort.

The global correlation matrix of all respective indices across all years (Table 75) indicates no strong correlations with all values in the time series. The best relationships are between the juvenile indices and four-year-old's (r values > 0.4 – in gray). XY plots of the two best relationships show a promising pattern (Figure 112), with three obvious outliers in each comparison. These also happen to be the years with the highest catch rates in the spawning stock survey (1992, 1993 and 2001). Looking further into the adult data, there was a shift in 1995 to increase hauls in the spawning reaches north of Kingston. Modeling results from the GAM model indicate catch rates are higher in the upper reaches; therefore, any change in sampling strategy likely impacted catch rates in this survey. There is also evidence for the removal of the 2001 outlier value. In 2001, the spawning stock survey lasted two weeks, with the upper reach only sampled four days. Fortunately, many shad were caught in those hauls, indicating sampling was timed perfectly with the spawning run. Unfortunately, this means the high catch rates may not have been representative of the entire spawning population and potentially resulted in an over-inflated abundance estimate. Since 1995, the average number of days sampled in the upper reach is more than 13, resulting in a mean of 55 hauls a year in this section of river. In 2001, only 17 hauls were conducted in the upper reach.

The bottom graphs in Figure 112 show the juvenile vs. four-year-old indices from 1995-2017, with 2001 removed. Removal of these years significantly improves the correlations with an r value of 0.78 with PYSLs and 0.76 with the GLM YOY, indicating a strong relationship that spans 21 years of sampling. This is a very promising sign that catches from the fishery-independent Spawning Stock Haul Seine Survey gears can be used to generate an index of relative abundance for spawning shad. Interestingly, the correlations with older ages are not as strong, indicating mature fish may have lower survival rates than expected during the years analyzed. As an in-river fishery was occurring during most years of the correlation analysis, it will be important to re-evaluate this correlation as sampling continues with the moratorium in place and hopefully more contrast in catch rates among the two surveys as recovery begins.

3.5.7 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance, mean length, and mean length-at-age. Total mortality estimators were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Please refer to section 2 for a description of the methods.

3.5.8 Results

3.5.8.1 Abundance Trends

3.5.8.1.1 Power Analysis

Five abundance indices for American shad, none of which are currently used for sustainability targets and monitoring in the SFMP, were developed for this system that contained estimates of PSE: the Hudson River YOY 3/8" Seine Survey, the Hudson River Utility Egg Survey, the Hudson River Commercial Gill Net CPUE, the Hudson River Spawning Stock Haul Seine Survey, and the Hudson River Utility Post-Yolk Sac Larvae Survey. Of these surveys, only the Hudson River YOY 3/8" Seine Survey, which possessed a median PSE of 0.090, exhibits sufficient power to detect a 50% increase in American shad abundance in 10 years (Table 25). If interested in detecting a 50% decrease, evidence suggests that both the Hudson River Utility Egg Survey and Hudson River Commercial Gill Net CPUE may be able to detect such a decrease with 0.80 power.

3.5.8.1.2 Mann-Kendall Analysis

Hudson River (JAI)

Hudson River JAIs increased though late 1980s, before generally declining until the early 2000s, remaining low since that time (Figure 113). Mann-Kendall results also found a significant decline for the entire time series from 1978-2017, but no trend for the period after 2005.

Hudson River (FD and FI CPUE)

A fishery-dependent Hudson River Commercial Gill Net CPUE index and three fishery-independent surveys were examined as indices of abundance for American shad in the Hudson River. The Hudson Commercial Gill Net CPUE index showed fluctuating levels between 1980 and 2001, with peaks in 1988, 1995, and 2001 (Figure 114). Mann-Kendall Trend analysis failed to detect a trend over the full time series or for the period after 2005. When plotted, all three of the fishery-independent surveys showed an increasing period early in the time series, peaking in the late 1980s or early 1990s, followed by decline and have remained at lower levels since (Figure 115 – Figure 117). Mann-Kendall trend results found a decreasing trend over the full time series in all three of the surveys, but failed to detect any trends for the period from 2005 forward.

3.5.8.2 Mean Length Trends

The Hudson River is a highly productive system. It is tidal for 254 km to the first impassable barrier. American shad spawn in the freshwater sections of the upper two-thirds of the river. New York DEC provided length data from the fishery-dependent Commercial Gill Net monitoring program and a fishery-independent Spawning Stock Haul Seine Survey. Plots of mean length versus year from the fishery-dependent survey showed an increase in mean lengths for both sexes from 1980-1987, followed by a general decrease through 2000, a small increase from 2001-2003 before again decreasing (Figure 118). There was a large decrease in lengths from 2008 to 2009. However, Mann-Kendall trend analysis only found a decreasing trend in mean length of female American shad over the time period. A plot of the fishery-independent Spawning Stock Haul Seine Survey was similar, showing a decrease in fish size from the mid-1980s through the late 1990s. Some larger fish began to appear in 2000 after ocean restrictions banning large mesh gill nets occurred, with mean lengths increasing through 2004, before decreasing considerably between 2004 and 2009 for both sexes (Figure 119). Again similar to the fishery-dependent data, Mann-Kendall trend analysis only found a significant decreasing trend in mean lengths of females over time.

3.5.8.3 Mean Length-at-Age Trends

Mean length-at-age data using scales were provided from two sampling programs, the Commercial Gill Net monitoring and the Spawning Stock Haul Seine Survey for the Hudson River. Data were provided for both sexes in both programs, with age 3 being the youngest fish aged in each program and fish aged as high as age 12 in the Commercial Gill Net CPUE data and age 11 in the Spawning Stock Haul Seine Survey. Mann-Kendall Trend analysis found a single increase in mean length-at-age for each sex, females age 11 and males age 10, in the Commercial Gill Net CPUE data, but found a decrease in mean length-at-age for females ages 4 through 9 and males ages 6 through 8 in the Spawning Stock Haul Seine Survey (Table 76).

3.5.8.4 Empirical Spawning Stock Abundance and Biomass Indices

Hattala and Kahnle (2007) calculated the spawning stock abundance (SSA) and biomass (SSB) indices for the Hudson River shad stock using the relative abundance index of female shad in the fixed gear commercial gill net fishery (area under the curve method of CPUE), age structure of females in the commercial fishery and the spawning stock and observed annual mean weight at age. These indices included the years 1985 to 2001, when commercial monitoring efforts were sufficient. To continue the time series after 2001, Hattala and Kahnle (2007) used the linear relationship between the EGG index and SSB index to project empirical spawning stock abundance (ESSA) and biomass (ESSB) indices through the end of the time series.

The same methods to calculate SSA and SSB used by Hattala and Kahnle (2007) were applied to the GAM-generated catch indices for the Commercial Gill Net CPUE. As with the previous estimates, the time series for the SSA and SSB using the GAM catch rates ends at 2001 due to poor sample sizes for the rest of the time series, requiring a surrogate index if the time series were to continue. A comparison of the fishery-dependent GAM index with the EGG index (Table 75) did not produce the same statistically significant correlations as those calculated by Hattala and Kahnle (2007), indicating the previous method of calculating catch rates in the Commercial Gill Net CPUE (area under the curve) appear more representative of the spawning stock than the rates calculated using a GAM on a single mesh size. Therefore, the best fishery-dependent adult index remains the AUC ESSA and ESSB indices presented in the 2007 stock assessment, with the EGG index serving as a proxy after 2001. Unfortunately, the commercial fishery closed in 2010 and the survey producing the EGG index stopped in 2016, so these particular ESSB indices can no longer be calculated.

The recently developed fishery-independent Spawning Stock Haul Seine Survey index provides another method to calculate spawning stock biomass. As in the previously explained SSB calculations, an index at age calculation was made by multiplying the fishery-independent, female GAM CPUE by the annual estimated proportions at age for females. Next, annual weight at age and index at age values were multiplied and then summed across ages to get the annual SSB estimate. Results are compared with the fishery-dependent SSB and the EGG index in Figure 120. As described earlier, the EGG index and the fishery-dependent SSB are very similar in trend, except for the years 1990 and 2001, indicating the EGG index is a suitable proxy for the fishery-dependent SSB. The fishery-independent SSB index conflicts with the fishery-dependent index and EGG indices in 1992, 1993, 2001, 2004 (EGG only) and 2005 (EGG only). After 2005, both the EGG and fishery-independent SSB indices are at all-time lows for each respective time series, indicating both have picked up the population collapse.

The differences in the fishery-dependent and independent indices are not unexpected as they are likely measuring two different abundances. From 1985 to 2001, the fishery-dependent index estimates the number of female shad that have made it to the lower section of the river, while the fishery-independent index provides an estimate of the number of females that made it past the lower river fishery and into the spawning reaches. Hattala and Kahnle (2007) report overfishing was occurring during much of this period of comparison and it is likely that the brackish fishery was a large portion of that harvest. 0 shows a correlation between these overlap years for these two SSB indices, providing evidence that the fishery-independent index may not be an appropriate surrogate for the fishery-dependent survey, especially during harvest years. This poor relationship between the two SSB estimates, the fishery closure and the end of the EGG survey, make it difficult to establish a recovery target SSB that would adequately incorporate the ‘best’ years available based on all the various NYSDEC and HRG monitoring surveys. As an alternative, a new fishery-independent gill net survey designed to mimic the protocols of the fishery-dependent survey might be better suited to establish any future SSB target. In addition, with the fishery now closed, the SSB estimates from the two surveys should be more comparable and hopefully provide more confidence in each survey through cross-validation of catch rates and biomass estimates.

3.5.8.5 Young-of-Year Recruitment Failure Level

The 25th percentile of a select set of years in a time series commonly used as the recruitment failure level for YOY relative abundance indices. Management triggers are often set to three consecutive years in a row below this recruitment failure level. Examples of ASMFC approved YOY recruitment triggers are in the NY River Herring Sustainable Fishing Plans (Hattala et al. 2012 and Eakin et al. 2017) as well as the Delaware Cooperative American Shad Sustainability Plans (Del. Coop. 2012 & 2017).

In previous state reports, the set of years considered for the recruitment failure of YOY shad in the Hudson River has been 1983-2001, the years considered the best for YOY production. High total mortality rates on adults coupled with annual YOY index values below recruitment failure each year after 2002 led to the moratorium on Hudson shad fisheries in 2010. Unfortunately, there has been no change in recruitment levels post fishery closure, indicating the stock remains in peril.

Any future recovery plan for Hudson River American shad must include this YOY index and the recruitment failure target. The Hudson River American shad YOY index is significantly correlated with another juvenile life stage index and can predict future spawner abundance estimates in the fishery-independent spawning stock index. Careful consideration must be given to the years used in setting a recovery target as well as the number of consecutive years above this target to indicate a consistent, positive change in recruitment. For instance, see Figure 122 which shows a longer time series of YOY, where the GLM YOY values have been projected backwards using the linear regression equation between the BSS and GLM. In looking at this graph, a conservative 25th percentile recovery target might be set using the years 1974 through 1992, rather than the current value used in compliance reports (1983-2001).

3.5.8.6 Total Mortality Estimates

Age composition data from length compositions and age-length keys derived from scales collected during the NYSDEC Spawning Stock Haul Seine Survey and Electrofishing Surveys were used for mortality estimates. Age composition data were combined across monitoring programs based on the recommendation of NYSDEC staff. Data met all criteria (see Section 2.6) for 25 and 23 years between 1983 and 2017 for females and males, respectively (Table 32). Mortality of both sexes increased in the 1990s and decreased in the 2010s to levels similar to those observed in the 1980s (Table 33 and Figure 123). The increase in mortality in the 1990s occurred just prior to a recruitment failure in the early 2000s identified by the NYSDEC. The three-year average female estimate in 2017 (0.59) was below the threshold ($Z_{40\%}$ = 1.07) and the average standard error for this estimate was 0.28.

3.5.8.7 Habitat Assessment Results

Current unobstructed American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Hudson system, current unobstructed habitat area represents 89.24% of the historical habitat extent (58.42 of 65.47 square kilometers).

3.5.9 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. Adult mortality status is sustainable as the three-year average female total mortality in 2017 was 0.59 which is below the $Z_{40\%}$ threshold (1.07). Though adult mortality was determined to be sustainable, it is important to note that maintaining sustainable adult mortality will not result in favorable abundance status if the previously mentioned unknown juvenile mortality is occurring at unsustainable levels.

There was a declining trend in female mean length detected from two data sets (1980-2009, 1985-2017). There was a declining trend in long-term YOY abundance detected from three data sets (1974-2015, 1974-2015, 1983-2017), but no trend since 2005.

Abundance
Based on the decline of in-river landings by more than an order of magnitude (Table 56, Figure 105) and significant declining trends in the fisheries-independent adult relative abundance index (Figure 117) and YOY indices (Figure 113, Figure 115, Figure 116) since the decline of landings coupled with a lack of response to the management action in 2005, abundance status is depleted. Additionally, there was a designated recruitment failure in 2002 (see section 3.5.8.5) that has persisted into recent years.

3.5.10 Research Recommendations

3.5.10.1 Progress on 2007 Stock Assessment Research Recommendations

1. A concerted effort needs to be made to identify bycatch in the other numerous fisheries that are implicated (e.g. Atlantic herring fishery) and identified bycatch fisheries need to be restricted to minimize catch of American shad.

- Research has been ongoing on this topic since the last assessment. There are several studies that lay the groundwork for the use of genetics to parse out riverine shad stocks from mixed-stock catches (e.g. Brown et al. 1999; Hasselman et al. 2013; Aunins et al. 2014; and Waldman et al. 2014). Unfortunately, the results of stock identification by river vary and are statistically limited. Hasselman et al. (2013) state this is likely due to several factors including straying rates and intensive inter and intra-regional historical stocking events. Aunins et al. (2014) note the lack of differentiation could also be due to the use of non-selective genetic markers in the microsatellite analyses, which might dampen regional or riverine differences. They also state single nucleotide polymorphisms (SNPs) might provide better differentiation among stocks, citing the work of Bourret et al. (2013) on mixed-stocks of salmonids.

- The Hudson River Fisheries Unit is currently involved in a research project to evaluate the potential to use rapid genome sequencing techniques to further elucidate regional differences. If successful, the next step would be to estimate regional compositions of mixed-stock fisheries.

2. *A fishery-independent CPUE survey be developed to track spawning stock abundance.*
- No CPUE survey has been developed since the last assessment. However, the correlation analyses provide some indication that the current Spawning Stock Haul Seine Survey reflects trends in young-of-year abundance. As mortality likely changed after the

moratorium in 2010, more years are needed to assess whether this correlation continues with several generations of protected year classes.

3.5.10.2 Additional Research Recommendations

- Spawning stock abundance estimation
  - Continue the development of a spawning stock abundance index using haul seine gears
  - Evaluate the use of side-scan sonar technology to estimate spawning stock abundance
  - Evaluate the use of fishery-independent gill net survey in the brackish sections of the river to replicate the former fishery-dependent commercial monitoring sampling
- Continue development of an ageing protocol with both scales and otoliths
- Evaluate the potential for advances in genetic techniques to estimate losses of Hudson River shad in coastal bycatch and mixed-stock fisheries
- Better understand in-river and coastal movement of adult shad using acoustic telemetry technology
- Determine age and spawning marks on scales from 2002-2014 to compare the NYSDEC beach seine YOY index to virgin female spawners. This would provide the best method to compare year classes with their respective first time spawners.

3.6 Delaware River

3.6.1 Habitat Description

3.6.1.1 Main Stem

The Delaware River begins in Hancock, NY and flows more than 454 kilometers (330 miles) before emptying into Delaware Bay (Figure 124). The tidal portion extends from the head of the bay to near Trenton, NJ (rkm 214, rm 133.1). The East and West Branches, Lackawaxen, Neversink, Lehigh and Schuylkill rivers are the major tributaries. The 33,038 square kilometer basin includes parts of four States: Pennsylvania (50 percent of the basin), New Jersey (23 percent), New York (19 percent), and Delaware (8 percent). As the drinking water supply for 15 million people (Philadelphia – New York City (NYC) metropolitan area), vast areas of the basin's headwaters have been protected from development and much of the river corridor retains its wild, free flowing character.

The Delaware River is unique along the Atlantic Coast in that it is free-flowing along the entire length of the main stem which allows numerous species of migratory fish to persist far up into its headwaters where in similar East coast aquatic systems they've been long extirpated. Since colonial times, however, the basin's resources have been exploited and depleted. By the early 20th century the estuary was considered one of the most polluted waterbodies in the United States and a recurring pollution block in the tidal portion of the upper Delaware Estuary severely hindered migratory fish runs, which were already severely depleted from overfishing and habitat degradation. The passage of the Clean Water Act in 1972, which established water quality standards to reduce municipal and industrial discharges, eventually led to improved water quality and the near elimination of the pollution block on the lower river. In 1992, DRBC adopted the special protection regulations to protect the high water quality of the river sections that had been designated as part of the National Wild and Scenic River system. The special protection regulations do not allow any degradation of "existing water quality" as defined by numeric standards for a number of water quality parameters. Through a series of amendments between 1994 and 2008, the special protection waters designation was expanded to apply to point and non-point discharges along the entire main stem downstream to Trenton, NJ.

Historically American shad spawned throughout the main stem freshwater Delaware River and its tributaries as well as tributaries connected to the Delaware Bay (Stevenson, 1898). The location of the salt front would have determined the extent of the potential spawning habitat in the freshwater tidal section of the river. Prior to the construction of the NYC reservoirs and subsequent diversions, the salt front was variable seasonally within and among years depending on the total volume of water being discharged from the Delaware River at any given time. Management of reservoir releases was thought to reduce the extreme variation of salinity in the estuary and hence moderate the migration of the salt front. Today the average location of the salt front is at rkm 111 (rm 69). During the drought of record in the 1960s the salt front reached rkm 164 (rm 102) upstream.

Water pollution since colonial times was severe, culminating in anoxic conditions in the lower Delaware River. During the 1940s and 1950s, heavy organic loading around Philadelphia, Pa. caused severe declines in dissolved oxygen (D.O.). A remnant of the American shad run in the Delaware River survived by migrating upstream early in the season, when water temperatures were low and flows were high, before the D.O. block set up. These fish, because of their early arrival, migrated far up the Delaware to spawn. Out-migrating juveniles survived by moving downriver late in the season during high flows and low temperatures, thus avoiding the low oxygen waters present around Philadelphia earlier in the fall.

Currently, American shad spawning is thought to be primarily in the middle and upper Delaware main stem spanning an area of approximately 236 river kilometers (147 river miles) from near Easton, Pa. (rkm 296, rm 184) to Hancock, NY (rkm 532, rm 330). Yet, American shad also appear to be using the lower non-tidal reaches and freshwater tidal reaches of the Delaware River. Entrainment of alosine eggs and larvae in industrial water intakes, suggest the lower freshwater reaches and upper tidal reaches of the Delaware River are nursery grounds. In addition, observed adult shad spawning behaviors support this assumption, however, ichthyoplankton surveys for documenting the occurrence of American shad eggs in this region should be a priority research topic (Maurice et al. 1987).

3.6.1.2 Major Tributaries

3.6.1.2.1 New York

The major spawning tributaries for shad in New York were the East and West Branches of the Delaware and, to a lesser extent, the Neversink River. Most of the East and West Branches of the Delaware no longer support shad spawning runs due to the cold water releases from the NYC reservoirs and direct loss of habitat due to the reservoirs themselves (Chittenden 1976). Shad historically migrated 68 km (42 miles) up the East Branch to former town of Shavertown which is now submerged beneath New York City's Pepacton Reservoir. There have been reports from fishermen of shad as far as 25 km (15.5 mi) up the East Branch, to the confluence with the Beaver Kill. Chittenden (1976) reported that shad ran up 6 km (3.7 mi) up the Beaver Kill, an East Branch tributary, but it is unclear whether they spawn there. Other reports have shad going as far as a mile up into the Little Beaver Kill, a tributary of the Beaver Kill (McPhee 2005).

3.6.1.2.2 Pennsylvania

Two of the largest shad spawning tributaries in the Delaware Basin are wholly located within the Pennsylvania; the Schuylkill River has a drainage area of 5,180 km2 and the Lehigh River has a drainage area of 3,484 km2. In the late 1880s shad were extirpated from all waters associated with the Schuylkill and Lehigh basins with the construction of various dam and canal systems. The building of the Delaware Canal on Pennsylvania's shoreline also disconnected many smaller tributaries from the main stem, precluding shad access. In addition to physical barriers, water quality is also an issue in the Lehigh. Just south of the municipality of Palmerton, PA water quality is poor due to impacts from several large municipalities that have discharges to the drainage and historic inputs from a former metal smelting operation.

3.6.1.2.3 New Jersey

In New Jersey, most tributaries that were tidally influenced had runs of shad that could support fisheries. In 1896 the Cohansey River ranked 3rd in New Jersey as a shad producing stream, surpassed only by the Hudson and Delaware (Stevenson 1898). Historic water quality issues likely impacted many of the shad streams in New Jersey. Current habitat impacts include dams, canals, tidal gates and water quality. Non-tidally influenced major tributaries of the Delaware River in New Jersey, including the Musconetcong River and the Paulinskill River historically supported small runs of American shad before extensive networks of dams were established on both systems.

3.6.1.2.4 Delaware

The current status of shad in most of the tributaries that are found in State of Delaware is unknown, but few have been caught in any of these tributaries during the past century and it is unlikely that any of them currently support spawning runs. However, shad were found historically in most tributaries (Mansueti and Kolb 1953, Stevenson 1899). In Wilmington, the Christina watershed (including White Clay Creek and the Brandywine) had a major spawning run of shad before dams and water pollution effectively eliminated the run. The majority of tributaries that once supported shad runs are impacted by dissolved oxygen and nutrient issues (DNREC 2005).

3.6.2 Fishery and Management History

Within the Delaware River Basin, the Delaware River Basin Fish and Wildlife Management Cooperative (Co-op) is responsible for the management of American shad. The Co-op adopted its first the Sustainable Fishing Plan approved by the ASMFC in 2012 (2012 SFP). The Co-op originally used four indices for monitoring the Delaware River American shad stock with associated benchmarks in the 2012 SFP. In a subsequent SFP approved and adopted in 2017 added an additional index and associated benchmark to monitor harvest on mixed-stock American shad that occur in the Delaware Bay. The Co-op judge these fisheries as sustainable while avoiding diminishing potential stock reproduction and recruitment as long as all five indices of stock condition remain within the defined benchmarks.

3.6.2.1 Commercial Fishery

Commercial exploitation of the Delaware River American shad stock is permitted by the States of New Jersey and Delaware within the basin. Harvest occurs generally during the spring spawning migration from late February into May principally using anchored or drift gill nets. In the 2012 SFP, the Co-op acknowledged that the commercial fishery in the Delaware Bay exploited American shad from mixed-stock fisheries, along with Delaware River stock. A demarcation line from Leipsic River, DE to Gandys Beach, NJ was established, where landings in the upper estuary are considered to be 100% Delaware River American shad stock and landings in the bay were of mixed-stock, with an estimated 40% of Delaware origin. Upon further examination of reporting regions in the State of Delaware, it was determined that the four reporting regions (River, Upper Bay, Mid Bay and Lower Bay) do not allow for landings to be divided at the Leipsic River. A new delineation point was selected for the State of Delaware (Bowers Beach), which now assigns landings to Delaware River stock harvest for the upper three reporting regions in that state. Available tagging and genetic studies, suggest continuance of assignment of the proportion of the Delaware River stock at a similar rate as the 2012 SFP.

Fishers in New Jersey represent a small directed fishery for American shad; whereas, landings of shad reported to the State of Delaware occur as bycatch from their concurrent Striped Bass fishery. Trends of combined landings, representative of the Delaware River stock, have been declining since 1990, with lowest levels observed in the most recent years (2008-2018), with the exception of a high harvest in 2014. The decline is most likely due to gear changes in Delaware's Striped Bass quota driven fishery and the low number of New Jersey fishers seeking American shad.

Harvest on the mixed-stock occurs in both Delaware and New Jersey in the Delaware Bay. Based on best available genetic data (Waldman 2006), the Co-op considered the mixed-stock fishery to mainly take place in the section of Delaware Bay below a line from Bowers Beach, DE to Gandys Beach, NJ. A new benchmark was developed to limit expansion of the fishery in this mixed-stock area. Mixed-stock landings were highest in the early 1990s and have been generally declining since that time. Landings on the mixed-stock have been below the time-series mean (1985-2018) since 2006.

In addition to the Delaware Bay fisheries, a small haul seine fishery (Lewis haul seine) occurs in the Delaware River, some 15 miles above the fall line at Lambertville, NJ. This fishery exists as an eco-tourism venture with nominal harvest of shad. Trends in this fishery are highly correlated to the Smithfield Beach CPUE time-series (Figure 125).

3.6.2.2 Recreational Fishery

Historically, a substantial recreational fishery for shad existed in the non-tidal reaches of the Delaware River; however, participation in this fishery is declining. The current recreational harvest is unknown. Most shad anglers practice catch-and-release. The mortality associated with catch-and-release of shad in the Delaware River is unknown but considered to be minimal based on studies in the Hudson River (Millard et al. 2003). The recreational creel limit is currently 3 shad in the Delaware River.

3.6.2.3 Sustainable Fishing Plan (SFP) Benchmarks

The Co-op currently uses five benchmarks for sustainability. The benchmarks have been set to respond to any potential decline in stock. Thus, all benchmarks are viewed as conservative measures. Failure to meet any of the defined benchmarks will independently cause immediate management action. The severity of the action will be situational and proportional to the number of benchmarks exceeded. All benchmarks are reviewed annually after completion of annual ASMFC Shad and River Herring compliance reports.

1. **Non-tidal JAI:** Data for this index is derived from the NJDFW/Co-op annual fixed station seining (1979-2007; 2012-2018) in the non-tidal Delaware River main stem from Phillipsburg, NJ to Milford, PA. The non-tidal JAI is standardized with respect to environmental covariates using generalized linear model methodology. The benchmark is based on data from 1988-2007 and 2012-2015. Failure is defined as the occurrence of three consecutive JAI values below a value of the 25th percentile of the historical data (1988-2015), where 75% of the values are higher (Figure 126).

2. **Tidal JAI:** Data for this index is derived from the NJDFW annual Striped Bass seining in the upper estuary. Only those stations from New Bold Island to the Delaware Memorial Bridge are included. The JAI index represents the annual geometric mean of the catch data. A benchmark was based on data from 1987 – 2015. Failure is defined as the occurrence of three consecutive JAI values below a value of 4.0 (i.e., the 25th percentile of the historical data, where 75% of the values are higher) (Figure 127).

3. **Adult CPUE:** This index is based on the annual CPUE (shad/net-ft-hr*10,000) in the PFBC gill net, egg-collection effort at Smithfield Beach. The benchmark was based on the entire data set (1990-2015), with failure defined as the occurrence of three consecutive CPUE values below a value of 37.5 (i.e., the 25th percentile of the historical data, where 75% of the values are higher) (Figure 128).

4. **Ratio of Harvest to Smithfield Beach CPUE:** This index is calculated as a ratio of the combined commercial harvest of the Delaware River American shad stock, in pounds, divided by relative abundance of adult survivors captured at Smithfield Beach (CPUE) divided by 100. The benchmark is based on data from 1990-2015 and failure is defined as the occurrence of three consecutive values above a value of 36.5 (i.e., the 85th percentile of historical data, where 15% of values are higher) (Figure 129).

5. **Mixed-stock Landings:** This index is calculated as the annual landings from the mixed-stock fishery. It is calculated as 60% of total shad landings below the demarcation line (Bowers Beach, DE to Gandys Beach, NJ). The benchmark is based on data from 1985 – 2015 and failure is defined as the occurrence of 2 consecutive years above a value of 47,650 (i.e., the 75th percentile of historical data, where 25% of values are higher) (Figure 130).

3.6.3 Anthropogenic Sources of Mortality and Productivity

3.6.3.1 Sources of Mortality

There are several large water intake systems at energy projects on the Delaware River. Recent estimates of impingement and entrainment (I&E) rates at water intake systems for American shad in the Delaware River indicate that individual projects can entrain millions of American shad eggs and larvae annually and impinge tens of thousands of juveniles. In a river system with numerous intake facilities that occur in spawning and nursery grounds for American shad, the cumulative impacts to the population could be substantial.

To put the American shad impingement rates into perspective, the Pennsylvania State Fish Hatcheries annually released 474,271 fry, on average, into the Delaware River Basin. Considering additional mortality between the fry and juvenile stage, from various projects with intakes, impingement rates are likely far greater than resource agency stocking efforts to protect and restore American shad to the Delaware River Basin. Impingement data for other important fisheries suggest that impacts may be occurring on Striped Bass and Weakfish populations, reducing the number of fish that would later be available for recreational and commercial fishing. Recent estimates derived by staff from the Delaware Department of Natural Resources and Environmental Control, Division of Fish & Wildlife (DFW) suggest that losses of early life stages of Striped Bass at the Project translate into losses of Adult Equivalents that rivals or even exceeds current commercial and recreational harvest in Delaware (Ed Hale, DFW, pers. comm.). Losses of large numbers of forage species also reduce the food resources available in the river, further impacting fish communities in the Delaware River.

Recognizing the considerable I&E losses on the Delaware River Basin shad populations (and other fishes), routine quantification of I&E shad losses would provide for better estimation of anthropogenic mortality. Co-op members also agree improved best management practices to eliminate or reduce I&E losses would be prudent. Current available data preclude annual estimation of mortality by these facilities. Data collection/reporting and improved technologies place an additional monetary burden on operators with water intakes, but the paucity of information hinders development of a more robust stock assessment of Delaware River Basin shad populations.

3.6.3.2 Sources of Productivity

Eggs collected from Delaware River shad have been used in restoration efforts on two Delaware River tributaries, the Lehigh and Schuylkill rivers, as well as in the Susquehanna River Basin, Raritan River and other systems. Since 1973, egg-take operations on the Delaware River have resulted in the use of an average of 765 adult shad per year. Eggs from these shad are fertilized and transported to the PFBC Van Dyke Anadromous Research Station. After hatching, the resulting larvae are reared until 10 to 30 days of age and stocked in areas above dams on the Susquehanna and Lehigh Rivers where fish passage projects are in place or are planned. When high water events occur, the larvae are held in the hatchery until the water recedes. Since 1985, the top priority for Delaware River larvae has been the Lehigh and Schuylkill rivers with more than 20 million fry stocked during this time. Since 2000, all Delaware River shad fry have been allocated to the Lehigh, Schuylkill and Delaware rivers.

3.6.3.2.1 Egg Collection and Hatchery Culture

American shad used to stock the Lehigh and Schuylkill Rivers were cultured by methods developed at the PFBC's Van Dyke Hatchery, which are similar to those reported by Howey (1985). Eggs are obtained from adult American shad collected by anchored gill nets set parallel to the current in the Delaware River at Smithfield Beach (rm 228). Ripe adults are strip-spawned and the eggs are fertilized and water-hardened at the collection site. Eggs are then delivered to the Van Dyke Hatchery for incubation and hatching.

Stocking of hatchery-reared American shad larvae in the Lehigh and Schuylkill Rivers began in 1985. Releases occurred at Northampton (Lehigh River km 38.6) or between Gibraltar and Hamburg (Schuylkill River km 108-158). Larvae were stocked annually, during May or June at 7 to 21 days of age. Between 1985 and 2005, 15.2 million marked hatchery shad larvae were stocked into the Lehigh River and 4.8 million were stocked into the Schuylkill River.

3.6.3.2.2 Future Plans

It is the PFBC's intention to continue to use Delaware River eggs for the shad restoration efforts on the Delaware River and its tributaries, specifically the Lehigh River and Schuylkill River. These rivers receive stockings from all strip-spawned eggs provided by Delaware River shad.

3.6.4 Fishery-Dependent Data Sources

3.6.4.1 Commercial

3.6.4.1.1 Landings

Delaware

Beginning in 1985, the State of Delaware required mandatory reporting of commercial landings under the provisions enacted by the Delaware General Assembly in 1984. Every fisherman holding a commercial food-fishing license is required to submit a monthly report specifying where they fished, the type and amount of fishing gear deployed, and the pounds landed of each species taken for each day fished. Commercial landings of American shad in Delaware occur in the concurrent Striped Bass fishery. American shad landings in Delaware are described as occurring in the Upper or Lower Delaware Bay as delineated fisheries occurring above or below Bowers Beach, Delaware (Figure 131).

New Jersey

NOAA Fisheries estimated American shad landings for the State of New Jersey through 1998. In 1999, the NOAA Fisheries estimates were combined with voluntary logbook data from New Jersey's commercial fishers. Since 2000, the data has been collected via mandatory logbooks through the limited entry program. Data required to be reported are where the fish were harvested, the type and amount of gear deployed, and the pounds landed of each species taken for each day fished. There are no estimates of underreporting, however it is assumed that harvest in the upper reaches of Delaware Bay, prior to 2000, was actually higher than the NOAA Fisheries data suggests. This is due to a lack of sampling by the NOAA Fisheries in this area. The evidence for underreporting can be found in New Jersey's mandatory logbook data since 2000, which shows that the five highest landings years occurred during this time period (i.e. after 2000), with a peak of more than 90,000 pounds in 2004. Commercial landings of American shad in New Jersey occur primarily through directed harvest in multi-species fisheries. American shad landings in New Jersey are described as occurring in the Upper or Lower Delaware Bay as delineated fisheries occurring above or below Gandy's Beach, New Jersey (Figure 131).

3.6.4.1.2 Biological Sampling

Biological data collected by the State of Delaware and New Jersey are gathered from New Jersey commercial fishers landing catches from the upper Delaware Bay. Otoliths and DNA samples are collected from several New Jersey shad fishermen. The otoliths have been archived for ageing in the future and the DNA samples have been contributed to a study examining the mixed-stock composition in the lower bay fishery. Length frequency and sex ratio information is also collected from the commercial fishery (Figure 132).

Scale samples also have been collected from these landings but have not been processed for age estimation. The Co-op members have finalized a standardized scale ageing protocol for the Delaware River Basin. Review of historic age data sets have been initiated with focus on fishery-independent collections (i.e., Smithfield Beach). Ultimately, the Co-op anticipates interpreting scale samples from the commercial collections with the intent for characterizing the commercial catches for age and repeat spawning frequencies. Historical age, length and weight distributions are reported in compliance reports.

3.6.4.1.3 Catch Rates (Lewis Haul Seine Fishery)

Index standardization was attempted with this index but trip level information and covariates (water temperature, river height, tide movement, and net length fished) were only available from 2008-2017. As the entire data set has information on the number of shad caught and number of hauls from 1925-2017, but not trip level data, a basic standardized index is recommended rather than a GLM or GAM index so that the entirety of the time series is able to be used.

The index was low and variable from 1925-1947 with a period of slightly higher values in the 1930s and early 1940s (Table 77, Figure 125). The index fell to the lowest values from 1948-1957 with a large peak in 1963 before falling again in 1965-1967. An increase was observed from 1968 through 1992 before the index fell again in the 1990s and 2000s. Since 2009, the index has been increasing again though not to levels as high as were observed in the 1980s.

3.6.4.2 Recreational Data

The last survey of the recreational fishery was an access point survey in conjunction with an aerial effort survey conducted by Versar, Inc. during 2002 (Volstad et al. 2003). The study area included all tidal and non-tidal waters from the Delaware Memorial Bridge to Downsville, NY. No recreational fishery surveys have been undertaken since 2002 due to the large area required to be covered and a lack of funding and resources to undertake such an effort. Most, if not all, of the recreational fishery takes place above the head of tide in the main stem Delaware and as a result this effort is not captured by the MRIP.

3.6.5 Fishery-Independent Data Sources

3.6.5.1 Adult Fishery-Independent Data Sources

3.6.5.1.1 Smithfield Beach Gill Net Survey (Delaware River)

Co-op members annually monitor the relative abundance of returning spawning adult shad in the Delaware River. Monitoring occurs after the commercial fishery, such that captured shad represent survivors from the fishery. The majority of this effort is currently being accomplished at one location at Smithfield Beach (RM 218) as a gill net survey on actively spawning adults. Collections at Smithfield Beach principally focus on capture of brood fish and subsequent strip-spawning to produce fertilized eggs in support of the PFBC restoration efforts in the Schuylkill and Lehigh rivers, the largest tributaries to the Delaware River. Approximately 8 to 18 gill nets (200 feet in length by 6 ft deep) are set per night with mesh sizes ranging from 4.5 to 6.0 inches (stretch). The total number of net sets by mesh size per night depends on the previous nights' catch for maximizing female captures. Nets are anchored on the upstream end and allowed to fish parallel to shore in a concentrated array. Netting/spawning operations typically begin on Mother's Day when river flows are workable and river temperatures reach 16C. Sampling occurs Sunday through Thursday evenings and is typically terminated near the end of May or early June when egg viability decreases and/or river temperatures reach 21C for an extended period of days. Typically, the sampling period encompasses three weeks of nightly effort. Biological data collected include gender, length (total and fork), weight (excluding ovarian weight due to the strip spawning procedures), otolith age, scale age, repeat spawning marks, and chemical marks placed on the otolith during rearing. No biological data were recorded prior to 1996. Influences of gill net size selectivity on reported relative abundance was evaluated in the 2017 revision of the Co-op's American Shad Sustainable Fisheries Plan.

The Co-op has finalized protocols for interpretation of age from scale microstructure. Agreed upon scale age distributions and associated mortality estimates have been prioritized for the most recent years of the Smithfield collections, 2015 – 2018, for only female shad. Subsampling of the historic scale collections from Smithfield Beach are currently being processed to determine precision/accuracy of original age determinations compared to the updated protocol. Once completed, the Co-op will pursue scale samples from the commercial fisheries and refocus on updating otolith protocols.

Catch Rates

The primary objective of this survey is to capture mature female shad for broodstock. Mesh sizes fished have varied among and within years to maximize catch of female shad and catch by mesh size is not available from 2010-2015. If the index is used to indicate adult population relative abundance, the proportion of spawning females in the population must be assumed to be proportional to non-spawning adults.

Sampling nights were treated as independent observations and effort was defined as the product of the number of gill nets fished and the total hours fished (net hours). There were twenty eight years of data with averages of 14.25 positive observations per year and 99% positive observations per year (Table 78).

A negative binomial GAM was used to estimate a standardized index of abundance accounting for variability in annual catchability effects. The final model included count of shad as the response variable and year, water temperature at the time of setting the nets, difference in daily average water flow relative to the previous calendar day (percent flow change), mean daily flow, and day of year as covariates. The number of net hours was included as an offset variable. A smoothing function with basis dimensions (i.e., k) of four was estimated for water temperature. AIC was used to select the final model type (GLM vs. GAM), covariates, and basis dimensions for smoothing functions. The final model converged with a dispersion statistic of 1.01, indicating the data were not over-dispersed relative to model expectations.

Catch rates are predicted to increase as water temperatures warm, exceed the overall mean catch rate at approximately 17°C, peak at approximately 20°C, and then remain relatively stable as water warms to the highest temperatures sampled. Catch rates are predicted to decrease as flow increases and also as the sampling season progresses. These predictions follow the survey biologists' observations of reduced spawning activity, and therefore catchability, following cold fronts as water temperatures decrease and flows increase (personal communication; Daryl Pierce, PFBC). The standardized index shows a slower rate of decline through the 1990s than the geometric mean catch rates before generally following the same trend as the geometric mean catch rates. The 2011 standardized index estimate is much larger than the geometric mean catch rate due to very unusual conditions during sampling in this year (very high flows and low temperatures) and is implausible given the surrounding index values. The index starts at time series highs in the early 1990s, generally flows a declining trend to lowest point of the time series in 2009, increases through 2012, then declines through 2016, before increasing in

2017. Annual CVs average 0.14 over the time series (Figure 140). Also of note is the change in sex ratio over time. Proportion of the catch that is female is greater than 0.75 when sex sampling began in the late 1990s, decreased to an around 0.6 for much of the 2000s, and then increased back above 0.75 for much of the 2010s. Reasons for these changes are unknown.

3.6.5.1.2 Lehigh River Electrofishing Survey

Using electrofishing gear, PFBC has sampled upstream migrating adults starting in 1996. American shad were targeted in the Chain Dam plunge pool (RM 2.99) and Palmer Township, Riverview Park pool (RM 2.55), during a one-day survey, typically in mid-June. Therefore, this survey was not included to assess abundance trends (see section 2.3.1). All shad collected are harvested for characterizing length, weight, gender, age, repeat spawns, and hatchery marks.

3.6.5.1.3 Schuylkill River Electrofishing Survey

Using electrofishing gear, the Philadelphia Water Department sampled upstream migrating adults starting in 2002, in the tidal river reach below the Fairmount Dam (RM 8.5). Annual estimates of relative abundance were calculated using CPUE. A subsample of American shad was collected for length, age, sex, repeat spawning, and hatchery evaluations.

3.6.5.1.4 Fairmount Fishway Count (Schuylkill River)

The Philadelphia Water Department monitors upstream fish passage on the Schuylkill River. Time-lapsed video monitoring of upstream migrating adults for passage began in 2004 at only the lower most fish passage at Fairmount Dam. Data from Fairmount Fishway were reported from direct analysis of recorded digital video, in which each-and-every fish was identified and counted, for each-and-every day from April 1st to June 30th. Total passage was not estimated in 2008 due to renovations to the fishway; and in 2014, due to severe spring flooding of the observation chamber, precluding operation of surveillance equipment. No monitoring occurs at Flat Rock or Norristown dams upstream of Fairmount Dam. Black Rock Dam, the upper most dam, is also monitored, but American shad passage is generally low.

Counts are provided in Table 80 and Figure 141.

3.6.5.1.5 Chain Dam and Easton Dam Fishway Counts (Lehigh River)

Total shad passage into the Lehigh River is estimated from the electrofishing CPUE below Chain Dam. A statistically significant positive relationship was found between concurrent estimates of Easton Dam fishway counts and the Lehigh River electrofishing from 1996 – 2012. Fishway counts are not conducted at Easton, Chain, Hamilton Street, or Cementon dams upstream of the Easton Dam.

Counts are provided in Table 79 and Figure 142.

3.6.5.1.6 Cooperative Tagging Program

New Jersey initiated American shad tagging in Delaware Bay as part of the ASMFC Interstate Cooperative Tagging Program in 1995. Drifting gill nets are deployed during March through April target and maximize capture and tagging of striped bass. American shad are caught incidentally and tagged whenever encountered. Annual catch is highly variable in this project. A more comprehensive program targeting only American shad is necessary to perform the project correctly.

3.6.5.1.7 Stocking and Hatchery Evaluation

Restoration of the Lehigh and Schuylkill rivers by stocking hatchery marked and reared shad fry has continued since 1983. The high percentage of hatchery origin shad observed through many of the years in the monitoring time series is suggestive that a self-sustaining wild shad run into the Lehigh River has not yet been realized. However, there is likely some level of natural reproduction occurring in the Lehigh River, as suggested by the general increase of wild (i.e., unmarked) origin shad represented in annual collections.

3.6.5.2 Young-of-Year Fishery-Independent Data Sources

3.6.5.2.1 Tidal Delaware River Striped Bass Seine Survey

In the tidal Delaware River, NJDFW collected data pertaining to young-of-year (YOY) shad during their annual Striped Bass recruitment survey. Since 1980, seining was accomplished using a 100 ft (30.48 m) by 6 ft (1.83 m) bagged seine of 1/4 inch (6.35 mm) delta mesh, during daylight hours. A series of fixed station sites were sampled twice a month June through November. November sampling was discontinued in 2016. Catches from sites were combined into two general regions. Region 2 represents sites (n = 16) from the Delaware Memorial Bridge, RM 70.9, to the Philadelphia Naval Shipyard, RM 94.4; whereas Region 3 represents sites (n = 8) from just north of the Betsy Ross Bridge, RM 105.8 to New Bold Island, RM 125.4. Data from lower Delaware Bay sites were eliminated where YOY American shad are less likely to be encountered in higher salinity waters. In 2015, a QA/QC check was completed on all data sets from the Delaware River resulting in updates to the recruitment indices during the time-series.

Biological and Environmental Sampling

After a seine haul is complete, and the net has been pulled onto the beach, all fish captured are sorted by species, counted and sub-samples of target species are measured. In addition to striped bass, target species include white perch, American shad, bay anchovy, Atlantic croaker, weakfish, blueback herring, Atlantic menhaden, Atlantic silverside, alewife, spot, blue crab, bluefish, hickory shad, winter flounder, black drum and summer flounder.

Water quality parameters such as salinity, water temperature and dissolved oxygen are recorded at every station with a handheld dissolved oxygen (DO) meter that simultaneously measures several different water quality parameters.

Evaluation of Survey Data

Due to sampling consistency, the period of 1987 to 2015 provides the best index of abundance for shad. Over this time period, there were several different sampling strategies relating to sample stations. Seventy-nine stations have been sampled at least once throughout the time series; however, only seven have been sampled consistently from 1987-2017. Twenty-one additional stations to the long term stations have been sampled since 1991, and are considered by NJ to be the 28 'core' fixed stations. From 1987 to 1997, 51 stations served as additional, stratified random stations sampled sporadically along with the core stations. All stations listed above are included in the nominal annual geometric mean JAI.

The historic, nominal index is a geometric mean catch per haul of all stations located between the Delaware Memorial Bridge and Trenton for years 1987 to 2017. The same subset of years and stations was used to calculate the nominal index was used in generalized linear model evaluation.

Initial covariates examined in model development were year, region, month, water temperature, salinity, dissolved oxygen and daily discharge at Trenton, NJ. This full list of covariates was initially run through the following models: Poisson GLM, a negative Binomial GLM, a Poisson GAM and a Negative Binomial GAM. The Negative Binomial GAM model was determined the best initial model based on comparisons of the dispersion parameter. A step-wise evaluation of covariates was then performed for the negative binomial GAM model. The only variable dropped from the data set was dissolved oxygen; the remaining variables significantly impacted catches. The best performing model was Counts ~ factor(Year) + factor(Month) + factor(Region) + s(Water temp) + s(Salinity) + s(Flow). Because of its inclusion of important covariates with catch, the Delaware Co-op considers the GLM index to be the more robust index of abundance for YOY American shad in the non-tidal portion of the Delaware River.

Abundance Index Trends

Model predicted annual catch rates ranged from 2.0 – 57.9 with a 25th percentile of 11.2, median of 19.6 and a 75th percentile of 25.5 (Table 81, Figure 137). There is a non-significant, slightly increasing overall trend in the time series (slope = 0.204; $R^2 = 0.02$), though minor trends are evident when splitting into smaller timeframes. Catch rates increase from 1987 to the first peak in the time series in 1996. This was followed by five consecutive years near the median relative abundance from 1997 to 2001. Catch rates were then highly variable from 2002 to 2008, where three of the lowest predicted as well as the second highest catch rates were observed. Catch rates increase from 2008 through the highest peak catch rate in 2013 and are subsequently variable to present. This survey is one of two in the Delaware River to catch YOY American shad. There is a weak correlation ($n = 26$, $R = 0.321$, $p = 0.111$) between the two indices when examining across the entire time series. However, when displaying both time series on the same plot, there is an obvious, high correlation from 1994 to 2007 ($n = 14$, $R = 0.85$, $p < 0.001$). It is concerning that this similarity in trend is not observed at the beginning or end of the time series.

3.6.5.2.2 Non-Tidal Delaware River Juvenile Seine Survey

The NJDFW conducted sampling for YOY American shad in the non-tidal Delaware River from 1979 – 2007. Sampling was conducted in non-tidal waters, to provide a juvenile abundance index (JAI) for management purposes. Beginning in 1979, only a single site, Byram (RM 157.0), was sampled. Other sites were added in later years with the addition of Trenton (RM 131.6) in 1980, Phillipsburg (RM 184.2) in 1981, Water Gap (RM 210.0) in 1983 and Milford Beach (RM 246.4) in 1988. Sampling was discontinued at the Byram site in 2002 due to heavy siltation without replacement as no suitable replacement beaches were identified. Since 1988, the Trenton, Phillipsburg, Water Gap, and Milford Beach sites were consistently annually monitored for YOY shad recruitment.

Sampling consisted of beach seining at fixed stations generally located adjacent to boat access points with suitable bottom substrates conducive to seining. A series of four seining hauls were accomplished once a month using a 300 ft (91.44 m) by 12 ft (3.6 m) bagless seine of 0.25 inch (6.3 mm) delta mesh, beginning at sunset, from August through October. Hauls occurred over the same swept area, but were separated by 30 minute intervals from the time of retrieval until the next deployment.

Historically production was estimated as annual geometric mean catches for these two separate beach seine surveys (non-tidal and tidal). However, indices showed some correlation from (1988-2007) leading to a proposal by the State of New Jersey to the ASMFC Technical Committee in January 2008 to discontinue the upper river survey as a cost cutting measure. The ASMFC Technical Committee agreed with the proposal and the upper river Non-Tidal Juvenile Seine Survey was eliminated.

Beginning in 2012, the Co-op reinitiated the NJDFW Non-Tidal Juvenile Seine Survey for monitoring American shad YOY production (Figure 126). The original four historic sites, Trenton, Phillipsburg, Water Gap, and Milford Beach are annually surveyed following the original NJDFW protocols. An additional site, located at Lackawaxen (RM 277), was also initiated in 2012. The intent was to provide better understanding of YOY production in the upper reaches of the Delaware River main stem that were not traditionally surveyed by NJDFW. The Lackawaxen site, however, was discontinued after the 2014 season due to excessive submerged aquatic vegetation beds occurring in 2013 and 2014 that effectively prevented seining. The Lackawaxen site was not included in any analysis or estimation of the YOY index.

The National Park Service (NPS) self-funded a one-year synoptic survey of YOY shad occurrence in the upper reaches of the Delaware River main stem, in 2015. The intent was exploratory sampling to identify potential long-term monitoring sites upstream of Port Jervis, New York (RM 254). Two sites were identified in the Delaware River main stem including Skinners Falls (RM 295) and Buckingham (RM 325). Fireman’s Launch (E. Br. Del. R.) and Balls Eddy (W. Br. Del. R.) were also sampled. Young-of-year shad are known to occur in the East Branch of the Delaware River; whereas, they are generally acknowledged to be extirpated from the West Branch of the Delaware River (Sheppard 1983). Outflows from New York City’s Cannonsville Dam begin at the undammed reach of the West Branch and are manipulated to maintain a trout tailwater, which is generally colder than thermal tolerances of YOY shad.

Beach seining was accomplished following original NJDFW protocols. Bottom substrates in the upper Delaware River are best characterized as a mixture of large cobble, rock and boulders. Alternative sampling methodology, including fyke netting and visual surveys, were also investigated with limited success and will not be pursued further (Table 82). As expected, no shad were captured at the Balls Eddy site, which was discontinued after the September sampling. Few YOY shad (< 100 individuals) were caught by seining at the other three sites (Table 82). Rough bottom substrates and flow hindered seine efficiency at the Buckingham site. It was determined that long-term monitoring seining was impractical at the Buckingham site, due to perceived gear inefficiency and poor accessibility to the site. Over the tenure of the 2017 SFP, Co-op members will develop a time-series at the other two sites (i.e., Skinner's Falls and Fireman's Launch) for comparing to downriver catches. Catches from these exploratory sites will not be used in the estimation of the non-tidal JAI index in the 2017 SFP.
Young-of-year shad lengths (i.e., fork length, FL) were measured to characterize trends in size over the time-series. A maximum of 25 individuals were measured for each haul at all non-tidal sites since 1979. Lengths from the four hauls at each non-tidal site were combined. Only lengths from 1983 to present were retained for analysis. Prior to 1983, non-tidal sites sampled and sampling frequency differed from the remainder of the time-series. Beginning in 2000, the first 30 individuals were measured at each site in the tidal reaches. Lengths from each tidal site were combined by region.

Biological and Environmental Sampling
Captured fish are transferred to bins on the shore after each consecutive haul and are not returned to the river until the nights' sampling is completed. A maximum of 25 shad are measured and water temperatures are recorded for each haul. Daily flow is available for the entire time series from the USGS gage at Montague, NJ.

Evaluation of Survey Data
The historic, nominal non-tidal index is a geometric mean catch per haul of all four stations and months combined from years 1980-2007; 2012-2017. In this index, the four consecutive hauls are treated independently as the flow at each station is unidirectional and it is assumed shad YOY are consistently recruited to the site as the night progresses. The resulting index begins in 1980; however, it was not until 1988 that the number of sampling events and current fixed stations were standardized.

During the 2017 Delaware River American Shad SFMP Update, this index was re-evaluated to first, improve the current nominal index and second, to develop a standardized index using generalized linear modeling. The nominal index was improved through the removal of the Trenton site from index calculation. The Trenton location differs from the other three stations as it is located near the head of tide in the Delaware River. Catch rates at this location are an order of magnitude less than the other three sites, and presence and catchability are potentially impacted by tidal influence. As further evidence, catch rates at Trenton are very similar to those observed in NJ's tidal shad YOY index. The new index of Phillipsburg, Delaware Water Gap, and Milford is called 'The Big Three' index and is the preferred nominal index for the Delaware Co-op moving forward. The Big Three index time series start in 1988, when sampling at Milford began.

The same subset of years and stations used to calculate the Big Three index was used in generalized linear model evaluation. Initial covariates examined in model development were year, station, nightly haul number, Julian day, and daily discharge at Montague, NJ. Julian day is a proxy for water temperature as the two are highly correlated throughout the time series (r^2 = 0.87). In addition, Julian day likely accounts for other potential covariates such as light attenuation and lunar cycle. Poisson, Negative Binomial and Zero-Inflated Negative Binomial generalized linear models were examined, and the negative binomial distribution was selected based on the dispersion parameter (1.046). Further evaluation of covariates was performed for the negative binomial models. Discharge and station were dropped the data set as they were not shown to significantly impact catch. The best performing model was Fish Caught ~ Year + Haul + Julian day. Trends in annual predictions from this final GLM model are very similar to the nominal index values except for higher catch rates from 2003 to 2005. Because of its inclusion of important covariates with catch, the Delaware Co-op considers the GLM index to be the more robust index of abundance for YOY American shad in the non-tidal portion of the Delaware River.

Abundance Index Trends

Model predictions of mean number of YOY captured per year, ranged from 52.63 – 485.03 with a 25th percentile of 154.21, median of 183.81 and a 75th percentile of 281.51 (Table 83, Figure 136). The overall trend in the time series is nearly flat (slope = 0.4682; R^2 = 0.0014); however, a couple trends are evident in portions of the time series. There is a slight increase from 1988 to the first peak in the time series in 1996. This was followed by five consecutive years below the median relative abundance from 1998 to 2002. Catches bounced back above the median for four of the next five years until sampling was halted in 2007. Catches have been variable since sampling resumed in 2012. Catch rates have oscillated between the lowest rate (2013) to the highest in the time series (2017), with relative abundances below the historic median in four of the six years.

3.6.5.2.3 Hierarchical Index of Abundance

Both YOY abundance indices are currently used as management benchmarks in the Delaware system. There is weak correlation between indices (Pearson's r=0.32), as well as several missing years of data for the non-tidal index during a period of lower abundance measured by the tidal index, confounding assessment of the overall YOY abundance. Biologists have hypothesized that improving water quality in tidal reaches of the Delaware River during recent years may have disincentivized expenditure of energy by returning adults to migrate upstream in search of suitable spawning habitat, changing the spatial distribution of spawning and, in turn, YOY abundance (personal communication, Daryl Pierce, PFBC). Changes in spatial distribution cannot be diagnosed by the index standardization approach applied in this assessment (GLM or

GAM; Conn 2010), so an underlying hierarchical index was estimated from the two available YOY indices with Bayesian analysis. The objectives were to develop a single, more accurate index of abundance that could be used (1) in subsequent assessment approaches and/or (2) directly to inform management as a suitability metric.

Conn (2010) showed through simulation analysis that his Bayesian model combining multiple available indices results in an index that performs similar to or outperforms the arithmetic mean across the available indices and often outperformed selecting one index from the multiple available indices to infer the true population trend. Specifically, the hierarchical index performed similar to the arithmetic mean across indices and better than selecting one index from multiple available indices when process and sampling error varied among surveys and when spatial dynamics (i.e., varying proportions of the population covered by the various indices) were included in the simulated data and performed better than both when multiple noisy indices were available. The hierarchical index was also robust to indices covering different time periods and varying selectivity patterns.

The analysis assumes all indices are measuring the same quantity (YOY abundance of the Delaware stock) with different catchabilities and varying levels of measurement error, which are input as CVs, and process error, which are estimated. Process error is due to interannual variation in catchability, which is often assumed to not occur (i.e., time-invariant catchability) when interpreting indices of abundance. Process error is assumed to be time-invariant, but variable among indices. Bayesian analysis is applied via MCMC to approximate the posterior distribution of parameters including survey-specific process error, survey-specific catchability (interpreted here as the scaling between the survey-specific indices and the resultant hierarchical index), and annual means of the hierarchical index. Analysis was performed in R (R Core Team 2019) and OpenBUGS via the R2OpenBUGS package (Sturtz et al. 2005).

Model specifications used by Conn (2010) were applied for this analysis. Prior distributions for survey-specific catchability on the log scale, annual means of the hierarchical index on the log scale, and survey-specific process error were specified as normal distributions with a mean of log(0.01) and standard deviation of 0.5, normal distributions with a mean of log(100) and standard deviation of 1, and uniform distributions with bounds of 0 and 5, respectively. Four independent MCMC chains with 60,000 iterations each were run to sample the posterior distributions. The burn-in period was the first 10,000 iterations of each chain and these samples were discarded. A thinning rate of 10 was applied so that 5,000 iterations were retained from each chain to estimate the posterior distribution.

Upper confidence intervals of Gelman and Rubin's convergence diagnostic values were one for all parameters indicating convergence on a posterior distribution across chains (Gelman and Rubin 1992). Survey-specific process errors are in Figure 133 and indicate that the Non-Tidal Delaware River Juvenile Seine Survey captures the underlying trend with more precision than the Tidal Delaware River Striped Bass Seine Survey. This can also be seen in comparison of the survey-specific indices with the hierarchical index, with the hierarchical index tending to be closer to the non-tidal survey index (Figure 134). There were particularly strong year classes in

1996, 2007, and 2017 and particularly poor year classes in 1998, 2003, 2006, and 2008 (Figure 135). The mean CV of the hierarchical index is 0.45, about 2 and 2.6 times the magnitude of mean CVs from the non-tidal survey (0.23) and tidal survey indices (0.17), respectively, which ignore process error. Conn (2010) found that process error estimates tended to be overestimated in some cases and, therefore, CVs of the hierarchical index may be more conservative estimates of the true error.

3.6.6 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance, mean length, and mean length-at-age. Total mortality estimators were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Please refer to section 2 for a description of the methods.

3.6.7 Results

3.6.7.1 Abundance Trends

3.6.7.1.1 Power Analysis

Three fishery-independent abundance indices for American shad, all of which are currently used for sustainability targets and monitoring in the SFMP, were developed for the Delaware River that contained estimates of PSE, the Smithfield Beach Gill Net Survey, the Tidal Delaware River Striped Bass Seine Survey, and the Non-Tidal Delaware River Juvenile Seine Survey. While the power analysis suggests all three of these survey would be able to detect a 50% decrease in abundance in 10 years, only the Smithfield Beach Gill Net Survey would be able to detect a 50% increase in abundance in 10 years with a power exceeding 0.80 (Table 25).

3.6.7.1.2 Mann-Kendall Analysis

Delaware River (JAI)

Separate tidal and non-tidal YOY seine surveys were used as JAIs on the Delaware River. The Non-Tidal Juvenile Seine Survey experienced a peak in 1996 followed by an alternating pattern of decreasing and increasing throughout the time series before again peaking in 2017 (Figure 136). There was an increase in the Tidal Striped Bass Seine Survey JAI through the mid-1990s followed by annual fluctuation with slightly higher peaks as the time series progressed (Figure 137). Mann-Kendall analysis did not detect any trends in either of these surveys from the Delaware River. Mann-Kendall analysis was also applied to the hierarchal index estimated from both of these survey and similarly detected no trend over the entire time series or since 2005 (Figure 138).

Delaware River (FD CPUE)

The fishery-dependent Lewis Haul Seine Fishery CPUE was used as an index for the Delaware River. A plot of the Lewis Haul Seine index showed low levels from 1925 through the early 1960s, followed by a large peak and subsequent decline in the mid-1960s, before gradually increasing through the early 1990s and decreasing again (Figure 139). Mann-Kendall analysis found an increasing trend for both the full time series and the period after 2005.

Delaware River (FI Index)
The fishery-independent Smithfield Beach Gill Net Survey was used as an index for the Delaware River. A plot of the Smithfield Beach Gill Net Survey showed a decline at the beginning of the time series until about 2000 and then a large peak in 2011 (Figure 140). Mann-Kendall analysis found a decreasing trend over the full time series, but failed to detect any trends in the period after 2005 for the Smithfield Beach Gill Net Survey in the Delaware River.

Schuylkill River (Fairmount Fishway Count)
Counts for most years from the Fairmount Fish Ladder on the Schuylkill River were available for analysis for the period between 2004 and 2017. A plot of the run counts by year showed that there was an initial increase from 2007 lows to a peak in 2011 followed by a quick decline (Figure 141). Likely related to the short time series and years with missing data, the Mann-Kendall trend analysis failed to detect a trend for either the full time series or the period after 2005.

Lehigh River (Easton Dam and Chain Dam Run Counts)
Passage counts from two dams on the Lehigh River (Easton Dam and Chain Dam) were provided for analysis for the period between 1994 and 2012. A plot of the run counts versus year showed that there was an initial increase from 1994 through 2001, a steep decline from 2001-2002 and then inter-annual fluctuation in the years following, but remaining at relatively low levels (Figure 142). Mann-Kendall trend analysis found no trend during either time period for the Easton Dam, but found a negative trend for both time periods at the Chain Dam.

3.6.7.2 Mean Length Trends

3.6.7.2.1 Delaware River

American shad length data was provided for the Delaware River from two sampling programs. Lengths from the fishery-independent Smithfield Beach Gill Net Survey are available by sex for all years between 1996 and 2017. A plot of mean lengths showed that mean length peaked in 2002/2003 before declining to the lowest of the time series in 2009/2010 followed by a moderate increase (Figure 143). Mann-Kendall analysis found a significant decreasing trend in female mean lengths, but no trends were found for males. Lengths from the fishery-dependent Lewis Haul Seine Fishery are available by sex for most years between 2008 and 2017. A plot of mean lengths showed that mean length peaked in 2012 before declining (Figure 144). No significant trends in mean length for either sex over time were found in the Mann-Kendall trend analyses for the Lewis Haul Seine Fishery. Three additional data programs were submitted, but excluded from analysis due to small sample size or because the time series was too short.

3.6.7.2.2 Lehigh River

American shad lengths data was provided from the fishery-independent Lehigh River Electrofishing Survey. Lengths are available for most years between 1995 and 2017. A plot of mean lengths (Figure 145) and Mann-Kendall trend analysis indicated no trend in mean lengths of either sex.

3.6.7.3 Mean Length-at-Age Trends

Mean length-at-age data for both scales and otoliths were provided from two sampling programs in the Delaware River, the Smithfield Beach Gill Net Survey and the Lehigh River Electrofishing Survey. Aged fish ranged between ages 3 and 9 for both sexes and only Males were present in the Lehigh River Electrofishing Survey. Mann-Kendall Trend analysis found a decrease in mean length-at-age over time for females ages 5 through 7 from the Smithfield Beach Gill Net Survey using both scales and otoliths (Table 84). Using scales for the Smithfield Beach Gill Net Survey, there was a significant decrease in mean length-at-age of males over time for ages 4, 6, and 7, but only for age 4 using otolith ages. A single decrease in mean length-at-age occurred for age 4 male American shad in the Lehigh River Electrofishing Survey (Table 84).

3.6.7.4 Total Mortality Estimates

Age composition data from length compositions and age-length keys derived from otoliths and scales collected during the Smithfield Beach Gill Net Survey, from scales collected during the Lehigh River Electrofishing Survey, and from scales collected from the Lewis Haul Seine Fishery were used for mortality estimates. Scale-derived data from the Smithfield Beach Gill Net Survey met all criteria (see Section 2.6) for 19 and 12 years between 1996 and 2017 for females and males, respectively (Table 32). Otolith-derived data from the Smithfield Beach Gill Net Survey met all criteria for 19 and 18 years between 1997 and 2017 for females and males, respectively. Female scale-derived data from the Lewis Haul Seine Fishery and Lehigh River Electrofishing Survey met all criteria for 5 and 7 years between 2000 and 2017, respectively. There were some limited otolith-derived data available from the Lehigh River Electrofishing Survey, but these data, along with male scale-derived data from the Lewis Haul Seine Fishery and Lehigh River Electrofishing Survey, did not meet all criteria for any period of three consecutive years and were therefore dropped from the analysis.

Overlapping female mortality estimates among monitoring programs were few and varied without any discernible pattern (Figure 147). Sex-specific mortality estimates between age structures from the Smithfield Beach Gill Net Survey resulted in different patterns (Figure 70). Scale-based estimates were generally lower for females and higher for males relative to otolith-based estimates. Sex-specific trends were more similar between age structures, with the exception of males in the early 2000s. Scale-based male mortality decreased at a greater rate than otolith-based estimates in the early 2000s which were relatively stable, but both age structures indicate a decline in mortality in the late 2000s and an increase in more recent years. Female mortality varied without much trend in the 2000s and decreased to lower levels in the 2010s. The decrease estimated from scale-derived data is more consistent and at a greater rate. The female peak age observed from scale data was lower (age-5) than from otoliths (age-6). This typically resulted in more of a plateau across the first two ages in scale-based data, suggesting a lower total mortality. There was also a more truncated age structure in the scale-based data for both sexes, particularly prior to 2009 and 2007 for females and males, respectively, which is consistent with the typical differences in age between structures (i.e., fish under-aged from scales relative to otoliths). Improved collaboration on ageing practices among agencies appears to have contributed to more consistency between structures since the late 2000s. The three-year average female estimate from otoliths in 2017 (1.3) was above the threshold (Table 33 and Figure 146) and the average standard error for this estimate was 0.49. There were no female data available from scales in 2015 precluding estimation of a three-year average for females in 2017 from this data set (Table 33 and Figure 147).

3.6.7.5 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Delaware system, current unobstructed habitat area represents 72.05% of the historical habitat extent (93.40 of 129.62 square kilometers).

3.6.8 Stock Status and Conclusions

Mortality
Juvenile mortality status is unknown due to lack of data to make this determination. Adult mortality status is unsustainable as the three-year average female total mortality in 2017 was 1.3 which is above the $Z_{40\%}$ threshold (1.07).

There were conflicting trends in female mean length detected from three data sets, with a declining trend detected from the Smithfield Beach Gill Net Survey (1996-2017) and no trend in the Lewis Haul Seine Fishery (2008-2017) or Lehigh River Electrofishing Survey (1999-2017). There were no trends detected in YOY abundance since the late 1980s or 2005 (two data sets).

Abundance
Abundance status is unknown. There have been no trends in YOY abundance (2 data sets) since 2005. There have been conflicting trends in adult abundance since 2005, with an increasing trend detected from the Lewis Haul Seine Fishery and no trend detected from the Smithfield Beach Gill Net Survey, further confounding assessment of adult abundance conditions in recent years.

3.6.9 Research Recommendations

3.6.9.1 Progress on 2007 Stock Assessment Research Recommendations

1. No relaxation of the current regulations or sampling requirements take effect until the shad population is estimated to be at least 750,000 fish throughout the entire spawning reach of the Delaware Basin for more than two consecutive years. This recommendation is taken from the original Delaware River Basin Plan and would be dependent on the Delaware Basin States *determination of a reliable estimator of the population throughout the entire spawning reach of the Delaware Basin.*

- There has been no relaxation of the commercial regulations since the 2007 assessment. Due to the limited entry and limited transferability nature of the American shad fishery in New Jersey landings since 2007 have been decreased by an average of 50% compared to 2000 through 2007. This can be attributed to a decrease through attrition of effort by fishermen and a lack of demand for the fish. Since the 2007 assessment the recreational bag limit in the main stem Delaware River has been decreased from six fish to three fish while the limit in Delaware remains at 10 fish. All sampling method requirements that were in place at the time of the 2007 assessment remain in effect and continue to be maintained. Due to a lack in faith of the methods (hydroacoustic) used to generate the target population of 750,000 shad, no further evaluation of the total shad population in this system has been carried out.

2. Undertake a more thorough investigation into predator-prey relationships to determine if predation on shad by striped bass or other predators is a significant problem.

- Predator-prey relationships continued to be investigated using MRIP striped bass catch data and commercial catch data from the American shad bay fishery. Although some analyses show potential interactions between shad and striped bass, there is no empirical data to attribute the shad decline in the Delaware River solely to striped bass as in Connecticut River.

3. Determine fishing mortality on the Delaware River stock from out of Basin activities including bycatch discard in other fisheries.

- Determining out of basin mortality from ocean intercept bycatch and discard in other fisheries remains a challenge on a coastwide basis. Since the 2007 stock assessment the adult shad in the lower bay have continued to be tagged when caught incidentally in New Jersey's Delaware Bay Striped Bass Tagging Survey, although numbers tagged have been on the decline. The low sample sizes limit the utility of the data in applying the stock composition in the Delaware Basin to that of the coastal migratory population.

4. Initiate investigations to ensure that habitat quality and suitability within the Delaware Basin is adequate to restore the American shad stock in the Delaware River and its tributaries.

- All member states and organizations of the Delaware River Basin Cooperative continue to work with governmental and non-governmental agencies within their jurisdictions on water quality and habitat projects to increase habitat quality and suitability within the basin

5. Obtain annual estimates of the recreational catch, harvest, and CPUE.

- The last survey of the recreational fishery was an access point survey in conjunction with an aerial effort survey conducted by Versar, Inc. during 2002 (Volstad et al. 2003). The study area included all tidal and non-tidal waters from the Delaware Memorial Bridge to Downsville, NY. No recreational fishery surveys have been undertaken since 2002 due to the large area required to be covered and a lack of funding and resources to undertake such an effort. Most, if not all, of the recreational fishery takes place above the head of tide in the main stem Delaware and as a result this effort is not captured by the Marine Recreational Information Program.

6. Require all commercial shad fisheries within the Delaware Basin to sample for hatchery-marked restoration fish.

- The states of New Jersey and Delaware collect otoliths from commercial shad fishermen for ageing purposes which can be used for determination of wild/hatchery origin fish. Due to research priorities and staff levels these otoliths are being archived until such time that they can be properly analyzed.

7. The Delaware River Basin Cooperative's Technical Committee reviews this assessment for guidance in developing a new management plan for the Delaware River Basin.

- The Delaware River Basin Cooperative's Technical Committee developed a Sustainable Fishery Management Plan for the Delaware Basin that was approved for implementation in 2012. That plan is currently on its second iteration and will be in place through 2021.

8. Continue to stock tributaries to the Delaware River with fish from the Delaware system.

- The stocking plans that were in place since the 2007 assessment have been continued. Since 2000 Delaware River shad fry have been allocated to the Lehigh, Schuylkill, and Delaware rivers.

3.7 Nanticoke

3.7.1 Habitat Description

The Nanticoke River is a large, eastern shore tributary of the Chesapeake Bay that once supported substantial runs of American shad. In a report of historical fisheries by Stevenson (1899), the Nanticoke ranked third in landings of American shad among Maryland rivers in 1896, trailing only the Potomac and Choptank. Through the early and mid-1900s, landings decreased substantially throughout the region, though the decline in the Nanticoke was more moderate than most other rivers; in 1960, the Nanticoke River commercial catch exceeded that of all other Maryland waterways outside of the main stem of the Chesapeake Bay. While the Nanticoke is one of many eastern shore Chesapeake Bay tributaries to originate in Delaware, it is the only river that provides any appreciable American shad habitat beyond the Maryland state line. Navigable waters begin near Seaford, Delaware and flow approximately 18 km to the Maryland state line, from which the river flows another 56 km to its confluence with Tangier Sound in the Chesapeake Bay (Mansueti and Kolb, 1953).

American shad are known to ascend the Nanticoke River at least to Seaford, Delaware, and Marshyhope Creek (a significant tributary) to Federalsburg, MD, 88 km from Tangier Sound (Walburg and Nichols, 1967). The majority of the Nanticoke River, as well as most of Deep Creek and Broad Creek are considered suitable adult American shad spawning habitat and YOY rearing habitat (current and historic). Any barriers to anadromous fish habitat use in the

Nanticoke River are located far enough upstream that they do not impact migration, spawning, or rearing of American shad (Martin and Apse, 2013). Within Maryland, 100% of the historical spawning and rearing habitat for American shad in the main stem of the Nanticoke River is currently available. Additionally, 100% of the historical spawning habitat in Marshyhope Creek is currently available (Capossela, 2014). River herring also spawn within two primary tributaries that flow into the Nanticoke River within Delaware boundaries: Deep Creek which begins at the dam below Concord Pond and flows into the Nanticoke proper at Seaford, DE, and Broad Creek, which extends from the dam below Records Pond in Laurel, DE and flows into the main stem of the Nanticoke just upstream of the Maryland state line. Although the dams on Deep Creek and Broad Creek inhibit upstream passage, there is sufficient spawning habitat below the structures to maintain a stable run.

The Nanticoke River watershed is dominated by agriculture (approximately 45%) and forest (approximately 40%). Given the low percentage of impervious surface cover (less than 5%), the river has been identified as a conservation watershed with respect to alosine fishes by the Maryland Department of Natural Resources Fisheries Habitat and Ecosystem Program (FHEP) (Uphoff et al., 2017; Capossela, 2014). However, the high density of agricultural land cover in the watershed may contribute to elevated sediment, nutrient, and pesticide loads within American shad habitat, which may negatively impact spawning success (Uphoff et al., 2017). The degree of siltation is likely less severe than that of western shore Chesapeake Bay tributaries as the flat land of the eastern shore coastal plain does not promote rapid runoff into rivers (Mansueti and Kolb, 1953).

3.7.2 Fishery and Management History

Commercial and recreational American shad fisheries have been closed in Maryland since a moratorium was enacted in 1980. Recreational catch-and-release fishing is still permitted and is concentrated below Conowingo dam on the Susquehanna River and to a lesser extent, the Potomac River. Little if any targeted recreational fishing for American shad occurs on the Nanticoke River. Beginning in 2001, Maryland implemented voluntary angler surveys to collect catch and effort data on the recreational catch-and-release American and hickory shad fisheries. Since the inception of these surveys, no attempts to capture American shad in the Nanticoke River by a recreational angler have been reported.

Maryland commercial fishermen are permitted to keep up to two American shad per day per commercial license holder if the shad were landed dead in commercial gear legally deployed for the capture of species other than American shad (COMAR, 2019). There is no data available on this harvest as it has rarely been observed by onboard biologists, but it is thought to be negligible.

Delaware closed the commercial and recreational fisheries for American shad in the Nanticoke River in 2000. It is unlawful for any person to take and reduce to possession any American shad from the Nanticoke River or its tributaries. The DE DFW discontinued monitoring American shad bycatch during the commercial Striped Bass season since no bycatch had been reported over a 10-year period from the Striped Bass Fishery. The Striped Bass fishery minimally impacts

American shad on the Nanticoke River because the Striped Bass season (February 15-March 31) occurs before American shad primarily migrate upriver through the fishing grounds and there is a low number of commercial fishermen (2018, N=3) that actively fish the Nanticoke River. Drift nets must be used. In addition, gill net fishermen tended to use larger mesh nets for Striped Bass over the past few years, preferring a 7” mesh that allows the majority of American shad to pass though the net.

3.7.3 Anthropogenic Sources of Mortality and Productivity

3.7.3.1 Sources of Mortality

Anthropogenic mortality of American shad in the Nanticoke River system is primarily attributed to bycatch of migrating adults by pound and fyke net fisheries targeting white perch, gizzard shad, and catfish species. Mortality estimates associated with these gear types have not been formulated.

3.7.3.2 Sources of Productivity

Stocking of OTC marked American shad of various early life stages was conducted the Nanticoke River from 1995 to 2006 by Maryland DNR (Table 85). Due to difficulty in obtaining juvenile American shad samples in the river, evaluations of hatchery contributions were not completed in the main stem. MD DNR also stocked OTC marked American shad in Marshyhope Creek, a major Nanticoke tributary, from 2002 to 2009 (Table 86). The proportion of hatchery to wild fish in the Marshyhope Creek Restoration Juvenile Seine Survey generally increased over time (Table 87).

The State of Delaware operates a hatchery on the Nanticoke River for American shad. The Nanticoke Shad Hatchery, built in 2003-2004 (Stangl 2004, 2005) and located adjacent to the river on State-owned property within the Nanticoke Wildlife Area, produces all of the American shad stocked into the upper Nanticoke River basin. The hatchery uses fish that are native to the Nanticoke River to preserve genetic integrity. Three-day-old shad larvae are stocked in the upper Nanticoke River, Deep Creek, and Broad Creek. The culturing provides a “jump start” for a struggling population by protecting the egg stage and early juvenile fry which frequently experience high rates of natural mortality in the wild. It is apparent from the hatchery efforts that many of the eggs expelled do not fertilize. In the wild, all eggs are exposed to predation and fungal infections. Crecco et al. (1983) demonstrated that larval phase mortality of American shad in the Connecticut River ranged from 19-26% per day. All hatchery-bred fish received an OTC mark by larval immersion. A subsample of American shad caught during juvenile monitoring was examined for OTC marks on the otolith to determine what portion of the juveniles was of hatchery origin and to ascertain survival and recruitment. American shad will continue to be stocked into the upper Nanticoke River until either natural reproduction is determined to be capable of sustaining shad populations or there are no observed improvements in the number of juveniles or returning adults noted.

3.7.3.2.1 Egg Collection and Culture

All tank spawning occurred from dusk to dawn, with no egg collections during daylight hours. Dispersed eggs were collected in an egg sock located in a rectangular egg collection tank following spawning events. The eggs were gently sifted to remove foreign particles and white or opaque (dead) eggs were removed using a siphon tube. Fertilized eggs were measured volumetrically and placed in incubation jars. The fertilization rate was determined approximately 24 hours following a spawning event after the initial culling of the dead eggs. A single row of eggs was placed in a Von Bayer trough and counted to determine the number of eggs per liter. A 10-ml sample of eggs was extracted with a glass siphon tube and placed in a Petri dish for examination under a Leica Zoom 2000 stereoscope. The number of fertilized eggs and dead eggs were recorded and the percentage of fertilized eggs was calculated. Egg viability was measured to determine the percentage of a batch of eggs that reached late-stage embryo development and to predict hatching success. Egg viability was calculated as the difference between the initial egg volume (i.e. the volume when first placed into the incubation jar) and the volume of “eyed” eggs remaining in the jar just prior to hatching. “Eyed” eggs were those embryos with pigmented eyes. The eggs began to “eye up” as early as the fourth day in the incubation jars, depending on water temperature. The incubation jars were moved to the culture tanks when the eggs reached the eyed stage, so that newly hatched shad larvae would flow directly into the culture tanks. Hatching was generally complete within six or seven days after spawning, but varied with river water temperature.

Larvae were marked within the culture tank at three days of age using a minimum four hour static bath treatment of 384-ppm sodium bicarbonate buffered OTC (Pennox-343) solution. During marking, the water flow going into the larval culture tank was stopped, and air diffusers were placed in the tanks to aerate and circulate the water. Normal culture tank flows were resumed following the marking bath treatment. The marked shad were stocked into the upper Nanticoke River tributaries later the same day.

3.7.4 Fishery-Dependent Data Sources

Delaware closed the commercial and recreational fisheries for American shad in the Nanticoke River in 2000.

3.7.4.1 Commercial Landings

Based on Stevenson’s (1899) data from 1896, American shad landings from the Nanticoke River were almost one million pounds (812,417 pounds landed in Maryland and 182,250 pounds landed in Delaware); there were over 400 gill nets, 38 pound nets, and 143 fyke nets fished in the river and it ranked third in landings for the state in that year.

Commercial landings data from the Nanticoke River, 1930 through 1980, are presented in Table 88. In 1960, the Nanticoke River ranked first in American shad landings in Maryland with 85,302 pounds (Walburg and Nichols, 1967) and an additional 2,000 pounds were landed in Delaware. It was primarily a gill net fishery with only 15 pound nets fished from Vienna to the mouth, which landed only 10,023 pounds of American shad (Walburg and Nichols, 1967). Although there is no effort associated with this data, they show a significant drop in reported landings during the time series.

3.7.4.2 Commercial Catch Rates

3.7.4.2.1 Nanticoke River Commercial Pound Net CPUE

The Nanticoke River has the longest time series of fishery-dependent CPUE data in Maryland for American shad. The same family of commercial watermen has cooperated with MD DNR since the inception of this project in 1988. American shad in the Nanticoke River were collected in zero to ten fyke nets and zero to four pound nets one to two times per week south of Vienna, Maryland between mid-February and late-April at the discretion of the commercial watermen. The nets were located between river kilometer 30.4 and 35.7 (Figure 148).

Biological Sampling Methods
Fish were sorted according to species and transferred to the survey boat for processing. All American shad were measured for length (mm), sexed, and scaled for ageing. Beginning in 2007, American shad landed dead were brought back to the lab for further analyses including weight and otolith removal. Otoliths were sent to the DE DFW for OTC mark examination to contribute to their hatchery versus wild origin population proportion estimates. Ages of these fish were determined by MD DNR by scale examination.

CPUE Estimation Methods and Trends
While other pound net sites have been sampled along the Nanticoke River, this index is based only on data from the Mill Creek pound net site. This site was chosen as it has been consistently used throughout the time series and has more catch records compared to other sites. The net has been sampled from 1996-2017 with no samples collected in 2004 or 2015. Only sampling events with data on water temperature and salinity were used in the analysis. While dissolved oxygen and conductivity were also available as potential covariates, dissolved oxygen values were missing from too many years to be usable and conductivity provided similar information as salinity. This net was sampled anywhere from 2-16 times during the sampling season (usually March-April) with an average sampling frequency of 8 times in a season. The nets were set anywhere from 3 to 10 days (mean: 3.9 days, median: 4 days). The data were fit using a negative binomial GAM that had year as a covariate, a smoother on water temperature, and an effort offset where effort was defined of days the pound net was fishing. Water temperature had a very non-linear relationship with catch and the model diagnostics generally looked good.

Starting in 1996, the index decreased to a low in 1999 before again increasing through 2003 (Table 96, Figure 154). The survey was very variable but without trend from 2005-2009. Another peak was seen in 2012 but all CPUEs since then have been low with a decrease in CPUE observed between 2016 and 2017.

Commercial Length/Weight/Catch-at-Age
From 1989 to 2017, male American shad sampled from the Nanticoke River ranged in age from 2 – 9 (Table 89); females ranged in age from 1 – 10 (Table 90). Age-4 was the most common age

for males while age-5 was most common for females. Eight-five percent of all fish captured by the survey, irrespective of sex, ranged in age from 4 – 6 (Table 91). The presence of repeat spawning fish in the river has increased over the time series (1989-2017; Table 92; Figure 149; $R^2 = 0.37$, $P < 0.001$). Mean fork length-at-age statistics are presented in Table 93 - Table 95.

Potential Biases, Uncertainty, and Measures of Precision
Relative abundance, measured as CPUE, was only calculated from catch at one sampling location (Mill Creek pound net) over the time series. While this net was chosen based on its presence in most years of the survey and its placement in favorable American shad habitat, there are concerns regarding the ability of this index to track changes in relative abundance. Given that American shad in-river migratory patterns are likely not fully spatially persistent year to year, this index is inherently biased relative to a random stratified survey design (Lee and Rock 2017).

3.7.5 Fishery-Independent Data Sources

3.7.5.1 Adult Fishery-Independent Data Sources

3.7.5.1.1 Nanticoke River Electrofishing Survey

The state of Delaware uses electrofishing to collect adult American shad. Electrofishing collections are conducted in two sections of the upper Nanticoke River drainage to establish an annual index of relative abundance. The catch rate of adult shad taken in Deep Creek and the upper Nanticoke River (Nanticoke Branch) during sampling and brood fish collections are used to calculate the index. An electrofishing raft (Figure 150), outfitted with a 5,000-watt Honda generator and a Coffelt VVP-15 variable voltage pulsator set on pulsed DC current is used for all collections (Stangl 2001). Voltage is applied on an intermittent basis, which allows the capture of numerous schools of fish within the sampling locations. All collections are conducted traveling with the tide. Zero catches at the start and end of the season are not used in the calculation for effort for the CPUE. Sampling ceases at the end of the season when the total number of American or Hickory Shad caught is fewer than five.

Previous sampling efforts indicated that many of the adult shad were encountered at the same locations on the streams year after year, demonstrating specific daytime habitat preferences. Sampling is normally conducted from April through May. The section sampled on Deep Creek extends from the base of the spill-pool below Concord Pond dam downstream to where the river widened (Figure 151). Downstream of this point, the electrofishing raft is less effective at consistently sampling shad due to the greater depth and volume of water within the river channel. The area sampled on the Nanticoke Branch begins at the Middleford Bridge and extends as far upstream as the raft can be navigated (Figure 152). The Nanticoke Branch above this point is blocked with numerous fallen trees. CPUE is calculated as the total number of adult shad caught per hour of electrofishing. Total length, sex and scale samples (taken below the dorsal fin) are collected from fish not retained for tank spawning to aid in characterizing the American shad population before releasing each fish. Total length and sex are recorded for Hickory Shad. American shad that die during electrofishing are retained for otolith analysis to estimate the proportion of hatchery-reared juveniles that return as adults to the upper Nanticoke River and Deep Creek to spawn. Adult otoliths are extracted and prepared using the same methods described above for juvenile shad. American shad in the mid-Atlantic region are typically iteroparous, they survive after spawning; therefore, scales collected for age analysis often include the presence of a repeat spawning mark. American shad scales are aged using techniques described by Cating (1953), although the efficacy of this method has been questioned for known-age fish obtained from the Delaware River (McBride et al. 2005). Ages are determined, and analyses of age and repeat spawning marks are performed.

Index values are provided Table 97 and Figure 156.

3.7.5.2 Young-of-Year Fishery-Independent Data Sources

3.7.5.2.1 Nanticoke River Juvenile Haul Seine Survey

Monitoring of juvenile American shad was initiated in 1999 by the DE DFW and has been continued annually to assess reproduction and recruitment. Sampling is conducted at four locations using a haul seine during ebb or low slack tide. Seining occurs approximately every two weeks from July through October at two sites located on the upper Nanticoke River, one site downstream of the Woodland Ferry, and one station located on lower Broad Creek (Figure 153). A 45.7-m long x 3.0-m deep haul seine constructed of 6.35-mm nylon mesh net is used to conduct the seining. One end of the net is anchored to the shoreline with the remainder of the net deployed from the bow of the boat in a semicircle pattern and hauled to shore. Alosine samples with more than 90 individuals per species are randomly sub-sampled for length with the remainder being counted. All other finfish collected are identified to species, counted, and released. The geometric mean number taken per haul is used as an index of relative abundance for each species. The method for calculating the geometric mean (GM) involved logarithmic transformation of the arithmetic mean as described in Sokal and Rohlf (1995), ASMFC (1992), and Crecco (1992). Typically, a few large catches of alosine species has occurred every year since the DE DFW began sampling with a haul seine in 1999. The geometric mean is used to smooth out the bias associated with single large catches of schooling species. Confidence limits (95%) of the log-transformed values are calculated for the geometric mean. Catch per unit effort (CPUE), recorded as fish caught per haul, and the associated standard error is calculated for each of the four species.

A sub-sample of juvenile American shad collected during haul seining is retained for otolith mark analysis. Sagittal otoliths are extracted and mounted on slides with Crystalbond 509 adhesive. Otoliths are ground to the core using 600-grit waterproof sandpaper, then examined for OTC marks under a 50x objective on a Zeiss Axioscope 40 epi-fluorescence microscope. The presence and location of a mark are recorded to determine the percentages of hatchery-produced and wild fish in the sample. In addition to determining an index of relative abundance, the percentage of marked fish over the time -series is examined to determine when natural reproduction overwhelms the numbers of stocked fish in the system. This will indicate that the stock is heading towards a stabilized naturally reproducing population.

Index values are provided in Table 98 and Figure 155.

3.7.6 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance, mean length, and mean length-at-age. Total mortality estimators were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Details for these methods are provided in Section 2.

3.7.7 Results

3.7.7.1 Abundance Trends

3.7.7.1.1 Power Analysis

The only abundance index for American shad in this region containing estimates of PSE was the fishery-dependent Nanticoke River Commercial Pound Net CPUE. This survey exhibited a median PSE of 0.306. Given this median PSE the power analysis suggests the survey would not be able to detect a 50% change in abundance (power > 0.80) in 10 years (Table 25). Currently, there is no SFMP for this system so this CPUE is not used for sustainability targets and monitoring.

3.7.7.1.2 Mann-Kendall Analysis

Nanticoke River (FD CPUE)
Maryland DNR provided Nanticoke Commercial Pound Net CPUE data for most years between 1996 and 2017. No apparent trend was observed when the data was plotted versus time (Figure 154) and Mann-Kendall trend analysis failed to detect a trend in either time period in the analysis.

Nanticoke River (JAI)
JAI for the Nanticoke River increased steadily from 2000-2004, remained fairly stable through 2007, peaked in 2009, and rapidly declined afterwards (Figure 155). Mann-Kendall trend analysis detected a negative trend in the years after 2005, but found no trend over the full time series.

Nanticoke River (FI CPUE)
Fishery-independent survey data from the Nanticoke River Electrofishing Survey was examined for the years between 2002 and 2017. No apparent trend was observed when the data was plotted versus time (Figure 156) and Mann-Kendall trend analysis failed to detect a trend in either time period in the analysis.

3.7.7.2 Mean Length Trends

Delaware DFW provided length data for the fishery-independent Nanticoke River Electrofishing Survey for 2002-2017 and Maryland DNR provided length data from the fishery-dependent Nanticoke River Commercial Pound Net Monitoring Program from 1988-2017. A plot of mean length versus year from the fishery-independent survey showed a slight decrease in mean lengths over time for both sexes, with the steepest decline occurring from 2006-2008, followed by a gradual increase back to lengths similar to the beginning of the time series (Figure 157). Mann-Kendall trend analysis did not detect a significant trend for either sex. A plot of the fishery-dependent monitoring showed a decrease in fish size from the late-1980s through 1994, an increase in lengths from 1994-2011/2012 and then a general decrease in mean length since (Figure 158). Mann-Kendall trend analysis did not detect a significant trend for either sex. Two additional data programs were submitted, but excluded from analysis due to small sample sizes or because the time series were too short.

3.7.7.3 Mean Length-at-Age Trends

Mean length-at-age data using scales were provided from two sampling programs, the fishery-independent Nanticoke River Electrofishing Survey and the fishery-dependent Commercial Pound Net Monitoring. Fish in the Nanticoke River Electrofishing Survey ranged from age 3 to 9, and in the Commercial Pound Net Monitoring ages were between age 2 and age 8. Mann-Kendall Trend analysis failed to detect any change in mean length-at-age over time in either of the surveys (Table 99).

3.7.7.4 Total Mortality Estimates

Age composition data tabulated from scales collected randomly or by census during the MD DNR Commercial Pound Net Monitoring were used for mortality estimates. Data met all criteria (see Section 2.6) for 12 and 18 years between 1989 and 2016 for females and males, respectively (Table 32). Female mortality varied without trend (Table 33 and Figure 159). Male mortality increased in the mid-1990s and late 2000 and decreased in the early 1990s and recent years. There were no female data available in recent years precluding estimation of a three-year average for females in 2017.

3.7.7.5 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Nanticoke system, current unobstructed habitat area represents 100% of the historical habitat extent (4.03 square kilometers).

3.7.8 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. The adult mortality status is also unknown as there were no recent estimates of female total mortality. The most recent three-year average female total mortality was 0.71 in 1996 which is below the $Z_{40\%}$ threshold (1.07).

There were no trends detected in female mean length from two data sets (1988-2015, 2004-2017). There was a declining trend detected in YOY recruitment since 2005, but no trend since 1999.

Abundance
Abundance status is unknown. There was a declining trend detected in YOY abundance since 2005, but no trends detected in adult abundance (two data sets) since 2005.

3.7.9 Research Recommendations

3.7.9.1 Progress on 2007 Stock Assessment Research Recommendations

1. Re-key lost data on the Nanticoke River

- Nearly the entire time series of fishery-dependent Nanticoke River data was made available for this assessment, with a couple notable exceptions. Data for the first year of the survey, 1988, were excluded after substantial discrepancies were found between currently available data and what was reported for the 2007 assessment. Additionally, no repeat spawning analysis was completed for 1994 due to missing values in digital data sets. No hard copies of 1988 or 1994 data have been found to reconstruct these portions of the data set.

2. Continue to collect fishery-independent data from the Nanticoke River

- Fishery-independent data generated by MD DNR are limited in the Nanticoke River to the Striped Bass Juvenile Seine Survey (SBSS; 1959-present) and a mid-water trawl survey (1985-1996), but both sample American shad YOY. However, these surveys collect few American shad in the Nanticoke River because the salinity in the sampling areas is often higher than the preferred maximum of 5 ppt for YOY shad. Therefore, results of these surveys do not produce reliable YOY indices.

- The fishery-independent data collections that were in place in Delaware since the 2007 assessment have been continued.

3. Define the predator-prey that may exist between piscivorous fish (e.g., striped bass, flathead catfish) and American shad by analyzing stomach contents of potential predators

- No concentrated efforts to identify the impacts of predation on American shad have been completed in Maryland or Delaware. However, Schmitt et al. (2017) analyzed prey selectivity of both blue catfish (*Ictalurus furcatus*) and flathead catfish (*Pylodictis olivaris*) in a Virginia Chesapeake Bay tributary, the James River. Their findings indicate that blue catfish had broad omnivorous diets but became more piscivorous with age. American shad were a minor component of their diet. Flathead catfish were exclusively piscivorous and selectively preyed upon American shad. Additionally, they found that migration obstacles may significantly increase the susceptibility of alosine fishes to catfish predation.

- Blue catfish have a widespread distribution and inhabit the freshwater and even brackish portions of most Chesapeake Bay tributaries within Maryland. In many rivers, such as the Nanticoke, their population has expanded rapidly and they are now the dominant catfish species caught by commercial fishermen. Flathead catfish distribution within Maryland is more limited, with populations concentrated in the Upper Chesapeake Bay, Susquehanna River, and Potomac River. Perhaps most disconcerting is that the most dense flathead catfish population occurs at the base of the Conowingo Dam on the Susquehanna River, a major aggregating point for American shad. Another invasive predator, the northern snakehead (*Channa argus*), may present a threat to primarily juvenile American shad. Diet studies are ongoing, but given their relative novelty in most Maryland rivers, the impacts of snakehead predation are unknown.

- Predator-prey relationships are planning to be investigated more thoroughly due to the increased presence of invasive species (e.g. Northern Snakehead, Blue Catfish), as staff and funding permits.

4. Partition the hatchery and non-hatchery components of the samples in the Nanticoke River and then calculate CPUE for each

- MD DNR extracts otoliths from a limited number of American shad that are found dead upon removal from commercial fishing gear in the Nanticoke River. Hatchery vs. wild determination is completed by the Delaware Division of Fish and Wildlife. Given the small sample size, these proportions are not considered representative of the entire population in Maryland's portion of the Nanticoke and CPUE has not been calculated separately for hatchery and wild fish.

3.8 Susquehanna River and Upper Chesapeake Bay

3.8.1 Habitat Description

The Upper Chesapeake Bay system comprises a complex of waterways that converge in the vicinity of the Susquehanna Flats. While the Susquehanna River and its tributaries provide the majority of American shad habitat in the Upper Chesapeake Bay system, it also includes a number of small rivers and creeks in Maryland that contribute minor amounts of habitat for American shad, but are not considered distinct stocks. These include the North East, Elk, Bohemia, and Sassafras Rivers, Principio Creek, and the C&D Canal. There are no barriers that restrict American shad habitat within these small tributaries, but significant barriers exist in the Susquehanna River (Martin and Apse 2013).

The Susquehanna River is a wide, shallow river characterized by erosion resistant sandstone ledges, alternating with long, gravel-bottom pools. It is the second largest river in eastern North America, draining over 71,225 square kilometers, including parts of New York and Maryland and nearly one-half of Pennsylvania. The main stem originates in Lake Otsego, New York and travels 714 km to its mouth at Havre-de-Grace Maryland. Major river tributaries include the West Branch (367 km) and the Juniata River (161 km) (Carlson 1968). The Susquehanna River provides greater than one-half of the freshwater input to the Chesapeake Bay, an average inflow of 32,000 cubic feet per second (Miller et al., 2010).

Historically, American shad migrated long distances and extended into the headwaters of the Susquehanna River Basin (Figure 160). Major seine fisheries were documented upstream to Huntingdon on the Juniata River, Lock Haven on the West Branch and well into New York on the North Branch (Gerstell 1998). The first dams to block shad migrations were the milldams on tributaries, beginning in the 1700s. During the early 1800s canal dams (most notably the Columbia Dam) were built to supply various barge canals with water. These dams effectively blocked shad migrations in some years, but were subject to breaching by floodwaters in high water years. Canal dams were abandoned as the railroad replaced the canal system for transport of goods across country. Construction of four hydroelectric dams (York Haven, Safe Harbor, Holtwood, and Conowingo Dams) in the lower river in the early twentieth century effectively blocked shad runs and inundated 73 km of riverine spawning habitat. York Haven was the first of these dams to be completed in 1904 at river km (rkm 88), followed by Holtwood (rkm 40) in 1910, Conowingo (rkm 16) in 1928, and Safe Harbor (rkm 51) in 1931 (Miller et al., 2010).

In addition to the inundation of spawning habitat, these dams significantly altered the flow regime of the river. With the exception of York Haven, these hydroelectric dams can operate in a peaking mode, resulting in higher flows during periods of energy demand and minimal flows during periods of low demand. Such operation alters the flow regime to the extent that flood and drought conditions may occur within minutes of each other. These conditions create poor habitat which few organisms can accommodate, particularly anadromous fish who require specific conditions for fish passage and spawning (Miller et al., 2010). Peaking mode operation can also create water quality concerns. Prior to the implementation of minimum flow requirements in 1971, Conowingo Dam could completely shut down river flow in periods of low energy demand. This resulted in low oxygen concentrations and caused fish kills of anadromous species in 1965 and 1971 (Carter 1973).

Adult American shad upstream passage at Conowingo Dam began in 1972 with a trap and truck transport operation. The Conowingo East Fish Lift, originally constructed in 1991, gained the capacity to independently pass fish to Conowingo Pond in 1997. Fish elevators became operational at both Safe Harbor and Holtwood Dams in 1997. A vertical slot fishway was installed at York Haven Dam in 2000, and planning of nature-like fishway for passage at this dam is currently ongoing. These fish passage operations have opened a total of 196 river km for American shad migration and spawning. However, overall fish passage has been consistently below expectations and well below the capacity of the fish lifts and fishways (Miller et al., 2010).

3.8.2 Fishery and Management History

3.8.2.1 Maryland

Commercial and recreational American shad fisheries have been closed in Maryland since a moratorium was enacted in 1980. Recreational catch-and-release fishing are still permitted and is concentrated below Conowingo Dam on the Susquehanna River. Maryland has implemented a voluntary paper logbook survey to collect data on the recreational hook and line, catch-and-release American and hickory shad fisheries since 2001. Beginning in 2014, paper logbook reports were supplemented with data from an online angler survey.

Maryland commercial fishermen are permitted to keep up to two American shad per day per commercial license holder, if the shad were landed dead in commercial gear legally deployed for the capture of species other than American shad (COMAR 2019). There are no data available on this harvest as it has rarely been observed by onboard biologists, but it is thought to be negligible.

3.8.2.2 Pennsylvania

No commercial fishing for American shad has occurred in the Susquehanna River above Conowingo dam since dam construction in the early 1900s. No recreational harvest of American shad is permitted in Pennsylvania waters of the Susquehanna River. There can be a very limited recreational catch-and-release fishery, concentrated below York Haven Dam and Dock Street Dam (a low head, partially breached dam at Harrisburg), when sufficient numbers of shad are passed at Safe Harbor and York Haven Dams. No data have been collected from these periodic recreational fisheries.

3.8.3 System-Specific Life History

3.8.3.1 Growth

Growth rate studies for American shad in the Chesapeake Bay have concentrated on young-of-year (YOY) and probably reflect the difficulty of ageing. Carter (1973) presented extensive data on weekly lengths of YOY American shad caught using various gear types in the Susquehanna River and Flats area in 1969. He reported high variation between sites and gear types that were likely associated with a change in preferred habitat as the fish grew; therefore, he was likely not measuring growth but rather movement and an extended hatching period.

Growth rates of YOY shad in the Susquehanna River are high, presumably due to ample prey and lack of competition in the lotic areas above Conowingo Dam. The largest YOY specimen recorded was a 210 mm shad taken at Peach Bottom Atomic Power Station on December 1, 1986. St. Pierre (1997) reported that YOY shad were larger in the Susquehanna River than in the upper Chesapeake Bay with specimens reaching 144 mm by the end of October 1996. During October and November, length frequency distributions are skewed toward smaller fish as one moves upstream, suggesting that larger fish out-migrate sooner or faster (Young 1987).

3.8.4 Anthropogenic Sources of Mortality and Productivity

3.8.4.1 Mortality

The earliest known turbine mortality study done at Conowingo Dam was by Whitney (1961) who tagged shad above and below Conowingo Dam during three consecutive years (1958-1960) and compared recapture rates. Recaptures came from the commercial fishery and were corrected for turbine mortality based on American shad tagged below Conowingo Dam. He found turbine mortality (includes shad passed over the spillway) to be 90.3 percent in 1958. No mortality estimates were done in 1959 because of poor recapture rates for fish tagged above and below Conowingo Dam. It should be noted that his mortality rates were based on recapture rates one year later and estimated rates of survival. These results are suspect because they contrast with more recent results (see below) and because many of the fish planted above the dam may have exhausted their energy reserves in the reservoir prior to exiting the system and may have suffered mortality regardless of turbine survival.

A turbine survival study of adult American shad passing downstream though Conowingo Dam in 2012 estimated 1-h survival at 93.0% (90% CI = ±4.2%) and 48-h survival at 88.3% (90% CI = ±10.5%) for a Francis unit, and 1h survival at 86.3% (90% CI = ±5.8%) and 48-h survival at 84.1% (90% CI = ±9.9%) for a Kaplan unit (Normandeau Associates Inc. and Gomez and Sullivan Engineers 2012a).

Adult American shad emigration behavior and entrainment rates at the Muddy Run Pump Storage Project on Conowingo Pond were evaluated in 2018. More than 91% of downstream migrating shad successfully passed the pump storage project (exceeding the resource agencies success criterion of 80%) with an estimated entrainment rate of 1.7% (90% CI = ±1.4%) (Normandeau Associates Inc. 2019). Similarly, entrainment rates for post-spawn adults at the pump storage project were estimated at 3.4% in 2001 and 3.9% in 2008 (Normandeau Associates Inc. 2001; Normandeau Associates Inc. and Gomez and Sullivan Engineers 2009; Mathur et al. 2018).

One-hour survival of adult American shad passing through turbines at Safe Harbor Dam was 87.0% for a mixed-flow turbine and 89.7% for a Kaplan turbine (Normandeau Associates Inc. 1998). This was not significantly different, so the data were pooled resulting in an estimated 88.3% survival (90% CI = 84.2% - 91.7%). Further, 24-h to 48-h survival was estimated at 86.2% (90% CI = 81.5% - 90.1%).

In 2012, a radio telemetry study was conducted to evaluate the effectiveness of the York Haven Dam and operations at passing emigrating, post-spawn adult American shad. Nearly 75% of the study shad passed the York Haven Dam via preferred routes (i.e. spillway, sluice gate, East Channel Dam spillway). The remaining 25% apparently passed though the powerhouse. The study was not designed to determine downstream passage survival, although, 83% of study fish were detected moving downstream of the York Haven Dam (York Haven Power Company, LLC. 2012).

Telemetered adult shad moving downstream from other studies in the 1980s exhibited about 50 to 60 percent survival at York Haven (though most fish likely spilled) and much less for Holtwood. The numbers of telemetered fish at Holtwood were too few to draw many conclusions, but it is assumed that adult American shad cannot successfully pass through the turbines at Holtwood Dam.

One-hour survival of juvenile American shad passing through a Kaplan turbine, operated at 55 to 56-wicket gate opening, at Conowingo Dam was 94.9% (RMC Environmental Services Inc. 1993). Forty-eight-hour survival was estimated at 92.9%. In 2011, an evaluation of juvenile

American shad survival passing through a Francis turbine estimated 1-h survival at 89.9% (90% CI = 84.1-95.7%), and 48-h survival at 91.2% (90% CI = 83.1-100.0%). Since the 48-h survival cannot exceed the estimated 1- h survival, 48-h survival was established at 89.9% (Normandeau Associates Inc. and Gomez and Sullivan Engineers 2012b).

One-hour survival of juvenile American shad passing through Francis turbines at Holtwood Dam was estimated at 89% (±9.8%) and 24-h survival was estimated at 78% (±16.5%) (Mathur and Heisey 1993).

One-hour survival of juvenile American shad passing through turbines at Safe Harbor Dam was 98%, 97.8% and 98.9% for Kaplan, mixed flow (unvented) and mixed flow (vented) turbines, respectively (Heisey et al. 1992). Forty-eight-hour survival was 98%, 100%, and 67% (adjusted for controls) for Kaplan, mixed flow (un-vented) and mixed flow (vented) turbines, respectively.

One-hour survival of juvenile American shad passing through turbines at York Haven Dam was 92.7% and 77.1% for a vertical shaft Kaplan (Unit 3) and a dual vertical shaft Francis turbine, respectively (Normandeau Associates Inc. 2002). Adjusted 48-hour survival exceeded the 1-hour survival and was not used.

Operational strategies for maximizing turbine survival of out-migrating juvenile American shad are in place at all four Susquehanna River hydroelectric projects. At Conowingo, the downstream juvenile plan calls for preferential use of low mortality Kaplan or mixed flow turbines during the hours of 1700 to 2300 during October and November (RMC Environmental Services Inc. 1994). When river flows exceed 40,000 cubic feet per second, higher mortality Francis turbines may be operated. This plan ensures that turbine passage survival is greater than 94 percent at Conowingo Dam.

The downstream juvenile protocol at Holtwood requires selective evening use of single-runner, Francis units closest to the eastern end of the powerhouse where fish historically gather and spilling at the trash sluice to draw fish from outside the skimmer wall or along the face of the dam.

The juvenile downstream passage protocol at Safe Harbor requires that the project selectively use one or more of the large, new units (9-12) at full capacity during evening hours in October and November.

The juvenile downstream passage protocol at York Haven Dam provides for monitoring the forebay to determine when out-migrating juveniles arrive at the project and starting “Downstream Operation” when juveniles arrive. Downstream Operation begins each evening at sunset and continues until about 2330 hours. Downstream Operation includes: turning on temporary lighting at the trash sluiceway and opening the sluiceway, preferentially operating only Units 1-6 when river flow is insufficient for operation of any of the remaining units, operating Units 7-20 only when river flow exceeds the hydraulic capacity of available Units 1-6, and ceasing downstream operation at the end of the run, based on monitoring and sampling in the forebay to determine when the juvenile shad emigration has ended for the season.

3.8.4.2 Productivity

American shad restoration efforts in the Susquehanna River basin have focused largely on the trapping of adult shad from below Conowingo Dam and transplantation to open river spawning habitat (1982-1997), upstream passage of adults through fishways (1997-present), and the production of hatchery-reared larvae and fingerlings (1976-present). The objective of the restoration plan is to produce a self-sustaining population of two million adult shad upstream of York Haven Dam. The role of the hatchery has been to produce adequate numbers of juvenile shad imprinted to the Susquehanna River to return to upstream spawning areas, thereby initiating spawning runs, which will be maintained by self-sustaining natural reproduction (Sadzinski and Hendricks 2007).

The stocking of some 216 million shad eggs (1971-1977) from various river sources, and the transplanting of over 25,000 adult shad from the Hudson and Connecticut Rivers (1980-1987) produced few juvenile shad and were ultimately discontinued. In 1976, the PFBC established the Van Dyke Research Station for Anadromous Fish to develop techniques for American shad culture for use in the Susquehanna River restoration effort.

Hatchery operations have been supported by the gill netting and strip spawning of wild broodfish from the Susquehanna, Hudson, Delaware, Connecticut, James, Pamunkey, Mattaponi, Potomac, Savannah and Columbia Rivers (Table 100). Eggs have also been obtained from tank-spawning efforts at the USFWS Northeast Fishery Center at Lamar, Pennsylvania and Conowingo Dam, Maryland. The most significant sources of eggs include the Columbia River (291.6 million eggs, 1974-1989), the Hudson River (189.6 million eggs, 1989-2006) and the Potomac River (115.7 million eggs, 2006-2017). Since 2006, the Potomac and Susquehanna Rivers have been the primary egg source rivers for restoration stockings within the Susquehanna basin, averaging some 15 million eggs per year for fry culture and restoration stockings.

Stocking of hatchery-reared American shad larvae in the Susquehanna basin has occurred at many sites in the Juniata River, main stem Susquehanna River, West Branch Susquehanna River, North Branch Susquehanna River, and several lower-basin tributaries (i.e. Conodoguinet, West Conewago, Swatara Creeks, and Conestoga River). Larvae are stocked annually, during May, June, and July at 7 to 35 days of age. Fingerlings are stocked between September and October, although fingerling culture has been substantially curtailed since 1994 and was discontinued in 2013.

In total, the PFBC has released some 227 million larvae and nearly 1.4 million fingerling American shad into the Susquehanna basin upstream of the four lower river hydroelectric dams between 1976 and 2017. Annual production in recent years (2007-2017), averaged nearly 2.7 million larvae per year. Table 101 provides a summary of juvenile American shad stocking activities and adult passage and transfers within the Susquehanna River basin above the main stem dams.

The Van Dyke facility also stocked approximately 31million American shad larvae and 400,000 fingerling shad in the lower Susquehanna River below Conowingo Dam between 1985 and 1993. This was done to avoid downstream passage losses at upstream hydroelectric stations, and to support restoration efforts in the upper Chesapeake Bay. The MD DNR also stocked juvenile American shad into the Susquehanna River below Conowingo Dam and the Susquehanna Flats between 1985 and 1996; stocking discontinued when shad abundance appeared to be self-sustaining in the lower river (Sadzinski and Hendricks 2007).

Since 1985, all hatchery-reared American shad larvae and fingerlings have been immersed in tetracycline antibiotics to mark their otoliths to distinguish hatchery-reared shad from wild, naturally produced shad (Hendricks et al. 1991). Since 1987, larvae have been marked by 4-6-hour immersion in 200-500 mg/L oxytetracycline or tetracycline hydrochloride. Marks produced by this protocol usually exhibit 100 percent mark retention. Multiple marks are produced by subsequent immersions at three or four-day intervals and have been used primarily to mark fish according to release site.

3.8.5 Fishery-Dependent Data Sources

3.8.5.1 Commercial

3.8.5.1.1 Commercial Landings (Historical)

The Upper Chesapeake Bay and Maryland’s portion of the Susquehanna River were once host to the most productive American shad fisheries in the state. However, commercial landing records specific to this region are limited. Declines in American shad stocks in the Chesapeake region were reported as early as 1876 (Uhler and Lugger 1876). Though intense and productive fisheries continued well past this time, some formerly productive rivers produced few if any shad by the beginning of the 20th century. Reports from the Chesapeake Biological Laboratory present one of the only time series of landings of American shad for this region of Maryland (Table 102; Hammer et al. 1948; Hensel and Tiller 1952; Hensel and Tiller 1954).

3.8.5.1.2 Commercial Catch Rates from Onboard Fishery Monitoring

From 1980 to 2001, MD DNR biologists accompanied commercial watermen to fish pound nets in the Upper Chesapeake Bay and Susquehanna Flats. At the discretion of the watermen, one- to three-pound nets were sampled two to four times per week from mid-March to early May. When fished, pound net cribs were pursed; fish were dipped with a hydraulic lift onto a culling board and American shad removed.

Biological Sampling Methods

American shad in good physical condition were marked with T-bar anchor tags and released, but all fish caught were used in the catch estimation. Subsamples of fish were scaled for ageing purposes. In addition, heads of dead adult American shad were frozen for later otolith extraction and analysis. Hatchery raised American shad were differentiated from wild fish based either on the presence of oxytetracycline marks on the otoliths or otolith microstructure (Hendricks et al. 1994).

Catch Estimation Methods and Trends

Pound nets set by cooperating waterman were sampled around the upper Chesapeake Bay from 1980-2001. However, no sampling was conducted in 1984 and 1986. Additionally, very few sampling days were conducted in 1983, 1985, and 1987. While the specific net locations sampled varied through time, the number of pound nets sampled per year ranged from 1 to 4, with an average of 2 sites sampled per year. These sites were sampled throughout the season multiple times, ranging from 1 to 51 sampling events per year (mean=25 sampling events per year). Pound nets were set for 1-12 days with a mean of 2.6 days and a median of 2 days.

Sample site names were standardized and only those sampling events that had water temperature data recorded were kept in the data set. One site (Perry Point) was removed from the data set as it was only sampled two times in the time series and its inclusion precluded bootstrapping. A negative binomial GAM was fit to the data using year and site as covariates, a smoother for water temperature, and an effort offset (days net was fishing). Model diagnostics were generally good.

The Upper Chesapeake Onboard Fishery Monitoring CPUE data were low in the early 1980s and have generally increased since 1987 (Table 104, Figure 170). Low years since 1987 have included 1992, 1996, and 1998 with peaks in 1991, 1997, and 2000, which was the highest CPUE in the time series.

Commercial Length/Weight/Catch-at-Age

American shad captured in the Upper Chesapeake Onboard Fishery Monitoring ranged in age from 2 – 10. However, 90% of all fish captured ranged in age from 4 – 6. Age-5 fish were the dominant age grouping in all years of the survey except for 2000 when age-4 fish were the majority (Table 103).

Commercial Discards/Bycatch

All American shad captured by this survey are considered commercial bycatch. Gear related and discard mortality specific to the Chesapeake Bay pound net fishery is unknown.

3.8.5.2 Recreational

3.8.5.2.1 Susquehanna River Recreational Creel Survey

Survey Methods

The MD DNR has conducted a non-random roving creel survey in the vicinity of the Conowingo Dam tailrace on the Susquehanna River since 2001. Each year, sampling was conducted between mid-April and the beginning of June. The frequency of sampling varied depending on flow conditions, which dictated the availability of river access points suitable for fishing. Interviews were generally conducted each day that MD DNR personnel visited the dam for fishery-independent hook-and-line sampling.

Catch Estimation Methods

Data generated by each interview included total American shad captured (catch), hours spent fishing (effort), and expected total hours of fishing (if angler was still actively pursuing American shad). Catch-per-angler-hour (CPAH) was formulated as a measure of relative abundance.

Recreational Catch Rates (CPUE)

Geometric mean CPAH from the MD DNR creel survey has generally declined from peaks observed in the early 2000s and follows a decreasing linear trend (Table 105, Figure 161; $R^2 = 0.24$, $P = 0.05$).

Recreational Discards/Bycatch

Short term catch-and-release mortality (within two days) of American shad angled by hook and line gear is likely less than 1% (Lukacovic, 1998). However, recreational fishing activity in the tailrace can be intense, and impacts on behavior and potential fish passage delay has not been studied.

3.8.6 Fishery-Independent Data Sources

3.8.6.1 Adult Fishery-Independent Data Sources

3.8.6.1.1 MD DNR Susquehanna Hook-and-Line Survey

Survey Methods

From 1980-present, adult American shad were angled by MD DNR staff from the Conowingo Dam tailrace on the lower Susquehanna River two to four times per week from mid-April through the beginning of June (Figure 162). Rods were rigged with two shad darts and lead weight was added when required to achieve proper depth. Most angling was done by boat anchored either just downstream from the East Fish Lift (EFL) or in front of the small generating units when permitted by flow. American shad were occasionally angled from shore.

Biological Sampling Methods

American shad were sexed (by expression of gonadal products), total length (TL) and fork length (FL) were measured to the nearest millimeter (mm), and scales were removed below the insertion of the dorsal fin for ageing and spawning history analysis. Fish in good physical condition, with the exception of spent or post-spawn fish, were tagged with Floy tags (color-coded to identify the year tagged) and released. Normandeau Associates, Inc. was responsible for observing and/or collecting American shad at the Conowingo Dam fish lifts. American shad collected in the EFL were deposited into a trough, directed past a 1.2 m x 3.0 m counting window, identified to species and counted by experienced technicians. American shad captured from the West Fish Lift (WFL) were counted and either used for experiments (e.g. hatchery brood stock, oxytetracycline [OTC] analysis, sacrificed for otolith extraction) or returned to the tailrace. For both lifts, tags were used to identify American shad captured in the Susquehanna Hook-and-Line Survey in the current and previous years.

Length/Weight/Catch-at-Age

From 1982 to 2017, male American shad sampled from the Conowingo Dam tailrace ranged in age from 2 – 9; females ranged in age from 3 – 10. Age-4 was the most common age for males while age-5 was most common for females. Ninety-percent of all fish captured by the survey, irrespective of sex, ranged in age from 4 – 6 (Table 106-Table 108). The presence of repeat spawning fish in the river has increased over the time series (1984-2017; Figure 163; $R^2 = 0.63$, $P < 0.001$). Mean length-at-age statistics are presented in Table 109-Table 111.

Catch Rates

Daily trips were treated as independent observations and effort was defined as fishing hours. Less than three observations occurred in 1983 and 2011 (after observations with missing covariate data were excluded), so data from these years were excluded from the data set. There were thirty four years of data with averages of 15 positive observations per year and 98% positive observations per year (Table 112).

A negative binomial GAM was used to estimate a standardized index of abundance accounting for variability in annual catchability effects. The final model included count of shad as the response variable and year, water temperature, water flow, and day of year as covariates. The number of fishing hours was included as an offset variable. Smoothing functions with basis dimensions (i.e., k) of four and ten were estimated for water temperature and day of year, respectively. AIC was used to select the final model type (GLM vs. GAM), covariates, and basis dimensions for smoothing functions. The final model converged with a dispersion statistic of 0.92, indicating the data were not over-dispersed relative to model expectations.

Catch rates are predicted to increase as water temperatures warm, exceed the overall mean catch rate at approximately 16^{o}C, peak at approximately 19^{o}C, and then decline as water warms to the highest temperatures sampled. Increasing water flow is predicted to have a negative effect on catch rates. Catch rates early in the sampling period (second half of April) are predicted to be stable and greater than the overall mean catch rate, though these predictions are uncertain. Catch rates are predicted to steadily decrease at approximately the midpoint of the sampling period (≈125 days into the year or early May) through the remainder of the sampling period. The standardized index shows more interannual variability, but follows the same trend as the geometric mean catch rates. The index increases to peaks in the late 1990s, decreases through the early 2000s, and has been relatively stable since the mid-2000s. Annual CVs averaged 0.17 over the time series (Table 112).

3.8.6.1.2 PFBC Susquehanna River Adult Fish Lift Catch and Passage

Survey Methods

Adult American shad encounter four successive hydroelectric dams along the first 90 river kilometers (rkm) of the Susquehanna River during their spring spawning migration (Figure 160). These dams include, in ascending order: Conowingo (rkm 16.1), Holtwood (rkm 39.6), Safe Harbor (rkm 51.8) and York Haven (rkm 90.3) Dams. Annual run counts, or passage, represents an absolute abundance above each successive dam.

The West Fish Lift (WFL) at Conowingo Dam (rkm 16.1) has been used to monitor adult American shad abundance and collect specimens for biological information since 1972. This lift operates in the traditional manner except that fish collected are dumped into a large steel trough where the catch is hand-sorted by biologists and trained technicians. Target species are enumerated, sampled, and then either released back into the Conowingo Dam tailrace, used for tank-spawning, or transported upstream, as dictated by restoration plan requirements. WFL operations and biological sampling have been conducted by a consistent contractor under contract with the dam owner/operator and resource agencies.

Since 1997, the Conowingo Dam East Fish Lift (EFL), and the fish lifts at Holtwood (rkm 39.6) and Safe Harbor Dams (rkm 51.8) have been operational for the purpose of providing passage to migrating adult American shad and other anadromous species. The vertical slot fishway at York Haven Dam (rkm 90.3) began fish passage operations in 2000. Each of the four fish passages were constructed with a viewing window (approximately 4-ft wide by 10-ft tall) where a biologists or trained technicians identify and enumerate target species as they exit the fishway and enter the upstream reservoir. During periods of peak passage, two observers may be used to identify and count fish. Passage counts are recorded hourly and/or daily. Additional data collected on each sample date included water temperature (°C), water transparency (inches, Secchi disc), river flow (cfs) was obtained from the USGS Marietta Gauge Station, hours of operation / observation, number of fish lifts, forebay and tailrace elevations, attraction flow (cfs), fishway entrance gates in use, and maximum number of generation units in use. No biological sampling of any fish occurs at the Holtwood, Safe Harbor and York Haven fishways.

Biological Sampling Methods

The WFL operates as a trap, where collected fish are dumped into a large steel trough and hand-sorted by trained technicians and biologists (1972 – present). Between 1991 and 1996, the EFL also operated as a trap (during years of adult trap and transport) and served as a source for specimen sampling. Every 100th, 50th, or 25th shad to enter the WFL and EFL (during trapping operations) were sacrificed to ensure a representative sample from each respective year’s spawning stock. Lift mortalities and fish in poor condition have occasionally been substituted for random samples. Starting in 2001, the WFL also collected American shad brood stock for tank spawning operations. In years of declining catch, a portion to all brood fish were also sacrificed to supplement annual biological samplings (2004-2017). Sacrificed shad were sexed, measured for TL and FL, scales were collected from the area below the dorsal fin and above the lateral line and stored dry in labeled envelopes, and heads were decapitated and frozen prior to otolith extraction and tetracycline tag analysis. Additional data collected on each sample date included water temperature (°C), hours of operation, and number of lifts.

Hatchery Evaluation Method

Evaluating the contribution of hatchery-reared American shad fry to adult spawning runs is an important component for tracking restoration success and future restoration strategies. The development of OTC otolith tagging has permitted critical evaluation of hatchery effectiveness. When larval American shad are immersed in OTC, the tetracycline chelates to calcium and is incorporated into daily bone growth. OTC tag detection is accomplished via viewing sagittae otoliths with an epifluorescent microscope under ultraviolet light (Lorson and Mudrak 1987; Hendricks et al. 1991). Since 1985, all American shad larvae reared at the PFBC’s Van Dyke

Hatchery have received OTC immersion treatments, thereby creating a chemical mark that distinguished hatchery-reared shad from naturally produced shad.

Sagittae otoliths were extracted from adult and juvenile shad collected during various surveys, cleaned, and mounted to microscope slides with Permount. For OTC mark analysis, otoliths were ground on both sides to produce a thin sagittal section, then examined under ultraviolet light for the presence of a tetracycline mark(s).

Hendricks et al. (1994) developed an alternative method to distinguish wild from hatchery-reared American shad using otolith microstructure without reference to chemical marks. This technology allowed identification of American shad reared in the hatchery prior to 1987 when tetracycline marking became 100% effective. Since development of these techniques, otolith evaluation has become one of the most important tools for tracking the progress of the Susquehanna River American shad restoration effort.

Monitoring for the contribution of hatchery-reared shad began in 1986 for juveniles and 1989 for pre-spawn adults captured at Conowingo Dam.

Adult Catch and Passage

American shad catches at the Conowingo Dam fish-lifts were extremely low, averaging 127 shad during the first ten years of operation (1972-1981) (Table 101). During the 1980s and 1990s fish-lift American shad catches steadily increased, reaching a time series-peak of 203,776 in 2001. Since 2001, fish-lift catch and passage have declined to a low of 9,184 in 2015 and have average 21,601 shad per year, 2008-2017. Both hatchery-origin shad and wild shad have exhibited the same trends, although hatchery shad generally dominated the catch (> 50%) from 1989-2006 (Figure 165).

American shad passage efficiency (expressed as a percentage of shad that passed the next lowest dam) at Holtwood, Safe Harbor and York Haven Dams has averaged 32%, 76% and 10%, respectively (Table 114). Cumulative passage of shad from Conowingo Dam to above York Haven Dam, where the majority of the historical spawning habitat is located, averaged 3%. Clearly, too few shad are reaching the spawning grounds above York Haven Dam for successful restoration. Other suspected causes for the decline in adult American shad in the Susquehanna River observed since the early 2000s include underperforming fish passage, predation, mortality (turbine, by catch in commercial offshore fisheries), decreased hatchery production, poor environmental conditions in some years (e.g., high flows).

Conowingo Dam Fish Lift Count data are not considered representative of interannual abundance changes and were not used in the assessment for abundance trend analyses (Table 20).

Length/Weight/Catch-at-Age

Adult American shad sampled at the Conowingo Dam fish lifts between 1995 and 2017 ranged in age from 2 through 11. Males are most commonly age-4, where females are age-5. Over 89% of shad sampled at the Conowingo lifts range in age from 4 to 6. Catch-at-age data is summarized in Table 115-Table 117. Mean fork length (mm) at age and mean weight (g) at age are presented in Table 118-Table 120 and Table 121-Table 123, respectively. The presence of repeat spawning, expressed as the percentage of occurrence per year, was greatest in 2002 and 2005 (45% and 43%, respectively), and lowest in 2001 (less than 1%) (Table 124-Table 126).

Hatchery Evaluation

Adult American shad captured at the Conowingo Dam fish lifts have predominately been hatchery in origin, averaging 55.9%, 1989-2017 (Table 127; Figure 166 and Figure 167). Hatchery contribution averaged 80% between 1989 and 1995, decreased to 29% in 1998, followed by an increase to 73% in 2003. A decrease in hatchery-origin shad was observed between 2003 and 2012 (time series low of 28.7%). Although, recent hatchery contributions have averaged 43.7% (2013-2017). Hatchery enhancement has had a positive impact on the Susquehanna population and played a major role in the adult population increase observed into the early 2000s.

Recruitment to the Conowingo Dam fish lifts by year class was determined for hatchery origin fish by partitioning the lift catch for each year into its component year classes based upon age composition and otolith tetracycline data. Only virgin adults were used to prevent double counting. Total recruitment by year class was determined for hatchery fish by summing the data for each year class over its recruitment history. The number of hatchery larvae required to return one adult to the lifts was determined for each year class by dividing the number of larvae stocked above dams by the total recruitment of adults which originated as hatchery larvae. Year classes after 2011 are not fully recruited and are not included in the analysis. For the period 1986 through 2011, the number of hatchery larvae required to produce one adult captured by the Conowingo lifts ranged from 67 larvae for the 1996 cohort to 1,745 larvae for the 2003 cohort. The mean number of hatchery larvae required to return one virgin adult shad to the Conowingo fish lifts was 469 larvae for the 1986-2011 cohorts (Table 128).

3.8.6.2 Young-of-Year Fishery-Independent Data Sources

3.8.6.2.1 MD DNR Upper Chesapeake Striped Bass Juvenile Seine Survey

Survey Methods

Juvenile abundance indices (JAIs) are derived annually from sampling at 22 fixed stations within Maryland's portion of the Chesapeake Bay. They are divided among four of the major spawning and nursery areas—seven in the head of bay region (Figure 164). Stations have been sampled continuously since 1954, with changes in some station locations. Sampling is monthly, with rounds (sampling excursions) occurring during July (Round I), August (Round II), and September (Round III). Replicate seine hauls, a minimum of thirty minutes apart, are taken at each site on each sample round. This produces a total of 132 samples from which Bay-wide means are calculated.

From 1954 to 1961, juvenile surveys included various stations and rounds. Sample sizes ranged from 34 to 46. Indices derived for this period include only stations that are consistent with later years. In 1962, stations were standardized and a second sample round was added for a total of 88 samples. A third sample round added in 1966, increased the sample size to 132.

Auxiliary stations have been sampled on an inconsistent basis and are not included in survey indices. These data enhance geographical coverage in rivers with permanent stations or provide information from other river systems. They are also useful for replacement of permanent stations when necessary. Replicate hauls at auxiliary stations were discontinued in 1992 to conserve time and allow increased geographical coverage of spawning areas.

A 30.5 m by 1.24 m bagless beach seine of untreated 6.4 mm bar mesh was set by hand. One end was held on shore while the other was fully stretched perpendicular to the beach and swept with the current. Ideally, the area swept was equivalent to 729-m2. When depths of 1.6 m or greater were encountered, the offshore end was deployed along this depth contour. An estimate of distance from the beach to this depth was recorded.

Biological Sampling Methods

Striped bass, American shad and selected other species were separated into 0 and 1+ age groupings. Ages were based on length-frequencies and verified through scale examination. Age-0 fish were measured from a random sample of up to 30 individuals per site, per round. All other finfish were identified to species and counted. Additional data included: time of first haul, maximum distance from shore, weather, maximum depth, surface water temperature (ºC), tide stage, surface salinity (ppt), primary and secondary bottom substrates, and submerged aquatic vegetation within the sample area (ranked by quartiles). Dissolved oxygen (DO), pH, and turbidity (Secchi disk) were collected beginning in 1997.

Catch Rates

There are 13 Head of Bay stations, spread among five rivers within the region: Bohemia River, Elk River, Northeast River, Sassafras River and Worton Creek. Upon further examination, two of the stations (Elk Neck Park and Howell Pt) are either in Chesapeake Bay proper or at the confluence with Chesapeake Bay. These two stations were-classified as ‘Bay’ stations for this analysis. Another station (Camp Rodney) is only sampled twice and was removed from the data set. Finally, five of the 12 remaining stations are replacements for original stations that were discontinued on the respective river system, located near the originals. Therefore, there are seven total locations sampled in the Head of Bay each year of the time series. Catch rates differ greatly among these river/bay sites. The Worton Creek station has the worst catch rate at 0.07 shad per haul and 95.1% zero hauls. Catch rates at the Bohemia River stations are nearly as poor at 0.48 shad per haul and 87% zero hauls. The Sassafras River site, Bay sites and Elk River sites have mean catch rates of 1.0, 2.1 and 3.6 fish per haul respectively. All three have less than 80% zero hauls. The Worton Creek and Bohemia River stations do not bring any value to an index of abundance for the ‘Head of Bay’ region and are removed from the data set. The final time series used for index standardization begins in 1962, when sampling was standardized.

A new nominal geometric mean index was calculated for the new subset of Head of Bay (Bay, Sassafras River and Elk River). Only the first haul of the day at each respective station was included. The resulting index was similar to the original geometric mean index, with the exception of the early 1960s and 2007. If the nominal index were to be used, the index calculated with new subset is the recommended version.

The same subset of years and stations used to calculate the new geometric mean index was used in generalized linear model evaluation. Initial covariates examined in model development were year, tide, SAV presence/absence, salinity, water temperature, Julian day, cloud cover, and river system. This full list of covariates was initially run through the following models: Poisson GLM, a negative Binomial GLM, a Zero-Inflated Negative Binomial GLM, a Poisson GAM, and a Negative Binomial GAM. The Negative Binomial GLM model was determined the best initial model based on comparisons of the dispersion parameter. A step-wise evaluation of covariates was then performed for the negative binomial model. Tide stage, water temperature, Julian day and cloud cover were sequentially dropped the data set as they were not shown to significantly impact catch. The best performing model was Counts ~ Year + SAV presence + salinity + river system.

The most noticeable trend in both the nominal and standardized indices is the large period of low catch rates in the middle of the time series (Table 113, Figure 169) Catches are variable from the beginning of the time series through 1972. Then from 1973 to 1992 there are no positive hauls in the GLM subset of data. Catches from 1993 to 2017 are variable, but similar to those early in the time series. With the 22 years of zero hauls removed (1973-1992; 1997; 2009), the mean catch model-predicted catch rate is 1.78 shad per haul, with a max of 14.04 and min of 0.04. The large gap in catch coincides with the absence of SAV at the stations, likely indicating a water quality impact on catch rates/presence of shad in the Head of Bay region. With the recovery of SAV, catch rates resumed to levels close to those predicted for the early years in the time series when SAV was present (median 0.75 vs 0.62, respectively). Based on the importance of the final model covariates on catch, the best index of relative abundance for the Upper Chesapeake Striped Bass Juvenile Seine Survey is the negative binomial GLM standardized index. However, this index should be used with caution as annual model CVs are large.

3.8.6.2.2 PFBC Susquehanna River Juvenile Abundance Surveys

Columbia Haul Seine Survey

In Pennsylvania, juvenile American shad were collected by haul seine and lift net to develop indices of abundance.

Haul seining in the lower Susquehanna River was scheduled once each week, mid-July through October (1990–present). Sampling was conducted by an environmental contractor in the Columbia-Marietta area, a riverine section just upstream of Lake Clarke (Safe Harbor Dam Reservoir). Sampling consisted of six hauls per day (one haul per station) beginning at sunset and continuing into the evening with a net measuring 400-ft x 6-ft with 3/8-in stretch mesh. Sampling was conducted by anchoring one end of the seine to shore and maneuvering the unattached end by boat, out into the current then back to shore forming a semicircle. A crew of three biologists was used to deploy and retrieve the net throughout the study.

Holtwood Lift Netting Survey

Lift-net sampling was conducted by an environmental contractor at the Holtwood Dam inner forebay beginning in September and continuing every three days through early December (1985 – 2009). An 8-ft square steel frame lift net was outfitted with ½-in stretch mesh and an inner liner of ¼-in stretch mesh. The net was lowered and raised manually by a rope fitted through a pulley attached to the end of a 20-ft steel beam. A 13-in diameter, 5-gallon bucket nested in the center of the lift net, which could be pulled up independently from the lift net to remove fish that funneled into the water-filled bucket. Sampling began at sunset and consisted of 10 lifts with a 10-minute interval between lift cycles. The lift net was placed on the north side of a coffer cell in the inner forebay. A lighting system was used to illuminate the water directly over the lift net to attract fish. This survey was discontinued after the 2009 redevelopment of the Holtwood facility and loss of the long-term sampling location (i.e. the inner forebay eddy became the location of new hydroelectric generation units).

Biological Sampling Methods

After each seine haul, catch was identified, enumerated, and all species were returned alive to the river. When available, the first 30 American shad collected on a sampling date were measured to the nearest millimeter total length (TL) and retained for otolith analysis for tetracycline tags. Other information collected included water temperature (°C), water clarity measured in inches with a Secchi disk, and river flow (cfs) obtained from the USGS Marietta Gauge Station.

Lift net surveys consisted of ten lifts per sampling date, starting approximately one hour before sunset and ending one hour after sunset. All fishes caught, were identified, counted, and released. The first 30 American shad caught on each sample date were measured to the nearest millimeter total length (TL) and retained for otolith analysis for tetracycline tags. Other information collected included water temperature (°C), water transparency (inches, Secchi disc), and river flow (cfs) obtained from the USGS Marietta Gauge Station.

Catch Estimation Methods

Juvenile indexes from the Columbia Haul Seine Survey were developed as the geometric mean catch of approximately 90 hauls (six hauls per day, one day per week) between mid-July and mid-October. Geometric mean catch per seine haul data is presented for 1997-2017. Although, similar haul sein collections occurred annually since 1990, and catch estimation was computed as mean and geometric mean combined daily CPUE, 1990-2017.

Juvenile indexes for the Holtwood Lift Netting Survey were developed from the geometric mean catch of approximately 300 lifts (10 lifts per day, every third day) from September to December. Geometric mean catch per lift net data is presented only for 1995-2009. Similar lift net collections occurred annually since 1985, and catch estimation was computed as mean and geometric mean combined daily CPUE, 1985-2009. The most recent ASMFC stock assessment recommends use of area-under-the-curve (AUC) methods in cases where sampling is targeted at migrants moving through an area (ASMFC 2007b). Because the Holtwood Dam lift net survey collected juvenile shad during the directed outmigration, AUC measures of juvenile abundance were also calculated for lift net collections.

These catch rate data are not considered representative of interannual abundance changes and were not used in the assessment for abundance trend analyses (Table 17, Table 19).

Abundance and Biomass Indices (-per-unit effort)
Juvenile American shad abundance indices for stocks above Conowingo Dam resulting from lift-net and haul seine surveys are summarized in Table 129 and Table 130, respectively. The lift-net CPUE at the Holtwood Dam inner forebay peaked in 1985 and steadily declined through the termination of the survey in 2009. Haul seine CPUE peaked during the mid-1990s and declined since (Figure 167).

Hatchery Evaluation
Analysis of otoliths from juvenile American shad demonstrated that hatchery juveniles dominated the catch in most years, apart from 1991, 1992, 1993, 1996 and 2001 (Table 131). Maximum wild contribution occurred in 1993 when 61% of the lift net and 80% of the haul seine juveniles were wild. The last appreciable increase in juvenile shad abundance detected in both surveys occurred in 2001, when some 89,800 adults were passed upstream of Safe Harbor Dam (of which 16,200 passed York Haven Dam). These data suggest that trucking / passage of adult shad from Conowingo Dam to optimal spawning habitat upstream of Safe Harbor Dam resulted in increased production of wild juveniles. The decline in juvenile shad abundance observed since the early 2000s is the result of many consecutive years of fewer and fewer adult shad reaching spawning habitat upstream of main stem dams (a result of underperforming fish passage) and a decline in hatchery production (due to the loss of productive egg sources and poor hatchery survival in some years).

3.8.7 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance, mean length, and mean length-at-age. Total mortality estimators were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. A population model was also used to evaluate abundance. Details for all methods except the population model are provided in section 2. Details for the population model are provided below.

3.8.7.1 MD DNR Population Models

The MD DNR produces population estimates of American shad in the Conowingo Dam tailrace using both mark-recapture and biomass surplus production model (SPM) methods. Mark recapture methods use Chapman's modification of the Petersen statistic (Chapman, 1951):

$$N = (C+1)(M+1)/(R+1)$$

where N is the relative population estimate, C is the number of fish examined for tags at the Conowingo East Fish Lift (EFL), M is the number of fish tagged minus 3% tag loss, and R is the number of tagged fish recaptured at the EFL excluding recaps of previous years' tags. *C* is corrected to include only fish that were lifted after tagging began in the tailrace. Prior to 2001, *C* was the number of fish examined for tags at both the EFL and Conowingo West Fish Lift (WFL), and *R* was the number of tagged fish recaptured at both lifts excluding recaps of previous years' tags. Observations at the WFL were omitted to avoid double counting beginning in 2001, as it became protocol for some fish captured at the WFL to be returned to the tailrace. Calculation of 95% confidence limits (N^*) for the Petersen statistic were based on sampling error associated with recaptures in conjunction with Poisson distribution approximation (Ricker 1975):

$$N^* = (C+1)(M+1)/(R^t+1)$$

where

$$R^t = (R+1.92) \pm (1.96\sqrt{(R+1)})$$

Overestimation of abundance by the Petersen statistic (due to low recapture rates) necessitated the additional use of a biomass surplus production model (SPM; MacCall 2002, Weinrich et al. 2008):

$$N_t = N_{t-1} + [r\, N_{t-1}(1-(N_{t-1}/ K))] - C_{t-1}$$

where N_t is the population (numbers) in year *t*, N_{t-1} is the population (numbers) in the previous year, *r* is the intrinsic rate of population increase, *K* is the maximum population size, and C_{t-1} is losses associated with upstream and downstream fish passage and estimated bycatch mortality in the previous year (equivalent to catch in a surplus production model). Fish passage mortalities are calculated as 100% of adult American shad emigrating back through Holtwood Dam (N_{Holt}) and 25% for adult American shad emigrating back through the Conowingo Dam (N_{Cono}). The estimated bycatch mortality is derived from ocean fisheries landings (*L*) known to encounter American shad as incidental catch (i.e. the Atlantic herring and mackerel fisheries). A bycatch coefficient (*b*) is estimated to fit the model to these fisheries' landings. Therefore, losses in the previous year are calculated as:

$$C_{t-1} = N_{Holt} + 0.25 * (N_{Cono} - N_{Holt}) + b * L$$

Model parameters were estimated using a non-equilibrium approach that follows an observation-error fitting method (i.e., assumes that all errors occur in the relationship between true stock size and the index used to measure it). The model is fit to indices of abundance for American shad in the Conowingo Dam tailrace. Assumptions include accurate adult American shad turbine mortality estimation and that the bycatch of American shad in the ocean fisheries is proportional to the directed fishery landings.

The SPM requires starting values for the initial population (B_0) in 1985, a carrying capacity estimate (*K*), an estimate of the intrinsic rate of growth (*r*) and a bycatch coefficient (*b*). For model development in 2015 the starting values were as follows: B_0 was set as 7,876, which was the Petersen statistic for 1985, *K* was set as 3,040,551 fish, which was three times the highest Petersen estimate of the time series, *r* was set as 0.50, and *b* was set at 0.032. These starting values were adjusted by the model during the fitting procedure using Evolver 4.0 for Windows that uses a genetic algorithm for optimization. The fitting procedure was constrained to search within *r* = 0.01 to 1.0, *K* = 100,000 to 30 million fish, B_0 = 5,682 (the lower confidence limit of the 1985 Petersen statistic) to 1 million fish and *b* = 0.001 to 1.0. The final estimates for each of these parameters in 2015 were then used as the starting values for model development in 2018 (B_0 = 54,176, *K* = 1,005,502, *r* = 0.57, and *b* = 0.51). The model was run multiple times varying the indices of abundance and the landings data from which bycatch mortality was derived. The run with the lowest sum of squares and reasonable parameter estimates was chosen.

3.8.8 Results

3.8.8.1 MD DNR Population Model Results

The Petersen statistic estimated 140,883 American shad in the Conowingo Dam tailrace in 2017 with an upper confidence limit of 203,028 fish and a lower confidence limit of 97,274 fish (Figure 168). The SPM with the lowest sum of squares that best represented American shad in the Conowingo Dam used the CPUE from the Susquehanna Hook-and-Line Survey, the lift index, and used the Atlantic herring and mackerel combined landings to estimate bycatch losses. This run estimated a population of 79,549 American shad in the Conowingo Dam in 2017 and produced realistic estimates of the model parameters r, *K* and B0 (r = 0.56, *K* = 1,684,428, B0 = 54,135; Figure 168). The 2017 SPM estimate is just below the lower confidence interval of the Petersen estimate for 2017.

Despite differences in yearly estimates, the overall population trends derived from each population model are fairly similar. Specifically, the SPM showed an increasing population size from the beginning of the time series to a peak in 2001, followed by a decline since that time (Figure 168). Petersen estimates follow a similar pattern if the high levels of uncertainty in 2004 and 2008 (due to low recapture rates) are considered (Figure 168). Both population estimates demonstrate that the Susquehanna River American shad population is currently stable at low levels.

The SAS had concerns with the data (landings of Atlantic herring and mackerel) and the model parameterization used to estimate American shad bycatch. The bycatch scale parameter (b), which estimates Upper Chesapeake Bay-origin ocean bycatch of American shad to be 55% of all coastwide Atlantic herring and mackerel landings, is considered to be biased high. The SAS recommended using the incidental catch estimates of American shad developed using observed data collected from fisheries that catch American shad in ocean waters (section 4.1.4) as a sensitivity run, but MD DNR has lost the capabilities to change or update this model as the program used (Evolver add-in for Microsoft Excel) is not compatible with the agencies recent upgrade to Microsoft Windows 10. Ultimately, the SAS recommended not using any estimates from this model for assessment conclusions. If the model is pursued in the future, the SAS also recommends parameterizing the model to include a scaling factor that estimates bycatch of

Upper Chesapeake Bay-origin fish as a proportion of the total American shad incidental catch estimates.

3.8.8.2 Abundance Trends

3.8.8.2.1 Power Analysis

Four abundance indices for American shad were developed for this system that contained estimates of PSE, the Susquehanna River Recreational Creel Survey, the upper Chesapeake Bay Onboard Fishery Monitoring, the fishery-independent Susquehanna Hook-and-Line Survey, and the fishery-independent Upper Chesapeake Striped Bass Juvenile Seine Survey. Of these surveys, only the Susquehanna River Recreational Creel Survey, which possessed a median PSE of 0.165, exhibits sufficient power to detect a 50% increase in American shad abundance in 10 years, while the upper Chesapeake Bay Onboard Fishery Monitoring would only be able to detect a 50% decrease (Table 25). Currently, there is no SFMP for this system so none of these surveys are used for sustainability targets and monitoring.

3.8.8.2.2 Mann-Kendall Analysis

Upper Chesapeake Bay (JAI)

Young-of-year production in the upper Chesapeake Bay has increased since 1995, before which time JAI values had remained very low since the 1970s. Both indices have shown wide year-to-year fluctuations with a time series peak high occurring between 2004 and 2007 (Figure 169). Mann-Kendall trend analysis failed to detect a trend for either time period examined.

Upper Chesapeake Bay (FD CPUE)

Data were provided from two fishery-dependent surveys conducted in the Upper Chesapeake Bay. A plot of the Commercial Pound Net Onboard Fishery Monitoring from 1980-2001 showed relatively low levels through 1990, after which a gradual increase continued, followed by a large increase from 1999-2000 (Figure 170). Mann-Kendall trend analysis found an increasing trend over the time series. Index values from the MD Creel survey showed a general decline since 2001 (Figure 172). Mann-Kendall trend analysis failed to detect a trend for the full time series or for the period after 2005.

Upper Chesapeake Bay (FI CPUE)

A plot of the Susquehanna Hook-and-Line Survey showed a general decrease from 1985-1998 and gradual decline thereafter (Figure 171). Mann-Kendall trend analysis failed to detect a trend for the full time series or for the period after 2005.

3.8.8.3 Mean Length Trends

The American shad stock was spatially restricted by construction of hydroelectric dams in the Susquehanna River in the early 1900s, blocking access to hundreds of miles of natural habitat in Pennsylvania and New York. Upriver habitat reopened beginning in 1972 with the retrofitting of fish-lifts in the four main stem Susquehanna River dams. The Susquehanna River has had American shad length data submitted by PFBC via Fish Lift Sampling at Conowingo Dam as well as the Maryland DNR via the fishery-independent Susquehanna Hook-and-Line survey. A plot of mean lengths for recent years, 2000-2017, at the Conowingo Dam shows a peak in mean length around 2003 with a subsequent decline thereafter (Figure 173). Mann-Kendall trend analysis found a decreasing trend in mean length of both sexes over the time series. A plot of the Susquehanna Hook-and-Line survey lengths from 1980-2017 shows inter-annual fluctuations with peaks occurring in 2003, with males showing a very slight increase over the time series and female mean length decreasing slightly (Figure 174). Mann-Kendall trend analysis found a decline in mean length of female American shad over the time series, but failed to detect a trend in mean length of males.

Maryland DNR provided American shad length data for the Onboard Fishery Monitoring program in the Upper Chesapeake Bay. A plot of mean total length from the fishery-dependent commercial survey showed a general decreasing trend in mean length from 1980-2001 for both sexes (Figure 175). Mann-Kendall trend analysis confirmed this, finding a significant decline in length for both males and females over that time period. Data from two additional programs were submitted, but excluded from analysis due to small sample sizes or because the time series was too short.

3.8.8.4 Mean Length-at-Age Trends

Mean length-at-age data using scales were provided from three sampling programs in the Upper Chesapeake Bay, including two programs in the Susquehanna River, the Conowingo Dam Fish Lift Sampling and the Hook-and-Line Survey, and the Commercial Onboard Fishery Monitoring program for the Upper Chesapeake Bay. All three programs included length-at-age information for both males and females, and while all programs had fish between the ages of 3 and 8, some included fish as young as age 2 and as old as age 9. Mann-Kendall trend analysis found decreases in mean length-at-age for several ages in all three programs, but also detected a single increase in mean length-at-age for age 3 males from the Hook and Line Survey (Table 132). Mean length-at-age data for the Conowingo Dam Fish Lift Sampling in the Susquehanna River were also provided using otoliths. American shad of both sexes, age 3 to age 8, were included in the analysis and Mann-Kendall Trend analysis found a decrease in mean length-at-age over time for most ages analyzed in the program.

3.8.8.5 Total Mortality Estimates

Age composition data derived from scales collected during the Susquehanna Hook-and-Line Survey and Conowingo Dam Fish Lift Sampling and otoliths collected during the Conowingo Dam Fish Lift Count were used for mortality estimates. The Hook-and-Line Survey age composition data were tabulated from scales collected randomly or by census while the Conowingo Dam Fish Lift Count age composition data sets (scale and otolith) were developed using random sampling of length bins and concomitant application of survey specific age-length keys. For the Susquehanna Hook-and-Line Survey, scaled derived data met all criteria (see Section 2.6) for 29 and 32 years between 1984 and 2017 for females and males, respectively (Table 32). For Conowingo Dam Fish Lift Sampling, otolith-derived data met all criteria for 16 and 11 years between 1995 and 2013 for females and males, respectively, while scaled derived female data met all criteria for 16 years (Table 32). Estimates between age structures for fish collected from the Conowingo Dam Fish Lift were quite similar (Figure 70). Regardless of structure, sampling program or sex, the impression is that mortality exhibited a cyclical pattern with periods of decreasing mortality in the early 1990s, early 2000s, and early 2010s and periods of increasing mortality in the late 1990s, late 2000s, and recent years (Table 33, Figure 176, and Figure 177). There were no female data available in 2017 and 2015-2017 from the Susquehanna Hook-and-Line Survey and Conowingo Dam Fish Lift Sampling, respectively (Table 33, Figure 176, and Figure 177), precluding estimation of a three year average for females in 2017 from either data set.

3.8.8.6 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Upper Chesapeake Bay system, habitat estimates were based on information from the Susquehanna River. Current unobstructed habitat area for the Susquehanna River represents 4.38% of the historical habitat extent (11.15 of 254.46 square kilometers).

3.8.9 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. The adult mortality status is also unknown as there was no estimate of female total mortality in 2017. The most recent three-year average female total mortality was 1.09 in 2016 which is above the $Z_{40\%}$ threshold (1.07).

There was a consistent declining trend in female mean length detected from three data sets with varying time series (1980-2001, 1984-2017, 2000-2017), while no trend was detected in YOY abundance (1962-2017, 2005-2017).

Abundance

Abundance status is unknown. There have been no trends in YOY abundance or adult abundance (two data sets) since 2005.

3.8.10 Research Recommendations

1. Establish required performance measures for upstream passage efficiency and downstream passage survival at each of the four FERC licensed hydroelectric dams and require studies to document compliance. Current downstream passage efficiency should be determined.

- American shad passage performance measures were incorporated as conditions of Federal Energy Regulatory Commission (FERC) operating license for the Holtwood Hydroelectric Station (2009), Muddy Run Pump Storage Facility (2014) and the York Haven Hydroelectric Project (2014). Shad passage performance measures include the upstream passage of 75% of the next downstream dam's shad passage total (with 50% pass within five days), or the passage of 85% of the shad found within a hydroelectric project's respective project waters. Downstream passage targets include 80% survival of post-spawn adults and 95% survival of emigrating juveniles. Further, evaluation and adaptive management strategies have also been incorporated as conditions of the recent FERC relicensing efforts and thereby creating a framework to continue towards restoration success.

2. Replace the Holtwood lift-net index with additional seine sites or with hoop net fished in the boils below Holtwood Dam.

- Between 2010 and 2014, haul seine sampling was conducted around City Island near Harrisburg, PA to increase juvenile shad monitoring on the Susquehanna River. The City Island survey site was selected as a possible replacement for the Holtwood inner forebay lift net survey. However, following five years of very limited catch and reduction in operating budgets, the City Island haul seine survey was discontinued. No additional juvenile shad surveys have been investigated or established within Susquehanna basin to date.

3. Expand tank-spawning operation at Conowingo Dam to provide more Susquehanna River source eggs for the restoration program.

- It has not been practical nor possible to expand the tank spawning operations at the Conowingo West Fish Lift. Limitations to expansion include: limited resource agency funding, increased expenses, limited space and water supply (especially following the 2015-2016 installation and annual operation of an American eel elver collection and holding facility). In 2017, the egg collection method was modified (replacement of the egg collection sock and shallow trough with a deeper trough and upwelling flows). These modifications improved viable egg yields markedly; annual average egg viabilities (percentage of live eggs from total egg collections) ranged from 35 to 45% following modifications (compared to less than 8 to 15% in preceding seasons).

4. Initiate otolith analysis of American shad from the Conowingo Dam tailrace.

- Sacrifice of American shad collected directly from the Conowingo Dam tailrace (via hook-and-line or other means of sampling) for otolith analysis has not been explored or pursued to date.

5. Use PIT tags to evaluate shad passage through existing fishways.

- Passive Integrated Transponder (PIT) tagging evaluations to assess American shad passage was used at the Holtwood Hydroelectric station during the 2015 through 2017 spring spawning seasons, as per mandated condition of the project's amended 2009 FERC operation license. Results indicated that shad passage was below passage performance targets (pass 75% of shad that passed Conowingo Dam with 50%

passing within 5-days). The three-year average passage rate of PIT tagged shad was 18%, with an average of 11% passing within 5 days. These findings triggered a multi-year radio telemetry evaluation of American shad passage behaviors between Conowingo Dam and through the fish lift at Holtwood Dam which is currently ongoing.

6. Determine the effects of peaking flow on reproductive success and survival of eggs and larval American shad below Conowingo Dam.

- The effects of peaking flow on American shad reproduction have not been evaluated. A 2012 study was able to determine that American shad egg and larvae concentrations from Conowingo Dam downstream to the interstate 95 bridge were similar to those observed in the early 1980s (Normandeau Associates, Inc. and Gomez and Sullivan Engineers, 2012c). The dam is currently operating under minimum flow requirements first implemented in 1989 (FERC, 1989). Flow regimes will likely be modified with the upcoming relicensure of Conowingo Dam.

7. Conduct a tag mortality study for adult American shad using floy and PIT tags and a combination of these tags.

- No floy or PIT tagging mortality studies have been completed by the MD DNR or PFBC.

8. Conduct a high-reward tagging program to determine reporting rate, accurate recreational exploitation rates, and commercial bycatch.

- No progress has been made, and funding limitations may inhibit the completion of this task. While the MD DNR does floy tag fish in the Conowingo dam tailrace in conjunction with the hook and line survey, very few of these fish are reported as recaptures by recreational or commercial fishermen. The MD DNR creel survey provides a cursory review of angler participation in tag returns; very few anglers report having captured a tagged American shad and fewer still reported these fish.

9. Collect characterization data from all American shad captured from the West Fish-lift while continuing to sacrifice every 50th or 100th fish.

- Characterization data has not been collected from all shad captured at the West Lift. Since the mid-2000s, West Fish Lift operations have gradually shifted to focus on brood fish collections to support tank spawning operations which supply fertilized shad eggs for larvae culture and restoration stockings. Additionally, available funding sources to maintain lift operations and tank spawning have not increased with operating costs. This has resulted in fewer days of lift operations per year and led the PFBC to direct the lift operations contractor to focus on maximizing egg collection efforts over other research and monitoring priorities. One of every 25th shad captured through the entire lift operation period are sacrificed to provide biological data to characterize the spawning run. However, sample sizes have decreased with a decrease in lift operations and a decline in the tailrace population. In response, the PFBC has directed its contractor to sacrifice most to all broodfish following tank spawning trials.

10. Determine the percent of hatchery marked American shad in Conowingo Dam's tailrace to determine if there is differential catchability from non-hatchery fish.

- This recommendation has not been a priority for evaluation by the Susquehanna River Anadromous Fish Restoration Cooperative.

11. Verify the accuracy of scale and otolith ages and the freshwater spawning marks.

- Accuracy of scale and otolith ages and spawning mark identification have not been evaluated for Susquehanna River American shad. Although, the PFBC has recovered and archived otoliths and scales from a small number (less than 30) of adult American shad captured at the Conowingo Dam fish lifts which were determined to have unique OTC tag sequences. The unique OTC tag sequences were administered in the mid- to late 2000s (unique OTC tag defined as only being administered once in a single year for a single cohort) to produce known-age specimens. The PFBC has also archived a small sample set of scale samples (less than 6 individuals) from adult shad captured and tagged in MDNR's hook-and-line survey of the Conowingo Dam tailrace and recaptured in a subsequent year by the West Fish Lift, and as such, represent known-return / known-repeat spawn fish.

3.9 Patuxent

3.9.1 Habitat Description

The Patuxent River is a western shore tributary the Chesapeake Bay. There is a long history of commercial shad harvest in the river, though yields were lower than that of the Nanticoke, Choptank, Wicomico, Potomac and Susquehanna (Stevenson 1899). By 1960, commercial harvest was almost non-existent, indicating a precipitous decline in abundance (Walburg and Nichols 1967). The river and its watershed lies entirely within Maryland, originating in Howard and Montgomery counties and travelling 177 km to its confluence with the Chesapeake Bay.

The main spawning ground for American shad in the Patuxent River lies between Drury (river kilometer 79) in Anne Arundel County downstream to Lower Marlboro (river kilometer 55) in Calvert County (Walburg and Nichols 1967). American shad have historically been documented 153 km upstream from the mouth, though few fish reached this far; the fall line and narrowness of the river at this point limit favorable habitat (Walburg and Nichols, 1967). Two large water storage dams are located just upstream of this point, but are thought to not restrict habitat use by adult or juvenile American shad (Martin and Apse 2013). One-hundred percent of the historical spawning and rearing habitat is still available (Capossela 2014).

The Patuxent watershed encompasses a diversity of land use types. The watershed is highly urbanized (41.7%) in the upstream reaches of American shad habitat. Downstream reaches are primarily a mix of forested (35.1%) and agricultural land (20.5%) (Uphoff et al. 2017). High densities of urban land are often associated with elevated conductivity levels in adjacent waterways, primarily due to contaminated runoff from impervious surfaces. The Maryland Department of Natural Resources FHEP sampling efforts have demonstrated that the presence of alosine eggs and larvae is negatively correlated with both the level of development and conductivity. (Uphoff et al. 2017). Given the high concentration of urbanized land, spawning and rearing success of American shad may be limited in substantial portions of the Patuxent River. Historically, much of the Patuxent watershed was dominated by tobacco agriculture, known to thrive in nitrogen poor, eroded soil. The siltation of spawning grounds likely attributed to the rapid decline of Patuxent shad stocks in the early to mid-1900s (Mansueti and Kolb 1953).

3.9.2 Fishery and Management History

Commercial and recreational American shad fisheries have been closed in Maryland since a moratorium was enacted in 1980. Recreational catch-and-release fishing is still permitted and is concentrated below Conowingo dam on the Susquehanna River and to a lesser extent, the Potomac River. Minimal amounts of targeted recreational fishing for American shad occurs on the Patuxent River. Beginning in 2001, Maryland implemented voluntary angler surveys to collect catch and effort data on the recreational catch-and-release American and hickory shad fisheries. Since the inception of these surveys, only two attempts to fish for American shad in the Patuxent River have been reported. Both trips were unsuccessful for American shad, though hickory shad were captured.

Commercial fishermen are permitted to keep up to two American shad per day per commercial license holder if the shad were landed dead in commercial gear legally deployed for the capture of species other than American shad (COMAR 2019). There is no data available on this harvest as it has rarely been observed by onboard biologists, but it is thought to be negligible.

3.9.3 Anthropogenic Sources of Mortality and Productivity

Stocking of OTC marked American shad of various early life stages in the Patuxent River occurred from 1994 to 2009 (Table 133). Hatchery contribution to the YOY American shad stock was high, ranging from 82% - 100% hatchery origin fish (Table 134).

Anthropogenic mortality of American shad in the Patuxent River is primarily attributed to bycatch of migrating adults by fyke net and pound net fisheries targeting white perch, yellow perch, gizzard shad, and catfish species. Mortality estimates associated with these gear types have not been formulated.

3.9.4 Fishery-Dependent Data Sources

MD DNR does not conduct any fishery-dependent monitoring of American shad in the Patuxent River.

Stevenson (1899) reports that Patuxent River once supported a substantial American shad fishery with 188,262 pounds landed in 1896. Landings severely declined through the early to mid-1900s (Walburg and Nichols 1967). It was also reported that a recreational fishery existed in this system prior to 1960 below Hardesty, MD (Mansueti and Kolb 1953). An additional unlicensed gill net fishery operated in the spawning area and data from 1960 estimated 2,000 pounds landed (Walburg and Nichols 1967).

Commercial landings data from the Patuxent River from 1944 to 1978 are presented in Table 135. Although there is no effort associated with this data set, it clearly demonstrates a precipitous decline and is attributed to overfishing and habitat degradation.

3.9.5 Fishery-Independent Data Sources

3.9.5.1 Adult Fishery-Independent Data Sources

3.9.5.1.1 Restoration Adult Electrofishing Survey

Survey Methods

From 2001 to 2014, adult American shad were electrofished by the MD DNR Fish Health and Hatcheries Program from the Patuxent River spawning grounds once weekly from mid-March to early June (Figure 178). Each river was sampled from upstream (38˚ 53’ 08.24” N 76˚ 40’ 29.53” W) to downstream (38˚ 51’ 05.09” N 76˚ 41’ 33.04” W) with constant voltage applied for the entire run. Total shock time (seconds) was recorded for CPUE calculations. Shad likely spawn in tidal freshwater areas downstream of this location, but increasing river width and depth reduced capture efficiency. Sampling upstream of this location was limited by boat accessibility.

Biological Sampling Methods

American shad were generally sub-sampled to no more than 20 individuals per day for otolith and coded wire tag (CWT) analysis. All other collected shad were counted for CPUE analysis. Fish collected were processed in the following manner: TL (mm), FL (mm) and sex identification. The fish were scanned for CWTs that were implanted in fish stocked as late juveniles. CWT data allow for analysis of specific stocking events, origin and age validation studies. CWT tagging was replaced with OTC otolith marking in 2012. Scale samples were taken for age and spawning mark analysis, and otoliths were extracted to identify hatchery OTC marks. All hatchery origin American shad are marked with OTC and/or CWT, which allows for data collection on hatchery contribution to the adult spawning stock.

Length/Weight/Catch-at-Age

From 2001 to 2014, male American shad sampled from the Patuxent River ranged in age from 3 – 10 (Table 136); females ranged in age from 3 – 9 (Table 137). Age-5 was the most common age for both males and females. Eighty-five percent of all fish captured by the survey, irrespective of sex, ranged in age from 4 – 6 (Table 138). The presence of repeat spawning fish was high, but varied without trend over from 2002 to 2014 (Table 139; Figure 179; R^2 = 0.00, P = 0.86). Mean length-at-age statistics are presented in Table 140-Table 142.

Catch Estimation Methods

Each electrofishing collection was treated as an independent observation and effort was defined as minutes of active electrofishing. There were 14 years of data with averages of 8 positive observations per year and 73.6% positive observations per year. Variables available for potential inclusion in the standardization model included sampling year (discrete) and water temperature (continuous). Electrofishing effort, in minutes, was used as an offset term in all models to account for variability in sampling effort on catches of adult American Shad. Model types considered included NB GLMNB GAM, ZINB GLM, and ZINB GAM. All GAM models were fit assuming cubic regression splines for continuous variables and with a gamma penalty of 1.4 for all models (NB GAM) and sub-models (ZINB GAM). AIC was used to select the final model type, covariates, and basis dimensions for smoothing functions. Prior to model fit, the data was constrained by excluding any collections with missing water temperature data or with observed water temperature less than or equal to 9^{o}C.

The best fit model, based on AIC, used to estimate a standardized index of abundance accounting for variability in annual catchability effects due to available covariates was a ZINB GAM. The final model included the catch of adult American Shad as the response variable and the variables sampling year (count sub-model only) and water temperature (binary (EDF = 1.00) and count (EDF = 2.9) sub-models) as main effects; the log of effort in minutes was included as an offset term in both sub-models.

The final model suggests the catchability of adult American Shad is affected by water temperature, with catches of Adult American Shad showing a parabolic relationship with water temperature with catches peaking at approximately 17^{o}C and declining at either higher or lower water temperatures.

The standardized index closely follows the same trend as the arithmetic mean catch rates across all years. The standardized index suggests a decreasing trend from the early- to mid-2000s followed by a sustained period of stable and low relative abundance through the early-2010s. In more recent years there was a brief increase in relative abundance, peaking in 2012, followed by declines through the terminal year. Annual CVs averaged 0.30 over the time series (Table 143).

3.9.6 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance. Details for these methods are provided in Section 2.

3.9.7 Results

3.9.7.1 Abundance Trends

3.9.7.1.1 Power Analysis

The only abundance index for American shad in this region containing estimates of PSE was the Patuxent River fishery-independent Restoration Adult Electrofishing Survey. This survey exhibited a median PSE of 0.258. Given this median PSE the power analysis suggests the survey would be able to detect a 50% decrease in abundance (power > 0.80) in 10 years assuming an exponential decline in abundance, though it would not quite be able to detect a 50% increase over the same period with power exceeding 0.80 (Table 25). Currently, there is no SFMP for this system so this survey is not used for sustainability targets and monitoring.

3.9.7.1.2 Mann-Kendall Analysis

The fishery-independent Restoration Adult Electrofishing Survey was used as in index for American Shad in the Patuxent River. A plot showed a decline in the index from 2001 through 2005, fairly stable values through 2010, increasing to a peak in 2012, and then subsequent decline (Figure 180). Mann-Kendall analysis did not detect any trends in either of the time periods (Table 21).

3.9.7.2 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Patuxent system, current unobstructed habitat area represents 100% of the historical habitat extent (5.23 square kilometers).

3.9.8 Stock Status and Conclusions

Mortality

Juvenile and adult mortality status is unknown due to lack of data to make this determination.

There were no mean length data available for trend analysis.

Abundance

Abundance status is unknown. There were no YOY abundance data available. There was no trend in adult abundance detected since 2005.

3.10 Potomac

3.10.1 Habitat Description

The Potomac River, a major tributary of the Chesapeake Bay, is located on the western shore. Of all East Coast rivers, the Potomac's watershed ranks fourth in area. The mouth of the river at the Chesapeake Bay is defined as a line from Point Lookout, Maryland to Smith Point, Virginia, and is about 12 miles wide. The estuary extends 113 miles from the Bay, up to just below Little Falls where it is but a few yards wide. At Little Falls, there is Brookmont Dam, a low head dam for water withdrawals that was built in the 19th century and traditionally had an ineffective fish passage way. That dam now has a functioning fish passage way (installed in 2000 by the U.S. Army Corps of Engineers) that allows shad to extend their range an additional 10 to 12 miles upstream to Great Falls, a natural barrier to all anadromous species. The fluvial portion of the River extends another 300 miles westward into the Appalachian Mountains. The total river basin drainage area is about 9.4 million acres, 1.6 million of which drain directly into the estuary. The yearly average freshwater flow is approximately 11,190 cubic feet per second at the head of the estuary (Lippson et al. 1980).

The Potomac River shad spawning area extends from about Stump Neck, Maryland and Cockpit Point, Virginia upriver to Great Falls, a distance of about 40 miles (Lippson et al. 1980; Figure 181).

It is assumed that the tidal freshwater area of the river had relatively healthy stands of indigenous submerged aquatic vegetation (SAV) throughout the 19th century. During the early and mid-part of the 20th century, however, water chestnut, a non-indigenous species of floating emergent aquatic plant that prevents light from reaching underlying SAV, became a "nuisance" that, along with nutrient and sediment pollution, prevented SAV from thriving. After years of periodic and occasionally intensive control measures, water chestnut was mostly eradicated from the Potomac River. The later half of the century saw the introduction of another non-indigenous species of SAV, hydrilla, but this species has functioned as a catalyst for the reemergence of native species of SAV. Today the tidal fresh water Potomac supports large beds of SAV that provide numerous benefits, including the provision of habitat and nursery grounds for numerous species of commercially and ecologically important fish and food for resident and migrating waterfowl. Additionally, SAV attenuates wave and current energy to reduce shoreline erosion and promotes the settlement of suspended solids, improving water clarity. SAV absorbs excess nutrients – which reduces the opportunity for algae blooms – and sequesters carbon, which is important in the global efforts to mitigate climate change. Recently, new populations of water chestnut have been noted in multiple locations throughout the tidal freshwater Potomac.

The tidal freshwater portion of the Potomac River has an SAV restoration target of 4,618 acres (not including the targets for Mattawoman and Piscataway Creeks). Progress towards this goal is tracked by the Chesapeake Bay Program's Bay-wide SAV aerial survey and monitoring program. Since 1984, the goal for this portion of the river has been exceeded multiple times, including the years 1991, 2005-2010, and most recently from 2014 to 2017, with 6,583 acres of SAV mapped in 2017 – the most SAV ever mapped in the tidal freshwater region of the river.

The most common species of SAV observed during ground surveys include wild celery, hydrilla, water stargrass, and multiple species of pondweeds and naiads.

3.10.2 Fishery and Management History

The low water mark of the southern shore Potomac River, exclusive of the tributaries, is the boundary line between the states of Maryland and Virginia, with Maryland being the owner of the river. Maryland and Virginia first entered into a compact in 1785 to regulate, among other things, the fisheries of the Potomac. After the adoption of the U.S. Constitution and the formation of a federal government, Maryland ceded the area, including that part of the Potomac River, which is now the District of Columbia.

There are five fishery management authorities on the Potomac River. The Potomac River Fisheries Commission (PRFC) is the Maryland-Virginia bi-state Commission with fisheries management authority for the main stem, exclusive of the tributaries on either side, from the Chesapeake Bay upstream to the southern Maryland-District of Columbia boundary line; the District of Columbia (D.C.) with authority for the Potomac to the Virginia shore and other waters within D.C.; the MD DNR with authority for the tributaries of the Potomac on the Maryland side of the river and the fluvial portion of the river upstream of D.C.; the Virginia Marine Resources Commission (VMRC) with authority for commercial fisheries in all tidal Virginia tributaries and for recreational fisheries in the saltwater portions of the tidal Virginia tributaries below the Route 301 Bridge; and the VDGIF with authority for recreational fisheries in the freshwater portions of the Virginia tributaries. Additionally the Federal government controls much of the shoreline of, and therefore access to, the Potomac through several military bases and the National Park Service.

During Colonial times the fisheries were essentially unregulated. In 1785 Maryland and Virginia adopted a compact to regulate the fisheries by requiring all fishery laws for the Potomac to be enacted jointly by the legislatures of both states. The first fishing license requirement was imposed by the Union Army during the Civil War, a period when fishing all but ceased. The historical record on shad and herring fisheries of the Potomac River date back to the Colonial period and most are anecdotal, but a few are fairly reliable. Listed here are a few examples:

1612: “Shad, great store, *of a yard long* and for sweetness and fatness a reasonable food fish.” Observation of William Strachey (italics added for emphasis; Tilp 1978).

1759: “Sturgeon and shad are in such prodigious numbers [in the Potomac]…and of the latter five thousand have been caught at one single haul of the seine,” observed Andrew Burnaby (Tilp 1978).

1814-1824: The very detailed records of George Chapman’s haul seine fishery provide valuable information about the size and extent of at least one person’s haul seine fishery located at the center of the prime spawning area. The records for each haul over an 11-year period are preserved in such detail that the numbers of shad and herring caught in ten-day periods are recorded, the timing of the runs is noted, the estimated mean shad catch per haul by ten-day period, and the estimated mean shad catch per haul for each year can be determined. During the 11-year period of record, 955,651 shad were landed. “Mr. Chapman’s single fishery had catches estimated to equal about 1/3 of the catches of shad by all gears from the entire Potomac River from 1946 to 1956” (Massmann 1961) (Table 146; Figure 182 and Figure 183).

1817: Thomas Fairfax of Alexandria, Virginia places an ad in the National Intelligencer of the National Capital calling for a meeting “to agree upon measures for preventing the destructive effects of tide or gill nets, which have been unlawfully set in the waters and have within the three last seasons so greatly lessened the number of Shad and Herrings taken out at the best landings" (Tilp 1978). It is uncertain if this is evidence of an early concern of overfishing in 1817, or just a squabble between gear types.

1832: "Some idea may be formed of the importance of these fisheries [in 1832] from the following statements:

- Number of fisheries on the Potomac, about …158
- Number of shad taken in a good season …22,500,000
- Number of herrings under similar circumstances …750,000,000…
- The Potomac can boast of the largest shad fisheries in the United States" (Tilp 1978).

Colonial 1880s: "Though the records of the average weight of shad in those days are lacking seven pounds is a fair estimate, and it may have been greater. The weights [in 1978] seldom exceed three or four pounds, because in the more recent years of intensive fishing, shad have been widely caught up as they returned from the ocean to spawn for the first time" (Tilp 1978).

1883: The Potomac River American shad population was apparently judged healthy enough by the U.S. Fish Commission to support their establishment of a station at Fort Washington, Maryland for the collection of eggs. Adult shad were captured with a shore haul seine that was approximately 810 feet long and 47 feet deep with most meshes of between 2.25 inches and 2.5 inches. Most eggs collected were sent to Central Station in Washington, D.C., although approximately 10 percent of the eggs harvested were hatched at the Fort Washington facility and released into the Potomac River in that vicinity. Central Station in Washington, D.C., was where the eggs from Fort Washington were processed for distribution. Eggs were distributed up and down the east coast, central U.S. and as far west as the Colorado River (Cummins, pers. comm.).

1898: "The 1898 total imports [in numbers of fish] to Alexandria, Washington, D.C., and Georgetown markets as taken by Charles Lundington, inspector of marine products for the Washington board of health: Shad 1,051,587; Herring 15,006,940; Hickory jacks 340,387; Sturgeon 1,650" (Tilp 1978).

1899: "Next to the oyster in value is the shad, of which 2,571,000 pounds were landed in 1899 ... the following year the aggregate catch was 2,356,759 pounds, or 621,911 fish [3.8 pounds average fish weight]" (Tilp 1978).

By the middle of the 20th century there were restrictions on gill net mesh sizes, net lengths, and seasons when they could be set. The shad and herring season ran from March to the end of May.

1940-1950s (approximated): Louis Harley remembers helping his father capture shad for a hatchery operation at Fort Belvoir and several Maryland fishermen remember their fathers working at the shad hatchery at Fort Belvoir, Virginia. "Fish-culturists at the old Fort Belvoir shad hatchery on the Potomac River" is mentioned several times in reports by Romeo Mansueti, but any further information could not be found (Cummins, pers. comm.).

In 1963 the PRFC was instituted and has regulated the fishery since. The portion of the Potomac River under the PRFC jurisdiction is not generally considered an area suitable for recreational shad fishing, so no regulations were enacted until 1982 when a two fish creel was imposed to "close" a perceived jurisdictional loophole.

Gill nets, pound nets, and haul seines were declared commercial gears and require licenses, and all commercial licensees are required to file catch reports. Table 147 contains a summary of the regulations for these gears as applied to the shad and herring fishery.

1964-1981: From 1964 through 1981 the commercial fishery on the Potomac was operating relatively freely. Landings declined from about 466,000 pounds to 4,200 pounds but averaged about 222,000 pounds for the period (Table 148; Figure 184).

1982-2017: The Potomac River has been closed to the directed harvest of American shad since March 1, 1982, when the fishery was limited by regulations such that it became a bycatch fishery only. Allowable harvest since then has been via a pound net by-catch provision that allowed up to two percent by volume of the total catch in possession to be American shad. In 1995, the hickory shad fishery was also closed with the same by-catch provision. Starting in 1996, the by-catch provision for both species of shad was further limited to two percent by volume, but could not exceed one bushel (approximately 60 lbs/bushel) per day per licensee. In 2004, a one-bushel limit of American or hickory shad by-catch was established for the gill net fishery. In 2012, approval was obtained to increase the by-catch limits from one bushel per day to two bushels per day because the restoration target was exceeded. Harvest of American shad has averaged about 3,400 pounds a year since 1982 (Figure 185).

The commercial American shad fishery and landings in the Potomac are today, by regulation, strictly bycatch of the pound nets and gill nets set for other fishes. Gill nets are fished from November through March 25 and pound nets can operate from February 15 to December 15 each year. Both gear types are "limited entry" fisheries such that no new licenses are sold.

The recreational fishery for American shad, although not a targeted fishery in the PRFC area, is currently closed. The District of Columbia conducts regular creel surveys, but has no creel data pointing to a recreational shad fishery in the District. A small group of fishermen at Fletchers Boathouse (just downstream of Little Falls) target American shad for catch-and-release; however, since D.C. has a closure on the recreational and commercial shad fishery, there is no legal harvest. This species appears to be on the rebound in D.C. and the District is considering requesting a limited recreational season.

The Potomac River Fisheries Commission instituted a mandatory harvester-based catch reporting system in the middle of 1963. Data from the first year is not considered reliable or consistent with later years because of problems with timing, participation, and collection.

Therefore data from 1964 to the present can be used. Failure to submit the required information can and does result in license suspension or revocation.

3.10.3 System-Specific Life History

The only unique life history difference between the Potomac River shad and many other East Coast river stocks is the lack of a long fluvial spawning reach. The fluvial spawning grounds are an area only 10 to 12 miles long between Little Falls and Great Falls. The major spawning area is in the tidal freshwater part of the Potomac, extending about 30 miles downstream from the fall line at Little Falls.

3.10.4 Anthropogenic Sources of Mortality and Productivity

The earliest restoration efforts date to about 1883 when the U.S. Fish Commission established a "Station" at Fort Washington, Maryland for the primary purpose of collecting American shad eggs for export to other river systems throughout the country. Some ten percent of the eggs that were collected were released back into the Potomac. Several personal accounts refer to a shad hatchery operation during the 1940s and 1950s at Fort Belvoir, Virginia, but no specific documentation has been uncovered to date.

An American shad restoration stocking project for the Potomac River began in 1995 as part of an effort by a coalition of federal, state, regional, and local agencies, and non-profit groups, organized as a Task Force, to open historic spawning and nursery habitat for native and anadromous fishes. The Little Falls Fish Passage Task Force members came from Virginia, Maryland, the District of Columbia, the Interstate Commission on the Potomac River Basin, the Potomac River Fisheries Commission, the USFWS, the U.S. Army Corps of Engineers, the National Biological Survey, the U.S. Environmental Protection Agency, the National Park Service, the National Marine Fisheries Service, Montgomery County, Maryland, the Chesapeake Bay Foundation, and The Potomac Conservancy. The Task Force has been inactive since 2002. An important milestone for this project was reached in 2000 when the U.S. Army Corps of Engineers completed a fishway at the Little Falls Brookmont Dam. During the eight-year stocking phase of the project, over 15.6 million shad fry were stocked into the Potomac River. The Restoration Stocking Program for American shad concluded in 2002, at which time recovery was considered sufficient for natural reproduction. Stocking American shad fry and viable eggs in the Potomac River continues, but now as "mitigation stocking" to replace the Potomac River American shad collected as brood stock for restoration activities in other river systems (Table 144).

Approximately 50,000 American shad have been collected as brood stock from the Potomac River for hatchery production by several agencies under special collection permits issued by the PRFC since 1995 (Table 145). The Interstate Commission on the Potomac River Basin (ICPRB) participated in the Restoration Stocking Program (1995-2002). In 2003, restoration stocking of the Rappahannock River in Virginia started using Potomac River origin eggs through a partnership between ICPRB, the VDGIF, and the USFWS Harrison Lake National Fish Hatchery. Between 1995 and 2015, the ICPRB released over 25 million fry into the Potomac. ICPRB also collected some American shad through a “Schools-in-Schools” partnership with Living Classrooms of the National Capitol Region, the Anacostia Watershed Society, and the Chesapeake Bay Foundation, starting in 1996 with three schools. One year, there were as many as 52 schools participating. Public involvement was a significant component of this program, with volunteers helping thousands of students over the years to hatch American shad in their classrooms and release the fry into the Potomac and Anacostia Rivers. The students’ efforts to help replenish American shad populations are notable, but more important is the link established between students, volunteers, the river, watermen, biologists and the shared fishery heritage. The lead for this school program was taken over by the Anacostia Watershed Society in 2016.

The MD DNR since 2001, VDGIF (2003 – 2014, and 2017), the USFWS since 2004, and the District of Columbia’s Fisheries and Wildlife Division of the Department of Energy and Environment (DOEE) since 2006, have caught American shad brood stock from the Potomac River under special collection permits issued by the PRFC (Table 145). Conditions of these permits require data reports, scale/otolith samples of ten percent of the American shad catch for biological analysis, and restocking of ten to fifteen percent of the shad fry produced back into the Potomac River as close to the capture site as feasible. Viable eggs were returned to the Potomac instead of fry in some instances.

The MD DNR began replacement stocking in 2007, and has released about 1.5 million fry into the Anacostia River, a tributary of the Potomac River in Washington D.C. and 1.4 million fry into the Potomac River. The DOEE has released approximately 7.2 million fry into the Anacostia River. The VDGIF reported a total of 7.1 million fry stocked in the Potomac, and the USFWS reported 902,000 fry stocked in the Potomac River as mitigation for egg collections. In addition, the USFWS released approximately 2.8 million viable eggs back into the Potomac River for mitigation. The Potomac River has been the egg source for all of Maryland’s shad restoration projects, Virginia’s shad restoration program in the Rappahannock River, as well as the Susquehanna River (MD/PA) and some of Delaware’s rivers since 2002.

The DOEE obtained a collection permit for American shad from the PRFC in 2017; however they were unable to conduct gill netting operations for the 2017 season due to water filtration issues at the fish hatchery. The VDGIF obtained a collection permit for American shad from the PRFC in 2017; however the data from that sampling season were lost.

3.10.5 Fishery-Dependent Data Sources

3.10.5.1 Commercial Fisheries

3.10.5.1.1 Commercial Landings

The PRFC has recorded shad landings by state since 1964 and by month, area, sex, and gear, including effort data for most years, since 1976 (Table 148).

The landings declined from 466,000 pounds in 1964 to just several hundred pounds in 1985, and then increased gradually to over 10,000 pounds in 2017 (Table 148; Figure 184). In 1982, regulations changed the fisheries to bycatch only, resulting in limited harvest from 1982 to 2017 (Figure 185).

Sampling Intensity

All licensed fishermen are required to submit reports of their daily harvest of all species by gear type on forms supplied by the PRFC. Originally fishermen recorded daily catch (in pounds) on separate forms for each gear they fished. The forms had columns for each species and one line for each day of the month, and space to record units of effort (number of nets, yards of net, etc.). From 1964 through 1980, the records submitted by the fishermen were tabulated by hand and summed for the month, and only the totals recorded. NOAA Fisheries port agents collected the actual paper records, which were used to publish the monthly Landings Bulletins for Maryland and Virginia.

Records of the harvest by area, by gear, and by month were hand tabulated and recorded from 1976 by the PRFC, and summary tables kept. Some of these records have been located and a few years have both effort information and pounds landed. In 1988 the daily records were still being hand tabulated, but the one line total was being entered into a computer program. In 1991 the reporting frequency was changed from monthly to weekly. Again the weekly reports were hand tabulated and a one-line entry made for the week. In 1999, computer programs were developed that permitted the daily information to be entered.

Commercial Discards and Bycatch

The mandatory harvest reporting system on the Potomac was modified in 1999 to include information on bycatch and value. The fishermen are asked to estimate the number of pounds discarded or released and record it in one of three categories: no market, too small, or closed season. Prior to this change, total catch was not reported.

Bycatch and discard/release information on shad is presented in Table 149 and Figure 185 and Figure 186, showing an overall increasing trend.

Biological Sampling

Data for American shad reported to PRFC from pound nets (primary gear), one of two gear in the Potomac River that is allowed a bycatch of American shad, has reflected changes in sex ratios since initiation of the reporting system (Figure 187). During the 1970s and early 1980s there were no regulations or limits on shad, so the entire catch was harvested and sex ratios likely reflect the run composition. From 1982 forward, sex ratios may reflect high grading for females because of bycatch limits; however, an increasing abundance of roe shad is evident.

There has been no other biological data (i.e., length, age) sampling from commercial catch.

Commercial Pound Net CPUE

The PRFC harvester-based reporting system includes estimates of effort (net-days, yards of net fished, etc.) for American shad by sex. The best fishery-dependent data on relative abundance of adult American shad is the 29-year series (1988-2017) of commercial pound net bycatch only index computed by the PRFC from the mandatory harvest reports (Figure 188), showing an increasing trend. As a result of regulatory actions instituted in 1982, pound net fishermen were allowed to keep one bushel per licensee per day of shad, and as of 2012 two bushels. Gill net fishermen are also allowed to keep two bushels. Fishermen must comply with mandatory reporting that includes providing effort, gear, and sex information on catches. Data on bycatch or discards are not available from 1982 through 1987. Additionally, fishers were not required to report numbers or weights of discarded shad until 1999. As a result, total catch is unknown for most of the period. In 1999, an additional regulation was established requiring reporting of discarded shad in catches. Total pound net catch can be calculated from 1999 to 2017, as the total number of bycatch plus the total number of discards (Table 149), and total CPUE for 1999 to 2017 (Figure 189). This time series depicts high annual variability, with strong peaks in 2003, 2009 and 2012 and a trend towards higher catch rates.

To assess the status of American shad on the Potomac River, current pound net landings (bycatch plus discards) was compared with historic data from the 1970s and the 1940s to 1950s. Catch-per-unit-effort in 1944 to 1952 was estimated from landings data provided by Walburg and Sykes (1957) (Table 150). The geometric mean of current pound net CPUE (only those years when bycatch plus discards were reported) was compared with the geometric mean of landings data from 1976 to 1980 and 1940s to 1950s (Walburg and Sykes 1957; Figure 190). From 1944 to 1956, Potomac River landings of American shad were relatively stable, averaging approximately 850,000 pounds annually, and ranging from about 500,000 to 1,300,000 pounds (Table 146). In the late 1970s, total landings of American shad decreased sharply from 120,000 pounds in 1976 to 17,000 pounds in 1980. A moratorium on the taking of shad was established in 1982.

The geometric mean of the 1940s to 1950s pound net landings is 31.1 pounds per net-day (when catches were sustainable presumably). The geometric mean of the 1970s data is 2.9 pounds per net-day. The geometric mean of the current data is 44.6 pounds per net-day, significantly above the 31.1 restoration target. The geometric mean of the current data has exceeded the restoration target every year since 2011. The previous stock assessment stated “there should be no new expansion of the fishery until the benchmark is reached”.

It should be noted that historic and current pound net catch data are combined landings from Virginia and Maryland pound nets. Locations of pound nets in the 1940s to 1950s may have been different than current locations, or locations in the 1970s, as fishers in the 1940s and 1950s were targeting river herring as well as American shad. The current pound net fishery in the Potomac River targets striped bass and menhaden (Carpenter, pers. comm.). Stevenson (1899) reported that pound nets in the Chesapeake Bay in 1886 were “of the single heart variety” and nets in the Potomac River shad fishery had multiple pounds (“first pound, second pound, main pound”) of varying meshes. For comparisons, it was assumed that the catching power of pound nets in the 1940s to 1950s is the same as in the current fishery (and in the 1970s).

Biases
The PRFC has enforced the mandatory catch reporting system for a full generation and believe the data are a reliable commercial database. Efforts have been made to improve the level of detail over the years while maintaining continuity throughout the time series. The Commission also has very accurate records on the number of licenses sold each year by gear type, and the commercial gears have remained relatively similar.

3.10.5.2 Recreational Fisheries

There is no historical information on recreational fishing in the main stem of the Potomac under PRFC jurisdiction. The most likely areas for a recreational fishery are located within the District of Columbia. The District of Columbia conducts regular creel surveys, but has no creel data suggesting recreational harvest of shad. Recreational catch-and-release of American shad does occur in the District of Columbia.

3.10.6 Fishery-Independent Data Sources

3.10.6.1 Adult Fishery-Independent Data Sources

3.10.6.1.1 MD DNR Potomac River Broodstock Gill Net Collections

Survey Methods
Since 2001, MD DNR biologists have set gill nets in the Potomac River at Marshall Hall, near Fort Belvoir. American shad historically spawned from the middle of April to the middle of May in this section of the Potomac River. Different areas along the Potomac River were evaluated for their ability to concentrate American shad. The channel in front of Fort Belvoir tended to concentrate the greatest amount of American shad. Nets were set parallel to the channel edge in 6 to 15 m of water. The time of net set depended exclusively on tide. Nets were set at slack tide when possible since slack tide sets were most productive. American shad generally spawn near or just after sundown and nets were set from 1530 to 2130. Setting nets to collect shad before or after this six-hour window was deemed ineffective.

Biological Sampling
Biological data were not obtained for captured fish prior to 2005. Starting in 2005, sub-samples of American shad were taken and data obtained on sex, fork and total length, and weight; scales and otoliths were removed for ageing analysis (Table 151 and Table 152). Data for 2005-2009 was not available.

Ageing Methods
See Section 1.1.4 for a description of ageing methods.

American shad ranged in age from 3 to 9. However, the vast majority of all shad aged were between 4 and 7 years old (Table 151).

Catch Data
Weather and temperature conditions in late March and early April greatly influence when American shad spawning begins. Gill netting started at the beginning of April to encompass the peak time for shad collection. Water temperature and location greatly affect the best time to initiate sampling. Early sampling should begin with temperatures between 13 and 15 °C. Significant numbers of ripe female shad were collected from 18 to 20 °C (Figure 191).

3.10.6.1.2 Potomac River Shad Egg Collections (ICPRB)

The ICPRB has collected American shad for hatchery spawning annually since 1995. From 1995 to 2002, the ICPRB and the USFWS jointly conducted this sampling for the Little Falls Fish Passage Task Force. The ICPRB became the primary monitoring entity in 2003. Between 2003 and 2014, restoration stocking of the Rappahannock River occurred, using Potomac River origin eggs through a partnership between ICPRB, VDGIF, and the USFWS's Harrison Lake National Fish Hatchery. Data collected provide some indication of abundance trends over time (0).

Survey Methods
ICPRB gill net collections were primarily performed for the collection of adult shad for brood stock. Two drifting gill nets, sequentially deployed, were fished together along the Virginia side of the channel at the mouth of Dogue Creek near Fort Belvoir. The nets were rigged in traditional manner for this section of the Potomac, approximately 91 meters (300 feet) long, 7 meters (23 feet) deep, 14 centimeter (5 ½ inch) stretch mesh, made of either #69 twine cotton or monofilament, with top line suspended below the surface approximately 1.5 meters (5 feet) from floating, 16 centimeter (6 inch) diameter corks rigged about every 4.5 meters (15 feet). The bottom line was very lightly weighted, rigged with 16 centimeter (6 inch) diameter 9 gauge galvanized metal rings set about 4.8 meters (16 feet) apart. A ring was rigged below each cork. The difference in spacing between the corks and rings was done because the bottom line was a little longer than the top line to help provide the necessary slack in the nets. The nets were fished at evening slack water, at either the high or low tidal shift, for approximately two hours and continuously tended as described in the following paragraph. Nets were fished approximately between 1600 and 2400 hours, depending on the tide, with the best fishing tides being near dusk. It was imperative that collections were made during slack tides because otherwise the currents in the Potomac River would be too strong for the nets to fish properly, they would hang loosely and drift considerable distances (miles), subjecting them to snags, potential damage, and loss.

The nets were allowed to drift until the bobbing of corks indicated that fish had become entangled in the net. That section of the net was lifted, fish were removed from the net, and the section of net was dropped and allowed to keep fishing. At the end of the drift, the net was taken up and all fish were removed, culling out the ripe females and a roughly equal number of males. Care was taken to release bycatch alive. Captured shad were examined for sex and maturity. Male and female shad that appeared ripe or running were kept alive on board the boat in a 100-gallon oval stock tank with water circulation and aeration. Typically any female shad that did not have roe running (i.e., green shad) were released back into the river. Some of the green shad that were kept were also the result of false positive decisions (i.e., they appeared to be running ripe females when captured and were therefore kept but at stripping they only produced a few eggs). Unfortunately, American shad do not handle well and all fish placed in the holding tank succumb to stress. Therefore, in some cases these green fish were not released.

When enough shad were collected (at least 6 females and a similar number of males) the fish were quickly transferred to shore or another boat for stripping.

Sampling Intensity

Sampling has occurred each year since 1995, approximately four evenings per week from mid-April to mid-May.

Biases

A potential bias of the study is that only one mesh size used. Net saturation has been an issue in recent years, as the population has increased. While the nets can capture over 100 shad per net, the nets tend to start sinking and collapsing when they have caught approximately 50 fish.

Ageing Methods

Beginning in 1998, the first year in which returning adults with OTC marks were expected, otoliths and scales were collected from approximately 60 to 100 fish per year. To obtain these, blocks of approximately 8 to 10 fish were randomly collected over the duration of each annual brood stock collection. In addition, all American shad captured at Great Falls (see Section 3.10.6.1.7) and a subset of angler-captured shad from the vicinity of Chain Bridge (Fletcher's Boat House) was targeted for ageing as well. Approximately 525 fish have been analyzed from the years 1998 to 2005 (Table 159). Analysis has been performed by varying partner agencies over duration of project: 1998 to 2000 by Mike Hendricks with the PFBC using otoliths and scales; 2001 to 2002 from USFWS (contract with Virginia Commonwealth University (VCU)); 2006 to 2017 from USFWS (Table 160 – Table 162).

Catch Rates (Numbers)

CPUE was calculated by two methods. The first CPUE (shad used/net-set) was based upon the number of shad used for egg collections and re-stocking of the Potomac and, starting in 2003, the Rappahannock River. It does not include shad which were netted but released, i.e. green females, spent females, or surplus males (tried to keep a 1:1 ratio of males to females). Starting in 2002, all shad netted were counted and a second CPUE (total shad/net-set) has been calculated using all shad brought to the boat, including those released (0).

These catch rate data are not considered representative of interannual abundance changes and were not used in the assessment for abundance trend analyses (Table 15).

Length, Weight, and Catch-at-Age

Collection of length, weight, and catch-at-age was coordinated by the USFWS. The percent of repeat spawners was determined by the presence of spawning checks on scales of a sample of the 2001 fish (Table 163).

American shad ranged in age from 3 to 9. However, the vast majority of all shad aged were between 4 and 7 years old. In 1998 age-4 fish were the most abundant, in 1999 through 2002 age-5 fish were predominant, and in 2005 age-6 fish accounted for the largest percentage (Table 159). Age structure broadened during the time period and mean age increased, especially in 2005. The age distribution truncated in recent years and fish over the age of 8 have not been observed since 2012 (Table 160).

Mean fork length by sex increased through 2002 and decreased in 2005.

In 2001, 61 of the 88 fish (69%) were repeat spawners. Details are found in Table 163.

The fraction of adult American shad with OTC marks has remained very low (1998-2005) (Table 159). Incomplete data since 2005 allows no interpretation.

3.10.6.1.3 Potomac River Shad Egg Collections (VDGIF)

Survey Methods

Virginia Department of Game and Inland Fisheries staff has set gill nets in the Potomac River since 2004 to collect American shad broodstock to support stocking activities for the Rappahannock River. The methods, areas, and timing were similar to that described and used by MD DNR and the ICPRB; data from this egg collection are included in the ICPRB's section of this report.

Sampling Intensity

Between April 14 and May 19, 2005, thirteen sampling trips were made. Two to five nets were set per day, with a total of forty-one sets over the 13 trips. Most American shad were caught in late April and at water temperatures of 16 and 17˚ C.

Biological Sampling

The sex and lengths, both fork and total length, were recorded for each of the broodfish. Otoliths and scale samples were taken from every tenth fish.

Age

The age of each of the sub-sampled fish was determined from the otoliths by personnel from the VDGIF's Age and Growth Section. The otoliths were also examined for an OTC mark. Results were combined and reported with the ICPRB results (Section 3.10.6.1.2).

3.10.6.1.4 DC DOEE Potomac River Stock Enhancement

DC DOEE has been working on American shad production and subsequent stocking in the Anacostia River since 2006. This work consists of four components: gill netting adult broodstock, strip spawning, hatching, and stocking larvae.

Survey Methods

Adult American shad typically begin to arrive in District waters in early April as part of their annual spring run, and lasts until mid-May. The gill netting mainly occurs down river at Marshall

Hall, MD. This section of the Potomac River is outside DOEE's jurisdiction, so a collection permit is acquired through PRFC. Gill Netting consists of fishing three nets that are 300 ft. x 24 ft. with five inch stretch. The nets are set during the evening slack tide, parallel to the shoreline along sharp edges on the river bottom, and retrieved after one hour. American shad are sexed, and the eggs of ripe females are stripped for incubation at the hatchery.

Sampling Intensity

Sampling timeframe is April 1 through May 31, on Monday through Thursday evenings.

Biological Sampling

Approximately five percent of the adult shad captured were kept and their lengths, weights, and sex were recorded. Otolith and scale samples were taken for age analysis (Table 164 and Table 165).

3.10.6.1.5 Combined Broodstock Catch Data

Total Catch

Broodstock collections for hatchery programs have occurred from 1995-2017 (Table 145). Broodstock catch in numbers was available from MD DNR, DC DOEE, collaborative efforts by PFBC/USFWS, and collaborative efforts by ICPRB/AWS/VDGIF. Broodstock programs generally fish drift gill nets with 5.5 inch mesh to target females and 4.6 inch mesh to target males, but mesh sizes have varied through time and across programs. Broodstock catch are generally available by date, program, disposition (retained, unknown discards, live discards, dead discards), sex, and maturity status. DC DOEE and PFBC/USFWS discard green and spent females, but this catch was not available for the assessment in electronic format. Only VDGIF specified disposition of discards (live vs dead).

Broodstock Catch-at-Age

Limited biological sampling of spawning adults in the Potomac River has been conducted by broodstock collection programs and the fishery-independent MD DNR Striped Bass Spawning Stock Survey (MD DNR SBSSS) requiring several pragmatic decisions to develop a time series of catch-at-age. Fork length data were explored visually and with linear regression models for characterizing the size composition of the catch and to inform borrowing data where necessary. Total length observations were converted to fork length with the coastwide regression estimates where necessary (Section 1.1.3.1). Factors explored for effects on mean size of the catch included year, month, sampling program, and sex. Disposition (retained broodstock vs dead broodstock discards; no data from unknown or live broodstock discards) was also considered during initial exploration, but there were few length observations from discarded fish and all were from one agency (VDGIF). Length distributions among maturity statuses and between harvest and dead discards are similar (Figure 192-Figure 194). Maturity status is the driving factor for harvest by broodstock programs (egg production) and serves as a proxy for disposition. Additionally, confirmed dead discards from broodstock programs are discarded due to mortality, not size. Therefore, it seems reasonable to assume the size composition of discards is the same as harvested fish.

Mean length was calculated by year, month, sampling program, and sex and any observations with fewer than 10 individuals measured were dropped from the data set. Sex had a relatively large, significant effect on mean size, with average length of males ≈45 mm smaller than females. Comparison of length distributions by program type (broodstock collection vs fishery-independent abundance survey) and sex suggest both program types are fully selective of the adult female population, while only the fishery-independent abundance survey is fully selective of the adult male population (Figure 195). The MD DNR SBSSS fishes smaller mesh sizes (3, 3.75 inches) than the broodstock collection programs and catches a similar size distribution of females, but a smaller size distribution of males. Mean lengths among broodstock collection programs were generally not significantly different, but there were generally significant differences between broodstock collection programs and the MD DNR SBSSS. Therefore, MD DNR SBSSS length data were not considered further for characterizing broodstock length compositions.

Mean length was significantly different between months, but the effect was relatively small, with average lengths in May ≈4.5 mm smaller than in April. Based on these results, length frequencies were tabulated by 10 mm bins within year, month, sex, and sampling program and assigned to total catch from the respective year, month, sex, and sampling program. If the number of individuals measured did not meet a sample size threshold of 49 or if catch was not available at this level, length data were pooled over months within year, sex, and sampling program and length frequencies were tabulated and assigned to catch. This threshold was defined based on the limiting sample size by year and sex after 2003 when continuous broodstock biological sampling data were available. If the length sample size threshold was still not met or catch was not available at the sampling program level, length data were pooled over months and broodstock collection programs within year and sex and length frequencies were tabulated and assigned to catch. Length composition data for all catch records from 2000 and 2004-2017 were available at this level. Length data were available for 20%, 17%, and 63% of the broodstock catch by year, month, and sampling program, year and sampling program, and year pooling levels, respectively.

Proportions-at-length were applied to broodstock total catch in numbers to calculate catch-at-length. There were some missing/unspecified sex-specific catch data, so average sex ratios from previous years' catch were used to partition total catch to sex-specific catch. To calculate total removals, a discard mortality rate was applied to live discards and reported discards with unknown disposition (i.e., dead or live). The mean daily proportion of observed dead discards from broodstock gill nets with reported disposition (12%) was used as an estimate of discard mortality for live discards and discards with unknown disposition. This should be viewed as a conservative estimate for discards with unknown disposition given observed dead discards account for immediate, at-net mortality only while discards with unreported disposition include immediate, at-net mortality and delayed, capture-associated mortalities.

Age length keys (ALKs) were constructed using multinomial logistic regression (Gerritsen et al. 2006; Stari et al. 2010, Weakfish Stock Assessment Subcommittee 2015, Black Sea Bass Stock Assessment Subcommittee 2016) using the multinom function in the nnet package for R (Ripley

2016). Both otoliths and scales have been collected by broodstock collection programs and scale samples collected by the MD DNR SBSSS were used to supplement age data. Age structure-specific ALKs were constructed whenever sample size for a given year and sex combination exceeded 30. This was based on exploratory work conducted during the black sea bass. In situations where sufficient samples were not available, aggregate-sex keys were built by combining data for males and females. All ALKs were based on fork length. When fork length was not available, total length was converted using formulas derived from data specific to that system.

Removals-at-length were summed within sex and year and applied to sex-, year-, and age structure-specific ALKs. ALKs were compared between subsequent years (in the data set, not necessarily in time) within sex and between sexes within years to identify proxy age-length keys for year and sex combinations when fewer than 30 age samples were collected. Mean differences in probability of being assigned an age at each length bin from these comparisons were generally smaller between sexes within years (Figure 196-Figure 197). Therefore, aggregate-sex age-length keys were used to calculate removals-at-age for sex and year combinations with fewer than 30 structure-specific age samples collected. Aggregate-sex scale ALKs were used for 2009 for both sexes. Aggregate sex otolith age-length keys were used for females in 2011 and 2015 and for males in 2005, 2011-2013, and 2015-2016. There were removals-at-length in 2004 and 2009, but no otoliths were sampled during these years so sex-specific age-length keys were borrowed from 2005 and 2008, respectively.

3.10.6.1.6 MD DNR Potomac River Striped Bass Spawning Stock Survey

Since 1985, the MD DNR has employed multi panel drift gill nets to monitor the Chesapeake Bay component of the Atlantic coast striped bass population. The primary objective of this survey was to generate estimates of relative abundance at age for striped bass. American shad are caught as bycatch and since 1997 MD DNR personnel have collected data on this species.

Survey Methods

Multi-panel experimental drift gill nets were deployed in the Potomac River and in the Upper Chesapeake Bay (Figure 198). The gill nets were fished six days per week from late March until mid-May. In the Potomac River, sampling was conducted from late March to mid-May.

From 1985-2014, individual mesh panels were 150 feet long, and ranged from 8.0 to 11.5 feet deep depending on mesh size. The panels were constructed of multifilament nylon webbing in 3.00, 3.75, 4.50, 5.25, 6.00, 6.50, 7.00, 8.00, 9.00, and 10.00-inch stretch mesh. Beginning in 2015, the length of the 3.00, 3.75, and 4.50 inch meshes was reduced to 75 feet in an effort to catch fewer blue catfish. This represents a small reduction in overall effort that is reflected in CPUE (number of fish caught/1000 yds^2 of net/hour) calculations. Due to the design of the fishing boat, the nets were split in half in the Potomac River, and the two suites of panels (5 meshes tied together) were fished simultaneously end to end. All 10 meshes were fished twice daily unless the weather prohibited a second set. The order of meshes within the suite of nets was randomized with gaps of 3 to 10 feet between each mesh. Overall soak times for each mesh panel ranged from 6 to 213 minutes.

Sampling locations were assigned using a stratified random survey design. One randomly chosen site per day was fished in each spawning area. Sites were chosen from a grid superimposed on a map of each system. The Potomac River grid consisted of 40-0.5-square-mile quadrants. Once in the designated quadrant, air and surface water temperatures, surface salinity, and Secchi depth were measured.

Biological Sampling
Prior to 2002, information collected from American shad in this survey was limited to length and sex. From 2002-2016, scales were collected from all American shad encountered and age determination was attempted for all samples. From 2017-present, scales have been collected from a subset of American shad based on length and sex (10 fish/20mm length bin/sex; Table 153 and Table 154). Scales are read for age and repeat spawning information (Table 155).

Ageing
See Section 1.1.4 for a description of ageing methods.

American shad ranged in age from 3 to 10. However, the vast majority (~94%) of all shad aged were between 4 and 7 years old. The age distribution truncated in recent years and fish over the age of 8 have not been observed since 2013 (Table 153). The arcsine-transformed percentage of repeat spawners varied with no trend from 2002-2017 (Table 155; $R^2 = 0.00$, $P = 0.93$).

Abundance Indices
Effort and depth (a candidate catchability effect) varied among mesh size panels fished during each sampling day, so each gill net panel of a specific mesh size was treated as an independent observation. Effort was defined as the product of the panel area and the total hours fished (square foot net hours). Mesh sizes fished were added to the survey and sites sampled were standardized in 1990, so data from years earlier than 1990 were dropped from the data set. There were no positive observations in 1990, so data from this year were dropped from the data set. There were twenty six years of data with averages of 41.4 positive observations per year and 8% positive observations per year (Table 157).

A negative binomial GAM was used to estimate a standardized index of abundance accounting for variability in annual catchability effects. The final model included count of shad as the response variable and year, sampling site, maximum depth, water temperature, and air temperature as covariates. The number of square foot net hours was included as an offset variable. Smoothing functions with basis dimensions (i.e., k) of three and twenty were estimated for maximum depth and water temperature, respectively. AIC was used to select the final model type (GLM vs. GAM), covariates, and basis dimensions for smoothing functions. The final model converged with a dispersion statistic of 1.29, indicating the data were not over-dispersed relative to model expectations.

Catch rates are predicted to increase to a peak at water depths of approximately 27 feet and then decline as water depths exceed 30 feet, though effects at these depths are relatively uncertain. Catch rates are predicted to increase as water temperature increases. Catch rates decrease as air temperature increases, thought the magnitude of this effect is small. The index follows the same trend as geometric mean catch rates, but there are notable differences in 2005, 2007, 2010-2011, 2014, and 2016-2017. The index starts at the lowest level of the time series, increases to the second highest point of the time series in 2007, decreases through 2009, and then increases to the highest point of the time series in 2015. There is a slight down turn in the index from 2016-2017. Annual CVs average 0.648 through the time series (Table 157).

3.10.6.1.7 ICPRB Dip Net Monitoring at Great Falls

Direct monitoring of the fishway on the Brookmont Dam at Little Falls, Potomac River, is not feasible due to the dangerous and remote location of the structure. Immediately downstream from the dam is a mile-long steep grade of rock outcrops and ledges. There are about 11,000 square miles of drainage above the dam, and springtime flows are typically very dangerous. Therefore, indirect monitoring is conducted at Great Falls, approximately 10 river miles upstream from the fishway. No adult-shad monitoring sites have been identified between Great Falls and Little Falls, primarily because of no or poor access and high risk.

Boat-electrofishing collections were performed in the Mather Gorge area about 4,000 feet downstream of Great Falls from 1999 through 2002. These electrofishing surveys had to be discontinued after 2002 due to budgetary reasons, but there were also concerns that this stretch of the river was not a good location to find the fish (high energy, not many resting areas, open to full sun), the boat ramp was difficult to use during low-flows (the apron wasn’t deep or long enough) and very dangerous, with poor capture efficiencies, at higher flows. Several gill net collections deployed by canoe in the first eddy below Great Falls on the Maryland side were performed in 2001; this was judged a poor method, and abandoned. Long handled dip net monitoring, protocol developed by Mike Odom of the USFWS in 2000, has been used with varying effort by the USFWS and the ICPRB since that time. It is now the primary method of monitoring the effectiveness of fish passage at Little Falls and serves as another indicator of the relative strength of the migratory activity. It is also meant to replicate the type of gear used traditionally, first by early Americans and then by others through the early 1900s, at this location.

Sampling Intensity

The sampling target was at least twice a week from mid-April to late June. This target was not often reached. The duration of sampling was typically 2 to 4 hours near dusk or dawn. Occasionally it occurred in broad daylight, which is not preferred. The effort varied primarily due to flow because it cannot be performed when water flow is above the season’s median. It also varied due to availability and health of personnel.

Biases

There are several biases in this monitoring survey. The survey employs one size net with uniform mesh. The net is deployed along the shore only in the fall-zone area—it is assumed that most movement by shad is along shoreline eddies. Capture efficiency is highly dependent on flow and reliant on the individual skill of the netter, although the three netters that have conducted this survey are likely of similar skill level because they are of similar age, size, and physical strength. Night sampling is not feasible due to a requirement to have National Park personnel present after dark. Netting can only be effectively done at flows of up to 14,000 cubic feet per second (cfs) and is best at 10,000 cfs, which is at or below the rough mean flow in this section of the Potomac in April and May. This means that approximately half the time dip nets are not effective sampling gear.

Ageing Methods

Otoliths and scales of captured fish were aged along with a subset of fish captured in tidal waters and were reported with the data from ICPRB egg collections.

3.10.6.2 Young-of-Year Fishery-Independent Data Sources

Three independent time series of juvenile abundance indices (JAI) are available: the MD DNR Seine Survey (1959-2017, standardized index, Table 166; Figure 199); DOEE Seine Survey (1990-2017, geometric mean, Table 167); and DOEE Juvenile Pushnet Survey (2005-2017, geometric mean, Table 168).

In general, indices were variable with respect to each other; however, elevated geometric indices were noted in the time series for the years 2004 and 2015, which could indicate strong year classes.

3.10.6.2.1 MD DNR Potomac River Striped Bass Juvenile Seine Survey

Survey Methods

Juvenile abundance indices (JAIs) are derived annually from sampling at 22 fixed stations within Maryland's portion of the Chesapeake Bay. They are divided among four of the major spawning and nursery areas—seven in the Potomac River. Stations have been sampled continuously since 1954, with changes in some station locations. Sampling is monthly, with rounds (sampling excursions) occurring during July (Round I), August (Round II), and September (Round III). Replicate seine hauls, a minimum of thirty minutes apart, are taken at each site on each sample round. This produces a total of 132 samples from which Bay-wide means are calculated.

From 1954 to 1961, juvenile surveys included various stations and rounds. Sample sizes ranged from 34 to 46. Indices derived for this period include only stations that are consistent with later years. In 1962, stations were standardized and a second sample round was added for a total of 88 samples. A third sample round added in 1966, increased the sample size to 132.

Auxiliary stations have been sampled on an inconsistent basis and are not included in survey indices. These data enhance geographical coverage in rivers with permanent stations or provide information from other river systems. They are also useful for replacement of permanent stations when necessary. Replicate hauls at auxiliary stations were discontinued in 1992 to conserve time and allow increased geographical coverage of spawning areas.

For a more complete description of the entire MD DNR young-of-year program, including sampling protocol, seining locations, and species-specific data visit the following website: https://dnr.maryland.gov/fisheries/Pages/striped-bass/juvenile-index.aspx.

Sample Protocol

A 30.5 m by 1.24 m bagless beach seine of untreated 6.4 mm bar mesh was set by hand. One end was held on shore while the other was fully stretched perpendicular to the beach and swept with the current. Ideally, the area swept was equivalent to 729-m^2. When depths of 1.6 m or greater were encountered, the offshore end was deployed along this depth contour. An estimate of distance from the beach to this depth was recorded.

Striped bass, American shad and selected other species were separated into 0 and 1+ age groupings. Ages were based on length-frequencies and verified through scale examination. Age-0 fish were measured from a random sample of up to 30 individuals per site, per round. All other finfish were identified to species and counted. Additional data included: time of first haul, maximum distance from shore, weather, maximum depth, surface water temperature (ºC), tide stage, surface salinity (ppt), primary and secondary bottom substrates, and submerged aquatic vegetation within the sample area (ranked by quartiles). Dissolved oxygen (DO), pH, and turbidity (Secchi disk) were collected beginning in 1997.

CPUE Estimation

Eleven stations have been sampled in the Potomac River from 1959 to 2017. Two of these stations were initially sampled in 1961, while four stations began later in the time series as replacements for original stations that were discontinued. These replacements are located near the originals. Therefore, beginning in 1961, there have been seven total locations sampled in the Potomac each year. Catch rates differ greatly among these stations. No YOY shad have been recorded at the Rock Pt and St George Island stations and should be removed from any index calculation.

Initial models included the northern five stations in the Potomac: Rt 301 Bridge station (and 3 replacements); Blossom Pt; Liverpool Pt; Indianhead and Fenwick (replaced by Hallowing Pt).

There is an overall trend in higher catch rates the further a station is upstream. However, after consideration of percent of positive tows, the Rt 301 Bridge and Blossom Pt stations were also removed from the data set, leaving Liverpool Pt, Indianhead, and Fenwick as the remaining stations in the data set.

A new nominal geometric mean index was calculated for the new subset of Potomac stations. Only the first haul of the day at each respective station was included. The resulting index was similar in trend to the original geometric mean index; however, values in the early years (1962-1978) of the original geometric mean index are higher than the revised, while the opposite is generally true from 1994 through 2017.

The same subset of years and stations used to calculate the new geometric mean index was used in generalized linear model evaluation. Initial covariates examined in model development were year, time of day, SAV presence/absence, salinity, water temperature, Julian day, and sampling site. This full list of covariates was initially run through the following models: Poisson GLM, a negative Binomial GLM, a Zero-Inflated Negative Binomial GLM, a Poisson GAM, and a Negative Binomial GAM. The Negative Binomial GLM model was determined the best initial model based on comparisons of the dispersion parameter and AICs. A step-wise evaluation of covariates was then performed for the negative binomial model. Time of day, water temperature, salinity and SAV presence were sequentially dropped the data set as they were not shown to significantly impact catch. The best performing model was Counts ~ Year + sampling site + Julian Day.

The most noticeable trend in both the nominal and standardized indices is the large gap of low catches in the middle of each time series (Table 169, Figure 199). Model predicted catch rates are low, but variable (mean of ~12 fish per haul) from the beginning of the time series through 1978. Then from 1979 to 1997 mean annual catch rates dropped below two fish per haul. This is followed by a steep increase in relative abundance beginning in 1998 and moderate to high catch rates continue through 2017. Mean annual catch rates in this last stanza are over 90 fish per haul. Based on the importance of the final model covariates on catch, the best index of relative abundance for the Potomac survey is the negative binomial GLM standardized index. However, this index should be used with caution as annual model CVs are large.

3.10.6.2.2 DC DOEE Potomac River Juvenile Pushnet Survey

Survey Methods

Seining and push-netting are currently used to calculate juvenile abundance indices and assess stock recruitment.

Sampling Intensity

The seining survey consists of pulling a 100’x4’x1/4” beach seine at six sites twice a month from June - October. These sites cover the entire distance of both the Potomac and Anacostia rivers within the District of Columbia’s jurisdiction. Protocol for the seine survey was adjusted in 2010 to increase the frequency of visits to the sites from once a month to twice a month. All specimens captured are enumerated and measured for total length before being released. For large samples, lengths are taken from 50 specimens of each species and the remainder of the sample is counted (Table 167).

In 2003, DOEE began a multiyear pushnet survey for YOY alosine species. This sampling was conducted over 11 nights from July through September at five sites in the Potomac River and one site in the Anacostia River. These sites covered the entire distance of the Potomac within the District of Columbia’s jurisdiction. The pushnet survey is conducted after sunset by pushing a 3’x4’x1/4” bag net mounted on a frame that pivots on the bow of the boat. This allows the net to be lowered into the water at a level where the net skims the top of the water as it is pushed along a transect, for five minutes. The boat is maintained at a constant speed of 5 mph covering around .83 miles. A flow meter is attached to the mouth of the net to determine the exact volume of water that passes through the net in order to calculate number of fish per volume of water sampled (Table 168).

3.10.7 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance, mean length, and mean length-at-age. Total mortality estimators were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. A statistical catch-at-age model was also used to evaluate abundance and mortality. Details for all methods except the statistical catch-at-age model are provided in section 2. Details for the statistical catch-at-age model are provided below.

3.10.7.1 Statistical Catch-at-Age Model

3.10.7.1.1 Configuration

A forward-projecting statistical catch-at-age model was developed in the integrated statistical framework software Stock Synthesis, version 3.30.14 (Methot and Wetzel 2013). This framework integrates information from data sets that can have varying time series shorter than the model time series, a key feature for the data sets available from this system. There were also concerns raised with the spawn history data in this assessment and these data were particularly limited from the Potomac, precluding the use of a custom model designed to track spawning history cohorts within year classes like that applied by Gibson and Myers (2003). The model tracked the sex-aggregate population at seasonal time steps from 1999 through 2017 due to the availability of complete removals data starting in 1999 and the highly seasonal nature of the these data. Seasons were set as January through February, March through May, June, July through September, and October through December. Spawning occurs May 1 and Crecco et al. (1983) found that juvenile year class strength in the Connecticut River is established between 30 and 42 days old, so YOY were set to settle June 1. Anthropogenic removals (i.e., removals by commercial fisheries and removals by natural resource agency broodstock collection programs) occur March through May and relative abundance is tracked among years from March through May (spawning adults) and July through September (YOY). Only natural mortality occurs during the other three seasons. The age structure tracked was ages-0 (YOY) through ages-8. Age-8 was treated as a plus group with all data for ages older combined with this age group. The plus group represented approximately 3% of the adult catch data. Total removal and index of abundance data are assumed to follow lognormal distributions. Age composition data are assumed to follow a multinomial distribution.

The model includes a Beverton-Holt stock-recruit relationship with a parameter controlling the variance around the expected recruitment (sigma R) fixed at 0.6 (Beddington and Cooke 1983) and steepness fixed at one to parameterize this relationship as deviations around the time-series mean recruitment (R0). Steepness cannot be estimated (i.e., hits the upper bound of one) and there have been varying levels of anthropogenic production (i.e., stocking) that are likely to further confound the stock-recruit relationship. Bias adjustments were applied to recruitment estimates to ensure mean unbiased recruitment from the lognormally distributed estimates following methods of Methot and Taylor (2011).

Thirty six parameters were estimated including catchabilities for all indices of abundance, logistic selectivity parameters for fleets and adult indices of abundance, R0, and annual recruitment deviations, including for the initial population age structure. Instantaneous direct anthropogenic mortality is estimated from total removals with a hybrid method of Pope's approximation and the Baranov catch equation and annual abundance estimates are derived from model estimated parameters. The term direct anthropogenic mortality is used here due to removals by commercial fisheries and natural resource agency broodstock collection programs. SBPR is also derived internally with specified age-specific maturity, natural mortality, and weight and model estimated direct anthropogenic mortality. The SBPR reference point was set at 0.40 ($SBPR_{40\%}$; Section 2.5). $Z_{40\%}$ and $DA_{40\%}$, the total mortality and direct anthropogenic mortality, respectively, necessary to achieve $SBPR_{40\%}$, is derived independently of the per-recruit reference points estimated for comparison against total mortality estimates (Section 2.6) as fleet-specific selectivity estimated internally is used in these calculations. Total anthropogenic removals are used in the model to estimate if total mortality rates (i.e., natural plus direct anthropogenic) are sustainable or unsustainable. It is recognized that broodstock collections are done to support natural productivity through hatchery programs, but these fish are removed from the population for these purposes and unable to contribute to future reproduction during subsequent spawning runs. Any gains in productivity from these broodstock collection efforts should be realized by direct observations of YOY and spawning adult relative abundance and reduce mortality rates if these gains outpace removals. A biomass reference point ($SSB_{40\%}$) associated with the SBPR reference point is estimated by projecting a population forward sampled from the model estimated recruitment distribution and subjected to the $Z_{40\%}$ threshold mortality level over time. This biomass reference point should be interpreted as 40% of the spawning stock biomass with no direct anthropogenic mortality expected under recruitment levels experienced during the model time series, not necessarily under historical recruitment levels. Relative female spawning stock biomass estimates ($SSB/SSB_{40\%}$) are provided to determine abundance stock status. Terminal three-year average relative SSB below one is considered depleted. The depleted status is used because of removals by commercial fisheries and natural resource agency broodstock collection programs.

3.10.7.1.2 Input Data

Four indices of relative abundance were included in the model: the MD DNR Potomac River Striped Bass Juvenile Seine Survey (YOY), the DC DOEE Potomac River Juvenile Pushnet Survey (YOY), the MD DNR Potomac River Striped Bass Spawning Stock Survey (spawning adults), and the PRFC Potomac River Commercial Pound Net CPUE (spawning adults). The Potomac River Striped Bass Spawning Stock Survey also had age composition data while the Potomac River Commercial Pound Net CPUE did not. All indices of abundance were scaled to their time series mean. CVs for indices were calculated from external standardization models or assumed equal to the average CVs from standardized indices tracking comparable life-history stages if not available (Potomac River Striped Bass Juvenile Seine Survey for the Potomac River Juvenile Pushnet Survey CV and the Potomac River Striped Bass Spawning Stock Survey for the Potomac River Commercial Pound Net CPUE CV). Effective sample sizes for age composition data are based on the actual number of annual age samples collected scaled to a range of 2 to 50 to avoid overfitting these data. Variance adjustments are calculated internally for total index and index catch-at-age data to account for process error and better align input variance data with model expected variance for each data set. Variance adjustments were implemented for the Potomac River Striped Bass Spawning Stock Survey age composition data by multiplying input sample sizes by the suggested variance adjustment (Francis 2011) from an unweighted model run (0.78), down-weighting these data. Variance adjustments were not implemented for total index data because (1) they generally resulted in poorer fits to the indices and Francis (2011) recommends abundance data sets should have primacy in model fitting and other data sets should not be allowed to preclude fitting abundance data sets well, (2) some indices have been standardized externally to account for process error (i.e., variation in catchability), and (3) RMSEs were close to one without weighting.

Removals are tracked across two fleets, commercial pound nets and gill nets (both commercial removals and broodstock removals). These fleet designations were necessary based on the lack of biological sampling from the commercial catch and based on assumed differences in size compositions of the catch. Comparison of length composition data from broodstock collections and the fishery-independent Potomac River Striped Bass Spawning Stock Survey that fishes a broader range of mesh sizes suggested the broodstock collection programs select females-at-size proportional to their composition in the spawning run while males larger than average in the spawning run tend to be selected. The broodstock collection programs are generally designed to mimic the historical gill net fishery. Further, commercial catch was primarily discarded due to the season being closed (89% of discards over the time series) or there being no market (11% of discards over the time series), while only 0.03% of fish were discarded because they were too small, so there is no reason to believe pound net fisheries are size selective. Therefore, the commercial gill net fishery is assumed to be size selective similar to the broodstock collection programs while the pound net fishery is assumed to be fully selective of spawning adults with a selectivity similar to the Potomac River Striped Bass Spawning Stock Survey.

Gill net removals were input as numbers derived from age composition data external to the model. Catch-at-age and removals in number from the commercial gill net fishery were derived by borrowing the broodstock length composition data applied with the same methodology described in Section 3.10.6.1.1 with an addition step necessary to convert catch in weight to catch in numbers. Sex-specific mean weights for each length bin were calculated from length-weight relationships and multiplied by length frequencies to calculate the sampling weight proportions in each length bin. Total catch weight was divided by sampling weight proportions to calculate the catch weight in each length bin. Finally, the catch weight in each length bin was divided by mean weights to calculate catch-at-length in numbers. There are no studies on American shad discard mortality rates in commercial fisheries, so values were assumed based on generally fishing practices. A rate of 100% was applied to commercial gill net discards. Broodstock gill nets are tended continuously and retrieved the same night they are set to maximize survival as live fish are necessary for broodstock. This practice is assumed to reduce the rate of mortality considerably relative to general commercial fishing practices of setting gill nets overnight or longer.

Pound net removals were input as removals in weight. Other gears accounted for small portions of total commercial catch and were grouped with pound nets. A rate of 20% was applied to commercial discards from pound nets to estimate post release mortalities, as these fish are held impounded and can be released following minimal interaction with the gear. No catch-at-age data are provided for the pound net fleet and the selectivity was set to mirror that of the MD DNR Potomac River Striped Bass Spawning Stock Survey.

There has been a moratorium on recreational harvest since at least 1982, depending on jurisdiction. Recreational catch-and-release has been legal, but there are no data on the magnitude of catch or mortality rate of recreational discards. Recreational removals are assumed negligible.

Standard errors of removals on the log scale were set at 0.1 for all years and both fleets. Effective sample sizes for age composition data are based on the actual number of annual age samples collected scaled to a range of 2 to 50 to avoid overfitting these data. Variance adjustments are calculated internally for removal age composition data to account for process error and better align input variance data with model expected variance for each data set. Variance adjustments were implemented for the commercial gill net survey age composition data by multiplying input sample sizes by the suggested variance adjustment from an unweighted model run (0.94), down-weighting these data.

All age data used in the base model were derived from otoliths. Otolith-based age-length keys were borrowed from broodstock collection programs to generate catch-at-age data for the Potomac River Striped Bass Spawning Stock Survey because the survey has only collected scales. Static sex-aggregate von Bertalanffy growth parameters (Section 1.1.5) and length-weight relationship parameters (Section 1.1.3.1) were used to generate weight-at-age data for converting pound net removals from weight to numbers and for population biomass estimates. A female maturity-at-age ogive estimated from the mortality-based method for southern iteroparous fish (Section 1.1.7) was used to calculate spawning stock biomass and SBPR. Natural mortality was specified using the Lorenzen estimator (Lorenzen 1996, Lorenzen 2000) to scale natural mortality-at-age according to mean size-at-age, estimated from growth parameters, and a natural mortality estimate for age-8+ fish based on the maximum observed age across iteroparous stocks (age-13, Then et al. 2015, Section 1.1.8).

The primary data limitations identified prior to model development was the lack of mixed-stock and ocean bycatch removal data. The only available information on these removals are estimates of proportion Potomac-origin fish in mixed-stock catches for one year (2010) in the Delaware Bay and Bay of Fundy mixed-stock fisheries (Waldman et al. 2010) and stock-aggregate total removals from several non-directed fisheries along the U.S. Atlantic Coast (Section 4.1.4). Proportions of Potomac-origin fish in the Delaware Bay and Bay of Fundy fisheries are relatively low (<1%) compared to some surrounding stocks, but it is unknown how these proportions have changed over the model time series. Bycatch of Potomac-origin fish in other non-directed fisheries, both of juveniles and adults, is unknown. These data limitations could bias estimates of absolute spawning abundance and fishing mortality if these unknown removals are not negligible. Model estimates of absolute juvenile abundance (ages 0-2) are also completely dependent on specified natural mortality as there are no data on these fish between their summer abundance as YOY and when they appear later in life during in-river spawning runs (age-3 at the earliest). The model decays age-0 recruit abundance according to assumed natural mortality rates to match the data on these fish once they mature and return to the river for spawning runs. If unaccounted removals of juvenile fish are not negligible, the absolute abundance of recruits would need to be larger to decay at the true, greater mortality rate (i.e., natural mortality plus non-riverine *F*) to allow the model to similarly match the data when these fish return as spawners. An initial attempt was made to provide more data on the scale of the recruit abundance by calibrating relative YOY abundance from the Potomac River Juvenile Pushnet Survey to absolute abundance using stocking counts across agencies and estimated percent hatchery contribution data from the Potomac River Juvenile Pushnet Survey. However, the resultant abundance estimates were considered too low and, therefore the Potomac River Juvenile Pushnet Survey were included as an index of relative abundance. Model estimated abundance for ages 0-2 should be considered with caution if at all.

3.10.8 Results

3.10.8.1 Abundance Trends

3.10.8.1.1 Power Analysis

Two abundance indices for American shad were developed for this system that contained estimates of PSE, the Potomac River Striped Bass Spawning Stock Survey (median PSE = 0.391) and the Potomac River Striped Bass Juvenile Seine Survey (median PSE = 0.450). Neither of these surveys are currently used for sustainability targets and monitoring in the SFMP and neither exhibited sufficient power to detect a 50% change in abundance in 10 years (Table 25).

3.10.8.1.2 Mann-Kendall Analysis

Potomac River (JAI)

The Potomac River Striped Bass Juvenile Seine Survey was very low between the early 1960s and 1995, after which it began to increase to a peak around 2004, subsequent decline, followed by another peak in 2015 (Figure 199). Mann Kendall trend analysis detected a positive trend for the entire time series in the Potomac, and found no trend for the period after 2005.

Potomac River (FD CPUE)

The PRFC provided fishery-dependent data from the Potomac River Commercial Pound Net CPUE from 1999-2017 for American shad. A plot of the data showed a general increase for 1999-2012, followed by a decline through 2014 and a relative leveling off for the final few years (Figure 200). Mann-Kendall trend analysis found an increasing trend over the time series, but no trend was detected for the period after 2005.

Potomac River (FI CPUE)

Data from the fishery-independent Potomac River Striped Bass Spawning Stock Survey from 1985-2017 was provided for American shad. A plot of the data showed a general increase for

1999-2007, a decline and then subsequent increase after 2009 (Figure 201). Mann-Kendall trend analysis found an increasing trend over the time series, but no trend was detected for the period after 2005.

3.10.8.2 Mean Length Trends

Several fishery management authorities regulate the American shad fishery in the Potomac River, and all sampling programs are fishery-independent. Broodstock Collection programs are conducted by MD DNR, ICPRB, VDGIF, and USFWS in the same area of the Potomac River. Lengths were combined for all broodstock collection programs and were available from 2004-2017. A plot of mean lengths over time showed peak length in 2005 followed by a continual decline afterwards for both sexes through about 2012 with a larger increase in males from 2013-2014 (Figure 202). A Mann-Kendall trend analysis failed to detect a trend in mean length over the time series for male American shad, but found a decline in mean length over time for females. The Potomac River Striped Bass Spawning Stock Survey conducted by MD DNR samples American shad that are caught as bycatch, and biological data are available beginning in 1997. A plot of mean lengths and Mann-Kendall trend analysis found no trend in mean lengths for either sex (Figure 203). Additional data programs were submitted but excluded from analysis due to small sample size or because the time series were too short.

3.10.8.3 Mean Length-at-Age Trends

Mean length-at-age data using scales were provided from the Potomac River Striped Bass Spawning Stock Survey. Ages ranged between 3 and 9 for female American shad, and between 3 and 8 for males. Mann-Kendall Trend analysis failed to detect any change in mean length-at-age over time for most ages of both sex, but did detect a decrease in mean length-at-age in age 8 females and an increase in mean length-at-age for age 3 males in the Potomac River (Table 170).

3.10.8.4 Total Mortality Estimates

Age composition data derived from scales collected during the Potomac River Striped Bass Spawning Stock Survey and scales and otoliths collected during several broodstock collection programs were used for mortality estimates. The Potomac River Striped Bass Spawning Stock Survey age composition data were tabulated from scales collected randomly or by census while the broodstock age composition data were initially developed for the SCAA model using age-length keys from age data across monitoring programs. Data from the Potomac River Striped Bass Spawning Stock Survey met all criteria for 6 and 5 years between 2003 and 2016 for females and males, respectively (Table 32). Scale-derived data from broodstock collections met all criteria for 14 and 9 years between 2000 and 2017 for females and males, respectively (Table 32). Otolith-derived data from broodstock collections met all criteria for 10 years between 2000 and 2017 for females; otolith-derived data from broodstock collections for males did not meet all criteria for any period of three consecutive years and were therefore dropped from the analysis (Table 32).

Overlapping estimates between scale-based data sets were few, but estimates from the Potomac River Striped Bass Spawning Stock Survey were generally higher for females and lower for males relative to estimates from broodstock collections (Figure 70). Overlapping estimates between age structures from broodstock collections were also few, but several were quite similar, particularly later in the time series. No time series show long term trends in mortality, but estimates in recent years indicate an uptick in mortality (Table 33, Figure 204, and Figure 205). The three-year average female estimate from broodstock scale collections in 2017 was above the threshold (Table 33 and Figure 205). There were no female data available from the Potomac River Striped Bass Spawning Stock Survey or broodstock otolith collections for 2015-2017 and 2015, respectively, precluding estimation of a three-year average for females in 2017 from these data sets.

3.10.8.5 Statistical Catch-at-Age

3.10.8.5.1 Base Model Results

The model converged on a solution with an invertible Hessian and maximum gradient of 3.57e-005 and no parameter estimates at bounds (Table 171).

YOY indices of abundance were generally fit well, with the exception of a few large year classes in the mid 2000s measured by the Potomac River Striped Bass Juvenile Seine Survey that the model did not agree with (Figure 206 and Figure 207). Conflict between the adult indices of abundance resulted in some residual patterning (Figure 208-Figure 210). The model could not reconcile increases measured by the Potomac River Striped Bass Spawning Stock Survey in the mid-2000s, decreases in the 2010s, and increases in the most recent years that were not indicated by Potomac River Commercial Pound Net CPUE. The model fit more closely to the smooth gradual increase measured by the Potomac River Commercial Pound Net CPUE. This conflict is explored with sensitivity analysis.

Total removals were fit closely given the assumed standard errors and hybrid estimation methodology (Figure 211).

Residuals from model fits to age composition data show reasonable fits to the data across most age classes and years (Figure 212). There is a pattern of overestimates for the plus group since the 2000s.

Recruitment deviations (Figure 213, Table 172) show a strong negative pattern for the initial age composition (1991-1998) that can be explained by the Potomac River Striped Bass Juvenile Seine Survey data during these years that were not included in the model (Figure 214). Deviations continue with a negative pattern early in the model time series given the continued low recruitment measured by the Potomac River Striped Bass Juvenile Seine Survey then fluctuate around the average recruitment for the remainder of the time series.

Estimated selectivity of the commercial gill net fleet (Figure 215) indicates this fleet is selecting larger individuals from the overall spawning population captured by the Potomac River Striped Bass Spawning Stock Survey. Age-6 direct anthropogenic mortality increases through the early 2000s, decreases through the late 2000s, and becomes variable with no discernible trend through the remainder of the time series (Figure 216, Table 173). Direct anthropogenic mortality in 2017 is the second highest estimate in the time series. SBPR declines through the mid-2000s then becomes relatively stable through the remainder of the time series (Figure 217, Table 174). There is a sharp decrease in 2017 to the second lowest point of the time series.

Age-0 recruits fluctuate around a slightly increasing trend (Figure 218, Table 175). There is a notably strong year class in 2015 which does not recruit to the spawning stock during the model time series. Age 3+ abundance increases from the time series low in 1999 to the second greatest abundance of the time series in 2010, declines for a few years, and then increases sharply to the highest abundance of the time series in 2016 (138 thousand fish; Figure 219, Table 176). There was a slight decrease in 2017. The spawning stock biomass reference point associated with the SBPR40% reference point was estimated at 11.56 metric tons (Table 171). Female spawning stock biomass increases through the early 2010s, but then follows a declining trend through the remainder of the time series (Figure 220, Table 177). Relative spawning stock biomass has been below one throughout the time series, increasing to a time series high in 2011 (0.67) and decreasing to 0.43 in 2017 (Figure 221).

3.10.8.5.2 Uncertainty Analysis

Asymptotic standard errors are calculated for parameters and derived values with the delta method. Standard errors are provided in Table 171-Table 178 and result in CVs less than 1, a reference point suggested by Cass-Calay et al. 2014. Uncertainty was further characterized with sensitivity analysis, bootstrapping, likelihood profiling, and retrospective analysis.

3.10.8.5.3 Sensitivity Analysis

Several alternative model configurations were run to evaluate sensitivity of the model to key assumptions and input data. Sensitivities included: no variance adjustments to any data sets (run 2), suggested variance adjustments to indices of abundance (run 3), Potomac River Commercial Pound Net CPUE selectivity set to mirror commercial gill net selectivity (run 4), PRFC CPUE excluded from the model (run 5), the Potomac River Striped Bass Spawning Stock Survey excluded from the model (run 6), constant natural mortality on ages 6+ (run 7), scale catch-at-age data in place of otolith catch-at-age data (run 8), maturity derived with the cumulative methodology (run 9), maturity estimated by Maki et al. 2001 (run 10), and the commercial gill net discard mortality rate equal to the commercial pound net discard mortality rate (20%, run 11). Sensitivity model runs were evaluated to confirm convergence on a solution and that parameter estimates were not at bounds.

Sensitivity model results generally follow the same trends and magnitudes as base model SBPR and relative female spawning stock biomass estimates (Figure 222 and Figure 223). The most notable deviation is the run with maturity estimated by Maki et al. 2001 which indicates full maturity at a younger age and, therefore, greater female spawning stock biomass and greater SBPR. The three-year average SBPR in 2017 from the model with Maki et al. (2001) maturity estimates (0.41) is just above the $SBPR_{40\%}$ threshold. Maki et al. (2001) estimates of maturity were considered a lower bound of uncertainty on maturity-at-age and were derived with spawn history data which the SAS expressed concern with using. The results of this model run are considered unlikely and interpreted as a bound on uncertainty. Three-year average SBPR estimates in 2017 from all other sensitivity runs are below the $SBPR_{40\%}$ threshold***.***

3.10.8.5.4 Bootstrapping

Input data were sampled from distributions defined by base model parameter standard errors to generate 1,000 bootstrap data files. The base model was run with each of these bootstrap data files to generate uncertainty about model parameter estimates and derived values.

Selected parameter and derived value distributions from the bootstrap analysis show some divergence between maximum likelihood estimates, but divergences do not suggest a different perception of the stock status in recent years (Figure 224-Figure 227).

3.10.8.5.5 Likelihood Profiling

Likelihood profiling was done over the mean recruitment parameter (R0) by running the model with the parameter fixed at values ranging from 5.2 to 10 at increments of 0.05 (Figure 228). Results show the lower end of the parameter space is well defined and supported by the various data sets and a minimum at the base model estimate of 7.0, but data appear less informative of the upper end of the parameter space as the negative log likelihood does not change as much relative to the minimum as at lower parameter values.

3.10.8.5.6 Retrospective Analysis

A retrospective analysis with a four year peel (2013-2017) was conducting by excluding the terminal year of data and running the model with the reduced time series.

There is a retrospective pattern resulting in overestimated biomass (Figure 229) and underestimated mortality (i.e., overestimated SBPR, Figure 230). The pattern affects that scale of estimates, but estimates scaled to means show similar trends across retrospective runs (Figure 231 and Figure 232). It was suspected that this pattern may by driven by the short time series, the exceptionally large year class in 2015, and the model’s understanding of average recruitment which scales the absolute stock abundance. This estimate varies across runs and scales the population abundance up or down. This was explored by fixing the R0 parameter to the estimate from the base model and rerunning the retrospective analysis, but the pattern remained and the cause of the pattern could not be confirmed.

3.10.8.5.7 Uncertainty Conclusions

There is generally high uncertainty in the estimates of the absolute scale of the stock. Another key uncertainty is the maturity ogive for the population which has implications on the status of the stock. Figure 233 and Figure 234 show the various maturity ogives considered in sensitivity analysis compared to the fleet-specific selectivity estimates from the base model. Maturity is generally assumed to be the driver of selectivity, particularly in non-selective, in-river data sets (i.e., the fishery-independent Potomac River Striped Bass Spawning Stock Survey, Figure 234). These figures show a wide spread in maturity around the model selectivity estimates which fall roughly in the middle of the most extreme maturity ogives.

The retrospective pattern is particularly concerning as it results in a scenario of overestimated spawning stock biomass and underestimated SBPR (i.e., mortality) that becomes apparent as years of data are added to the model. There is reasonable certainty in the estimate trends and terminal year status estimates as these are consistent across most of the model runs reviewed throughout the analysis, the mortality status agrees with total mortality status estimates derived with catch curve analysis, the direction of the retrospective pattern is more suggestive of an unsustainable mortality status than a sustainable mortality status, and the mortality status only changes with the assumption of maturity set to what is considered the less likely, lower bound on maturity-at-age (Maki et al. 2001 estimates).

3.10.8.6 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Potomac system, current unobstructed habitat area represents 90.02% of the historical habitat extent (41.96 of 46.61 square kilometers).

3.10.9 Stock Status and Conclusions

The SAS selected the SCAA model as the preferred method (over total mortality estimators) due to its use of integrated data sets on abundance-at-age and total removals.

Mortality[2]

The stock is experiencing unsustainable mortality, as the terminal three-year average SBPR in 2017 was 0.26 which is below the $SBPR_{40\%}$ threshold (0.40; Figure 235).

There were conflicting trends in female mean length detected from two data sets, with a declining trend detected from the Broodstock Collections (2004-2017) and no trend in the Potomac River Striped Bass Spawning Stock Survey (2002-2017). There was a positive trend detected in YOY abundance since 1962, but no trend since 2005.

Abundance[2]

The stock is depleted, as the terminal three-year relative female spawning stock abundance in 2017 was 0.43 which is below the threshold of 1 (Figure 236).

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[2] This status determination changed following the Peer Review Workshop. See the addendum (Section 9) for final status determination.

3.10.10 Research Recommendations

2020 Stock Assessment Recommendations

- Transition to a sex-specific statistical catch-at-age model configuration.
- Explore alternative data weighting methodologies for the statistical catch-at-age model such as the Dirichlet multinomial.

3.11 Rappahannock

3.11.1 Habitat Description

The Rappahannock River, which is approximately 195 km in length (172 km is tidal; 118 is salt water), has its headwaters in the piedmont and is fed by the Rapidan River. The Rappahannock watershed encompasses a total of 7,032 km2 (Jenkins and Burkhead, 1994), and the average annual discharge at the fall line is 45 m3/s (O'Connell and Angermeier 1997). An estimated 125 tributaries of the Rappahannock River are potentially used by alosines (O'Connell and Angermeier 1997).

3.11.2 Fishery and Management History

The management area on the Rappahannock River system extends from a line drawn between Rogue Point and Urbanna, Virginia upstream to the extent of spawning.

Prior to 1991, there were no restrictions on the American shad commercial fishery in Virginia rivers and the Chesapeake Bay. A limited season (February 4-April 30) was established for 1991 by the VMRC, and kept in place in 1992. In 1993, a further limitation to the season was established (March 15-April 15, 1993). However, due to bad weather conditions, the season was extended through April 30. A complete moratorium was established in 1994. The current regulation states that: "On and after 1 January 1994 it shall be unlawful for any person to catch and retain possession of American shad from the Chesapeake Bay or its tidal tributaries" [VMRC Regulation 450-01-0069]. The prohibition applied to both recreational and commercial fishers. The moratorium was imposed at a time when commercial catch rates of American shad in Virginia's rivers were experiencing declines.

In 2006, a proposal by the VMRC to the ASMFC for the initiation of a limited bycatch fishery was approved by the Shad and River Herring Management Board. Since this date, bycatch allowances have been continually approved by the Management Board, and are managed by VMRC Chapter 4VAC20-530-31. In the Rappahannock River, the bycatch area is restricted to the tidal waters of the Rappahannock River, from the Norris Bridge upstream to the Rt. 360 Downing Bridge at Tappahannock. Additionally, number of permits available for entry into this fishery is limited. There is a 10 shad-per-vessel-per-day bycatch limit during the striped bass season, and the fisher must possess at least an equal number of fish of only the following food-grade species: spot, croaker, bluefish, catfish, striped bass or white perch. American shad must be harvested only as bycatch by anchored gill nets and staked gill nets. Every fisherman permitted for the American shad bycatch fishery shall contact the commission's interactive voice response system once weekly to report the following for the preceding weekly period:

name, registration number, number of fishing trips taken, water body fished, number of nets set, number of American shad caught and number retained.

Currently, monitoring of American shad stocks and fisheries in Virginia is conducted cooperatively by the VMRC, USFWS, VDGIF, and VIMS.

3.11.3 Anthropogenic Sources of Mortality and Productivity

Bycatch and habitat alteration.

Stocking of American shad on the Rappahannock River occurred between 2003 and 2014, using the progeny of Potomac River brood stock. In the years since stocked hatchery fish would be expected to return (i.e., age 4 fish in 2007), the percent hatchery origin fish encountered in the Rappahannock River ranged from 0% (2007) to 8.9% (2016) (Hilton et al. 2018). Due to the low level of return, VDGIF has ceased stocking American shad in the Rappahannock River for the foreseeable future.

3.11.4 Fishery-Dependent Data Sources

Permitted bycatch fishery (Table 179), but this data source does not provide catch data that can be analyzed as a CPUE; it does provide additional biological data on the stock (e.g., sex, age, length, weight, hatchery origin, and reproductive condition). In addition, VIMS has monitored bycatch of American shad in pound nets located off Reedville, Virginia annually since 2002. In this program, fisherman are contracted to log daily catches of shad prior to their release. Additional nets were monitored at the mouth of the Rappahannock River (2007-2018). Subsamples of up to 50 American shad were also collected from these locations bi-weekly and returned to the laboratory for biological analysis.

3.11.5 Fishery-Independent Data Sources

3.11.5.1 Adult Fishery-Independent Data Sources

3.11.5.1.1 VIMS Rappahannock River Adult Gill Net Survey

Survey Methods

The current monitoring program for American shad employs methods that have been consistent for the entire time series (1998-2019), with the exception that effort was reduced from two to one day per week in 2015; similar catch indices were found with one or two days per week of effort. In 1998, a sentinel fishery was developed that was as similar as possible to traditional shad fishing methods in the middle reaches of Virginia's rivers. When the in-river fishing moratorium was imposed in 1994, commercial fishermen who held permits for existing stands of staked gill nets (SGNs) were allowed to retain priority rights for the locations of those stands in the various rivers. VIMS has records of the historic fishing locations, and one of these locations on each river (the James, York and Rappahannock) was used to monitor catch rates by SGNs in this monitoring program. Three commercial fishermen were contracted to prepare and set SGN poles, hang nets, replace or repair poles or nets, and set nets for each sampling event during the monitoring period. Authors of historic logbooks on the Rappahannock River were either retired or not available. Thus, a commercial fisherman who had previous experience in SGN fishing but who had not participated in the shad fishery on the Rappahannock River in the 1980s was chosen. Scientists accompanied commercial fishermen during each sampling trip and all catches were returned to the laboratory for analysis.

The current spawning stock monitoring program yields catch rate information that is comparable with historic catch records recorded in commercial logbooks from the 1950s and the 1980s. However, multifilament gill nets were used in the 1950s and monofilament nets were used in the 1980s (as well as in the current monitoring program). A Latin square design was employed to test the differences in relative fishing power of the two gear types over two years of seasonal sampling on the York River (Maki et al. 2006). Estimates suggest that monofilament nets are roughly twice as efficient as the multifilament nets. Reported catch rates in the 1950s and 1980s are roughly equivalent. However, when adjustments are made for differences in fishing gear, catch rates for the 1950s are twice as high as during the 1980s. The data collected with this gear may not collect data robust for male American shad as the commercial gear used was designed to target the more economically valuable female shad.

Potential Biases and Uncertainty

- Because the gear being fished mimic a historical row fishery, the catches of males and younger (i.e., <age 3) females are not reliable.
- Influence of unpredictable environmental factors that affect catch efficiency (e.g., bycatch of Blue Catfish, turbidity, discharge, etc.)
- Possibility of variability reflecting run timing (e.g., short bursts missed).

Biological Sampling Methods

One SGN, 912 ft (approximately 277 m) in length, was set on the Rappahannock River (Figure 237). Sets were located in the middle Rappahannock River near the Rappahannock River bridge (at Tappahannock, Virginia) at river mile 36 (37° 55.9' N, 76° 50.4' W). To insure that catch rates in the current monitoring program were comparable to logbook records, nets on the Rappahannock River were constructed of 5" (12.7 cm) netting. Panel lengths were consistent with historical records (48 ft [14.63 m] each on the Rappahannock River). Each week, nets were fished for one day (i.e., a 24-h set) and then hung in a non-fishing position until the next sampling episode. Occasionally, weather or other circumstances prevented the regularly scheduled sampling on Sunday, and sampling was postponed, canceled or re-scheduled for another day.

Individual American shad collected from the monitoring sites were measured and weighed on an electronic fish measuring board interfaced with an electronic balance. The board recorded measurements (fork length (FL) and total length (TL)) to the nearest mm, received weight input to the nearest g from the balance, and allowed manual input of additional data (such as field data and comments) or subsample designations (such as gonad tissue and otoliths) into a data file for subsequent analysis.

Ageing Methods

See section 1.1.4.2.12.

CPUE Estimation Methods

Area Under The Curve (Weight-Based Index)

Catch data from each river are used to calculate a standardized catch index (the area under the curve of daily catch rate versus time of year); because the gear is biased to larger individuals (being mimicked on a roe fishery), only females are included in the catch index. The catch index, the duration of the run in days, the maximum daily catch rate in each year and the mean catch rate in each year are compared to summaries of historical logbook data to provide a measure of the relative size of the current shad runs.

In monitoring years 1998-2014, catches on two successive days were separated by up to five days in each week of sampling. From 2015-2017, catches were made once per week and separated by up to six days in each week of sampling. In some rare cases, catches are separated by more than six days. To compute the catch index during all monitoring years, catches on skipped days were estimated using linear interpolation between adjacent days of sampling.

Index Standardization (Number-Based Index)

Each gill net fished was treated as an independent observation and effort was defined as soak days. There were twenty years of data with averages of 17.9 positive observations per year and 88% positive observations per year (Table 186).

A negative binomial GAM was used to estimate a standardized index of abundance accounting for variability in annual catchability effects. The final model included count of pre-sawn female shad as the response variable and year and day of year as covariates. This survey uses mesh sizes that mimic the historical commercial fishery that targeted females with roe, so the survey does not reliably index male relative abundance. The number of soak days was included as an offset variable. A smoothing functions with basis dimension (i.e., k) of four was estimated for day of year. AIC was used to select the final model type (GLM vs. GAM), covariates, and basis dimensions for smoothing functions. The final model converged with a dispersion statistic of 1.13, indicating the data were not over-dispersed relative to model expectations. In addition to a number-based index of abundance, a weight-based index of abundance was also provided for the assessment.

Catch Rates

Area Under The Curve (Weight-Based Index)

For the Rappahannock River, a restoration target of 1.45 (the geometric mean of the catch index values observed in 1980-1992) is available. However, because effort of the historical fishery was lower on the Rappahannock than the other rivers, it is possible that this benchmark is artificially lower, and there is uncertainty about what an appropriate target level should be for this stock.

Catches on the Rappahannock River for the period 1980-1992 are reported in Table 180, and those for the current monitoring program (1998-2017) are reported in Table 181. On the Rappahannock River, the 2017 index was 3.74. The current geometric mean (3.74) is higher than the mean of the historical data (1.45). There is little evidence of severe stock decline in the Rappahannock River, and this stock is considered to be low but stable (Figure 238).

Index Standardization (Number-Based Index)

Catch rates are predicted to increase to a peak at approximately 90 days into the year (early April) and then decline through the remainder of the sampling period. The standardized index follows the same trend as geometric mean catch rates, but there are notable differences in 1998, 2003-2006, and 2012-2014. The index generally follows an increasing trend to the highest point in the time series in 2014, declines sharply through 2016, and then increases back to a relatively high level in 2017. Annual CVs average 0.19 over the time series (Table 186). Annual CVs in 2016-2017 exceed 0.4. The weight-based index also follows the same trend as the modeled index, with the most notable difference occurring in 2003.

Catch/Length/Weight-at-Age

Average catch-at-age for female American shad in the Rappahannock River is given in Table 182. In the Rappahannock River, ages 3 to 11 are present in the time series, with only ages 5, 6, and 7 present in every year (age 4 absent only in 2016 and age 8 absent in 2010 and 2016). On all rivers, age 5 fish are the largest average component of the catch, followed by age 6 and then by age 4.

Mean lengths-at-age for female American shad from the Rappahannock River is shown in Table 183. On average, fish from the James and Rappahannock are largest. Ages 5-10, and in particular age 8 fish, on the York tend to be smaller than same-age fish from both the James and Rappahannock rivers, whereas age 3-9 fish from the James and Rappahannock rivers are similar in length-at-age. Age 10 and 11 fish tend to be larger in the Rappahannock River than in the James River, and, interestingly, age 11 and 12 fish tend to be longer in the York River than in the Rappahannock River.

Mean weight at age for female American shad from the Rappahannock River is shown in Table 184. For almost all ages, fish from the Rappahannock River are heavier at age than both the York and James rivers. The only exception is that age 11 fish tend to be heavier on the James River than on the Rappahannock River. Fish from both the James and Rappahannock rivers are heavier at age than the York River for all ages.

Evaluation fo*r* Hatchery Origin

Stocking of American shad in the Rappahannock River began in 2003 and ended in 2014. Occurrence of hatchery origin American shad in the Rappahannock River is shown in Table 185.

3.11.5.1.2 VDGIF Rappahannock River Boat Electrofishing Survey

Survey Methods

Weekly boat electrofishing for adult anadromous fishes is conducted from March to June on the James, Chickahominy, and Rappahannock River. Each river reach contains several sampling stations to cover the area. The inter-annual trend of catch per unit effort (CPUE) is used as a measure of relative run strength.

The Rappahannock River is sampled in the tidal area just below the tidal/non-tidal interface at Fredericksburg and at Motts Run (five miles upstream of the former Embrey Dam, which was removed in 2004/2005).

Potential Biases and Uncertainty

- Uncertainties that are inherent in electrofishing surveys (e.g., dipnetter efficiency and experience, variation in field of shocking)
- Unknown variation in passage efficiency due to discharge and flow
- Influence of unpredictable environmental factors that affect dipnetter efficiency (e.g., turbidity, discharge, etc.)
- Possibility of variability reflecting run timing (e.g., short bursts missed).
- Difficulty in evaluation of CPUE due to lack of standardized sampling plan over time and space

Biological Sampling Methods

At each station, sex, fork and total lengths, and weight are recorded for a subsample of 25 of American shad.

CPUE Estimation Methods

Each electrofishing collection was treated as an independent observation and effort was defined as minutes of active electrofishing. There were 16 years of data with averages of 5 positive observations per year and 12.5% positive observations per year. Variables available for potential inclusion in the standardization model included sampling year (discrete), sampling location (discrete or random effect), and water temperature (continuous). Electrofishing effort, in minutes, was used as an offset term in all models to account for variability in sampling effort on catches of adult American Shad. Model types considered included NB GLM, NB GLMM, NB GAM, NB GAMM, ZINB GLM, ZINB GLMM, ZINB GAM, and ZINB GAMM. All GAM models were fit assuming cubic regression splines for continuous variables and with a gamma penalty of 1.4 for all models (NB GAM & NB GAMM) and sub-models (ZINB GAM, ZINB GAMM). Mixed models included sampling location as a random effect, either through specification in the GLM modeling framework or by modeling as a smoother and invoking the random effect basis function in GAM models; in non-mixed models, all full models included sampling location as a main effect. AIC was used to select the final model type, covariates, and basis dimensions for smoothing functions. Prior to model fit, the data was constrained by 1) excluding the years 1994-1997, 1999, 2005-2006, and 2009 from the analysis because either survey effort was low of because no American Shad were captured in the survey during the year in question, 2) excluding collections that didn't catch any of the reported species since after 2001 the survey managers did not record 0 tows if they didn't catch any of the priority species, and 3) excluding any collections missing any considered covariate data.

The best fit model, based on AIC, was a ZINB GLMM. The final model included the catch of adult American Shad as the response variable and the variables sampling year (count sub-model only) and water temperature (binary and count sub-models) as main effects and sampling location (binary and count sub-models) as a random effect; the log of effort in minutes was included as an offset term in both sub-models.

The final model suggests the catchability of adult American Shad is affected by sampling location and water temperature. Catches of adult American Shad decrease as water temperature increases across the range of water temperatures historically encountered by the survey.

The standardized index follows the same trend as the arithmetic mean catch rates for most years. The standardized index remains stable, with noise, from survey inception through the terminal year. Annual CVs averaged 2.35 over the time series (Table 188).

3.11.5.2 Young-of-Year Fishery-Independent Data Sources

3.11.5.2.1 VIMS Rappahannock River Juvenile Seine Survey

Survey Methods

Field sampling is conducted during five biweekly periods (rounds) from June or July through August. During each round, seine hauls were conducted at 18 index stations and 21 auxiliary stations in the James, York and Rappahannock river systems (Figure 239). The Index stations have been sampled annually from 1967 to 1973, and from 1980 to the present. Auxiliary sites were added to the survey in 1989 to provide better geographic coverage and increase sample sizes within each river system.

Collections were made by deploying a 100 ft (30.5 m) long, 4 ft (1.2 m) deep, and 0.25 in (6.4 mm) mesh minnow seine perpendicular to the shoreline until either the net was fully extended or a depth of approximately 4 ft (1.2 m) was encountered and then pulling the offshore end down-current and back to the shore. During each round, a single haul was completed at each auxiliary station, and duplicate hauls, with an interlude of at least 30 minutes, were completed at each index station. Even with a 30-minute interlude between hauls at index stations, second hauls cannot be considered independent samples and their use violates a key assumption necessary for making inferences from a sample mean (Rago et al. 1995); only the first haul at each index station is used to calculate the annual index of American shad.

From 1999-2015, the VIMS seine survey used a net comprised of 0.25 inch knotless oval mesh. However, this netting was no longer available from the manufacturer in 2015, so a new net was constructed from 0.25 inch knotless rhomboid mesh material. To test if the mesh material influenced the relative catch efficiency of the net, paired hauls of old and new nets were conducted during the 2015-2017 sampling seasons; the estimated calibration factors were not significantly different from 1 for either Striped Bass and White Perch, so there is no adjustment prior to estimation of abundance indices.

Potential Biases and Uncertainty

- Inherent biases of seine surveys (e.g., escapement issues)
- Influence of unpredictable environmental factors that affect catch efficiency (e.g., bycatch of Blue Catfish, turbidity, discharge, etc.)
- Unknown misidentification of American shad (vs. other sympatric alosines)

Biological Sampling Methods

Every fish collected during a haul was removed from the net and placed into a water-filled bucket. A sub-sample of American shad of up to 25 individuals was measured to the nearest mm FL. Sampling time, tidal stage, and weather conditions were recorded at each sampling location. Salinity, water temperature, and dissolved oxygen (DO) concentrations were measured after the first haul using a handheld YSI water quality sampler.

Catch Rates

On the Rappahannock River, the highest JAI values in the time series were recorded in 2015 and 2016 (Table 187). The Rappahannock River time series depicts no measurable recruitment in 1980-1981, 1985, 1988, 1991-1992, 1995, and 2002.

3.11.6 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance, mean length, and mean length-at-age. Total mortality estimators were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Details for these methods are provided in Section 2.

3.11.7 Results

3.11.7.1 Abundance Trends

3.11.7.2 Power Analysis

Data from three-fishery-independent surveys were examined as indices of American shad abundance in the Rappahannock River, all of which had associated PSEs: the Rappahannock River Boat Electrofishing Survey, the Rappahannock River Adult Gill Net Survey (standardized, number-based index), and the Rappahannock River Juvenile Seine Survey. Of these surveys, only the Rappahannock River Adult Gill Net Survey, which possessed a median PSE of 0.156, exhibits sufficient power to detect a 50% decrease in American shad abundance in 10 years (Table 25). Currently, there is no SFMP for this system so none of these surveys are used for sustainability targets and monitoring.

3.11.7.2.1 Mann-Kendall Analysis

The Rappahannock River Boat Electrofishing Survey provided data for 1999-2017, and when plotted with error showed little fluctuation over the time series with peaks in 2002 and 2013 (Figure 240). Index values from the Rappahannock River Adult Gill Net Survey (standardized, number-based index) showed an increase in values from 1999-2003, followed by decline and increase again from 2007-2009, decrease in 2010, and subsequent increase through 2014, followed by decline again (Figure 241). Mann-Kendall trend analysis failed to detect a trend in either of these two fishery-independent indices for either of the time periods examined. The Rappahannock River Juvenile Seine Survey supplied data from 1980-2017 and when plotted showed little trend from 1980-2013, but a large increase in index values from 2013-2015, with a decline again in 2017 (Figure 242). Mann-Kendall trend analysis found an increasing trend for both the full time series and for the period after 2005.

3.11.7.3 Mean Length Trends

VIMS submitted length data for female American shad from the Rappahannock River Adult Gill Net Survey conducted from 1998-2017. Plots of mean lengths over time showed increasing mean lengths from 2000-2002, a continual decrease through 2009, increase through 2014, and decline thereafter (Figure 243). Mann-Kendall trend analysis found no trend in mean lengths of females over the time series.

3.11.7.4 Mean Length-at-Age Trends

Mean length-at-age data using scales were provided from the Rappahannock River Adult Gill Net Survey. Only female samples were included in the analysis, and fish aged ranged between ages 3 and 10. Mann-Kendall trend analysis failed to detect any change in mean length-at-age over time for any age in the program (Table 189).

3.11.7.5 Total Mortality Estimates

Age composition data tabulated from scales collected randomly or by census during the Rappahannock River Adult Gill Net Survey was used for mortality estimates. Data met all criteria (see Section 2.6) for 16 years between 2002 and 2017 for females; data were not available for males (Table 32). Female mortality increased slightly through the 2000s and declined in recent years (Table 33 and Figure 244). The three-year average female estimate in 2017 (0.50) was below the threshold ($Z_{40\%}$ = 1.07) and the average standard error for this estimate was 0.44.

3.11.7.6 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Rappahannock system, current unobstructed habitat area represents 95.98% of the historical habitat extent (22.69 of 23.64 square kilometers).

3.11.8 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. Adult mortality status is sustainable as the three-year average female total mortality in 2017 was 0.50 which is below the $Z_{40\%}$ threshold (1.07).

There were no trends in female mean length detected (1998-2017) and increasing trends were detected in YOY abundance since 1980 and 2005.

Abundance

Abundance status is unknown. There was an increasing trend detected in YOY abundance since 2005. There were no trends detected in adult abundance (two data sets) since 2005

3.11.9 Research Recommendations

3.11.9.1 Progress on 2007 Stock Assessment Research Recommendations

- Mixed-stock composition has been evaluated using genetics (Aunins 2010)
- The Rappahannock River stock has been continuously monitored to document effects of dam removal; periodic sampling has taken place above former dam site
- Recruitment variability has been monitored via seine survey; also see Tuckey (2009)
- Monitoring of bycatch fishery is ongoing

2007 Recommendations yet to be completed:

- A stock-specific validation study has not been completed; such a study using isotopes as a natural tag has been completed for the York River system
- Estimates of natural mortality have not been calculated

3.11.9.2 Additional Research Recommendations

- Continuing to estimate larval and juvenile abundances and sources of mortality
- Evaluate reliability of bycatch fishery as an estimate of fishing mortality
- Calculate natural mortality using bycatch fishing mortality and estimates of total mortality
- Evaluate pound net bycatch, including assessment of mixed-stock composition
- Continue juvenile recruitment studies to include habitat use and migration patterns
- Evaluate efficiency of seine survey for production of JAI

3.12 York

3.12.1 Habitat Description

The York River system includes the Mattaponi and Pamunkey rivers, which merge at West Point, VA, to form the York River (53 rkm). This is the smallest of the three western tributary systems, with a watershed of 6,892 km2 (Jenkins and Burkhead, 1994); the Pamunkey drainage is larger and has greater average spring discharge than that of the Mattaponi (3,768 km2 and 47.5 m3/s vs. 2,274 km2; 27.2 m3/s, Bilkovic 2000). Tidal propagation extends to approximately 67 rkm in the Mattaponi and 97 rkm in the Pamunkey (i.e., approximately 120 km and 150 km, respectively, from the mouth of the York River; Lin and Kuo, 2001). The extent of the salt intrusion varies by season, but moderate salinity values (>2 ppt) are often observed in lower portions of these rivers.

3.12.2 Fishery and Management History

The management area on the York River system extends from Gloucester Point, Virginia at the George P. Coleman Bridge upstream to the extent of spawning and includes all drainage areas of the Pamunkey and Mattaponi rivers.

Prior to 1991, there were no restrictions on the American shad commercial fishery in Virginia rivers and the Chesapeake Bay. A limited season (February 4-April 30) was established for 1991 by the VMRC, and kept in place in 1992. In 1993, a further limitation to the season was established (March 15-April 15, 1993). However, due to bad weather conditions, the season was extended through April 30. A complete moratorium was established in 1994. The current regulation states that: “On and after 1 January 1994 it shall be unlawful for any person to catch and retain possession of American shad from the Chesapeake Bay or its tidal tributaries” [VMRC Regulation 450-01-0069]. The prohibition applied to both recreational and commercial fishers. The moratorium was imposed at a time when commercial catch rates of American shad in Virginia's rivers were experiencing declines.

In 2006, a proposal by the VMRC to the ASMFC for the initiation of a limited bycatch fishery was approved by the Shad and River Herring Management Board. Since this date, bycatch allowances have been continually approved by the Management Board, and are managed by VMRC Chapter 4VAC20-530-31. In the York River, the bycatch area is restricted to the tidal waters of the York River, from the George P. Coleman Bridge upstream to the Rt. 33 Eltham and Lord Delaware bridges at West Point. Additionally, number of permits available for entry into this fishery is limited. There is a 10 shad-per-vessel-per-day bycatch limit during the striped bass season, and the fisher must possess at least an equal number of fish of only the following food-grade species: spot, croaker, bluefish, catfish, striped bass or white perch. American shad must be harvested only as bycatch by anchored gill nets and staked gill nets Every fisherman permitted for the American shad bycatch fishery shall contact the commission's interactive voice response system once weekly to report the following for the preceding weekly period: name, registration number, number of fishing trips taken, water body fished, number of nets set, number of American shad caught and number retained.

Currently, monitoring of American shad stocks and fisheries in Virginia is conducted cooperatively by the VMRC, USFWS, VDGIF, and VIMS.

3.12.3 Anthropogenic Sources of Mortality and Productivity

Drift-net fishing by two Native American tribal governments and the taking of brood stock by federal and state agencies (USFWS, VDGIF) for stock restoration are permitted on the spawning grounds of the York River system (Mattaponi and Pamunkey rivers). In the former case, tribal landings and effort are unknown. In the latter case, brood stock caught in drift gill nets is sacrificed for egg taking and the number of females killed is recorded (Table 190).

3.12.4 Fishery-Dependent Data Sources

The bycatch fishery data source does not provide catch data that can be analyzed as a CPUE; it does provide additional biological data on the stock (e.g., sex, age, length, weight, hatchery origin, and reproductive condition).

3.12.5 Fishery-Independent Data Sources

3.12.5.1 Adult Fishery-Independent Data Sources

3.12.5.1.1 VIMS York River Juvenile Seine Survey

Survey Methods

The current monitoring program for American shad employs methods that have been consistent for the entire time series (1998-2019), with the exception that effort was reduced from two to one day per week in 2015; similar catch indices were found with one or two days per week of effort. In 1998, a sentinel fishery was developed that was as similar as possible to traditional shad fishing methods in the middle reaches of Virginia's rivers. When the in-river fishing moratorium was imposed in 1994, commercial fishermen who held permits for existing stands of staked gill nets (SGNs) were allowed to retain priority rights for the locations of those stands in the various rivers. VIMS has records of the historic fishing locations, and one of these locations on each river (the James, York and Rappahannock) was used to monitor catch rates by SGNs in this monitoring program. Three commercial fishermen were contracted to prepare and set SGN poles, hang nets, replace or repair poles or nets, and set nets for each sampling event during the monitoring period. Two of these commercial fishermen were authors of the historical logbooks on the York and James Rivers. Scientists accompanied commercial fishermen during each sampling trip and all catches were returned to the laboratory for analysis.

The current spawning stock monitoring program yields catch rate information that is comparable with historic catch records recorded in commercial logbooks from the 1950s and the 1980s. However, multifilament gill nets were used in the 1950s and monofilament nets were used in the 1980s (as well as in the current monitoring program). A Latin square design was employed to test the differences in relative fishing power of the two gear types over two years of seasonal sampling on the York River (Maki et al. 2006). Estimates suggest that monofilament nets are roughly twice as efficient as the multifilament nets. Reported catch rates in the 1950s and 1980s are roughly equivalent. However, when adjustments are made for differences in fishing gear, catch rates for the 1950s are twice as high as during the 1980s. The data collected with this gear may not collect data robust for male American shad as the commercial gear used was designed to target the more economically valuable female shad.

Potential Biases and Uncertainty

- Because the gear being fished mimic a historical row fishery, the catches of males and younger (i.e., <age 3) females are not reliable.
- Influence of unpredictable environmental factors that affect catch efficiency (e.g., bycatch of Blue Catfish, turbidity, discharge, etc.)
- Possibility of variability reflecting run timing (e.g., short bursts missed).

Biological Sampling Methods

One SGN, 900 ft (approximately 274 m) in length, was set on the York River (Figure 245). York River sets were located in the middle York River near Clay Bank at river mile 14 (37° 20.8' N, 76° 37.7' W). Historical catch-rate data on the York River was derived from nets constructed of 4 7/8" stretched-mesh monofilament netting. To insure that catch rates in the current monitoring program were comparable to logbook records, nets on the York River was constructed of 4 7/8" (12.4 cm) stretched-mesh monofilament netting. Panel lengths were consistent with historical records (30 ft [9.14 m] on the York River). Each week, nets were fished for one day (i.e., a 24-h set) and then hung in a non-fishing position until the next sampling episode. Occasionally, weather or other circumstances prevented the regularly scheduled sampling on Sunday, and sampling was postponed, canceled or re-scheduled for another day.

Individual American shad collected from the monitoring sites were measured and weighed on an electronic fish measuring board interfaced with an electronic balance. The board recorded measurements (fork length (FL) and total length (TL)) to the nearest mm, received weight input to the nearest g from the balance, and allowed manual input of additional data (such as field data and comments) or subsample designations (such as gonad tissue and otoliths) into a data file for subsequent analysis.

Ageing Methods

See section 1.1.4.2.12.

CPUE Estimation Methods

Area Under The Curve (Weight-Based Index)

Catch data from each river are used to calculate a standardized catch index (the area under the curve of daily catch rate versus time of year); because the gear is biased to larger individuals (being mimicked on a roe fishery), only females are included in the catch index. The catch index, the duration of the run in days, the maximum daily catch rate in each year and the mean catch rate in each year are compared to summaries of historical logbook data to provide a measure of the relative size of the current shad runs.

In monitoring years 1998-2014, catches on two successive days were separated by up to five days in each week of sampling. From 2015-2017, catches were made once per week and separated by up to six days in each week of sampling. In some rare cases, catches are separated by more than six days. To compute the catch index during all monitoring years, catches on skipped days were estimated using linear interpolation between adjacent days of sampling.

Index Standardization (Number-Based Index)

Each gill net fished was treated as an independent observation and effort was defined as soak days. There were twenty years of data with averages of 18.6 positive observations per year and 92% positive observations per year (Table 196).

A negative binomial GAM was used to estimate a standardized index of abundance accounting for variability in annual catchability effects. The final model included count of pre-sawn female shad as the response variable and year and day of year as covariates. This survey uses mesh sizes that mimic the historical commercial fishery that targeted females with roe, so the survey does not reliably index male relative abundance. The number of soak days was included as an offset variable. A smoothing functions with basis dimension (i.e., k) of eight was estimated for day of year. AIC was used to select the final model type (GLM vs. GAM), covariates, and basis dimensions for smoothing functions. The final model converged with a dispersion statistic of 1.19, indicating the data were not over-dispersed relative to model expectations. In addition to a number-based index of abundance, a weight-based index of abundance was also provided for the assessment.

Catch Rates

Area Under The Curve (Weight-Based Index)

For the York River, a restoration target of 17.44 (the geometric mean of the catch index values observed in 1953-1957) was accepted as an appropriate benchmark to assess the stocks since American shad abundance in the 1980s was insufficient to support the fishery. In the 1950s, shad abundance was higher (estimated at 131,000-218,000 total females annually using data from Nichols and Massmann, 1963), and landings were relatively stable in the face of a high fishing rate (50%). Thus, restoring the York River shad stocks to a 1950s level could allow for a sustainable fishery operating at a lower level of exploitation. On the York River, the seasonal catch index in 2017 was 1.25; this is the lowest catch index on the York from 1998 to 2017. Since 2005 index values have been low, but stable. In years prior (1998-2004) index values were higher (5.42-14.71). The geometric mean of the historical data during the 1980s on the York River is 3.22. The geometric mean of the current monitoring data is higher (4.71), but this mean is still much lower than the benchmark based on 1950s data (17.44). In contrast to trends in the other two rivers, catch indices in the York River have been trending downward through the time series and, with the exception of 2014, are at all-time lows.

Catches on the York River for the periods 1953-1957 and 1980-1992 are reported in Table 191, and those for the current monitoring program (1998-2017) are reported in Table 192. The overall trend for the York River stock suggests that American shad persist at a low level that is close to or lower than its average abundance during the 1980s (Figure 246 - Figure 247). As noted previously, the stock level was low during that period and was evidently incapable of supporting an active fishery. Since 2005, the catch index has shown no recovery to the higher levels seen earlier in the time series, and is cause for concern and continued monitoring. Although there is a moratorium on American shad harvest in the Chesapeake Bay, there are fish taken in the York River each year from several sources. Since 2005 there has been a limited bycatch fishery of American shad. The Mattaponi and Pamunkey tribal governments harvest American shad from the York River system but do not report landings to the VMRC, following the treaty of 1677. In past years there have also been losses to capture of brood stock on the Pamunkey River by the VDGIF. In comparison to other rivers in Virginia, there is currently no stocking of hatchery fish in the York River. The stock is currently well below the proposed 1950s target when abundance of American shad was higher and harvest was apparently sustainable (Nichols and Massmann, 1963). As a result, the stock requires continued protection.

Index Standardization (Number-Based Index)

Catch rates are predicted to be stable and less than the overall mean catch rate during the earliest part of the sampling period (second half of February), increase at approximately 60 days into the year (early March), peak at approximately 80 days into the year (late March), and then decline through the remainder of the sampling period. The standardized index follows the same trend as geometric mean catch rates, but there are notable differences in 1998 and 2004. The index generally follows an increasing trend to the highest point in the time series in 2003 and the declines for the reminder of the time series to the lowest point of the time series in the terminal year of 2017. Annual CVs average 0.19 over the time series (Table 196). The weight-based index also follows the same trend as the modeled index, with the most notable difference occurring in 2003.

Catch/Length/Weight-at-Age

Average catch-at-age for female American shad in the York River is given in Table 193. In the York River, ages 3 to 12 are present in the time series, with ages 5, 6, and 7 present in every year (age 4 is absent in 2016 and 2017, and age 8 is absent in 2012). On all rivers, age-5 fish are the largest average component of the catch, followed by age 6 and then by age 4.

Mean lengths-at-age for female American shad from the York River are shown in Table 194. Ages 5-10, and in particular age 8 fish, on the York tend to be smaller than same-age fish from both the James and Rappahannock rivers. Age 11 and 12 fish tend to be longer in the York River than in the Rappahannock River.

Mean weight at age for female American shad from the York River is shown in Table 195. Fish from both the James and Rappahannock rivers are heavier at age than the York River for all ages.

Evaluation for Hatchery Origin

No individuals with hatchery marks have been detected on the York River.

3.12.5.2 Young-of-Year Fishery-Independent Data Sources

3.12.5.2.1 VIMS York River Juvenile Seine Survey

Survey Methods

Field sampling is conducted during five biweekly periods (rounds) from June or July through August. During each round, seine hauls were conducted at 18 index stations and 21 auxiliary stations in the James, York and Rappahannock river systems (Figure 239). The Index stations have been sampled annually from 1967 to 1973, and from 1980 to the present. Auxiliary sites were added to the survey in 1989 to provide better geographic coverage and increase sample sizes within each river system.

Collections were made by deploying a 100 ft (30.5 m) long, 4 ft (1.2 m) deep, and 0.25 in (6.4 mm) mesh minnow seine perpendicular to the shoreline until either the net was fully extended or a depth of approximately 4 ft (1.2 m) was encountered and then pulling the offshore end down-current and back to the shore. During each round, a single haul was completed at each auxiliary station, and duplicate hauls, with an interlude of at least 30 minutes, were completed at each index station. Even with a 30-minute interlude between hauls at index stations, second hauls cannot be considered independent samples and their use violates a key assumption necessary for making inferences from a sample mean (Rago et al. 1995); only the first haul at each index station is used to calculate the annual index of American shad.

From 1999-2015, the VIMS seine survey used a net comprised of 0.25 inch knotless oval mesh. However, this netting was no longer available from the manufacturer in 2015, so a new net was constructed from 0.25 inch knotless rhomboid mesh material. To test if the mesh material influenced the relative catch efficiency of the net, paired hauls of old and new nets were conducted during the 2015-2017 sampling seasons; the estimated calibration factors were not significantly different from 1 for either Striped Bass and White Perch, so there is no adjustment prior to estimation of abundance indices.

Potential Biases and Uncertainty

- Inherent biases of seine surveys (e.g., escapement issues)
- Influence of unpredictable environmental factors that affect catch efficiency (e.g., bycatch of Blue Catfish, turbidity, discharge, etc.)
- Unknown misidentification of American shad (vs. other sympatric alosines)

Biological Sampling Methods

Every fish collected during a haul was removed from the net and placed into a water-filled bucket. A sub-sample of American shad of up to 25 individuals was measured to the nearest mm FL. Sampling time, tidal stage, and weather conditions were recorded at each sampling location. Salinity, water temperature, and dissolved oxygen (DO) concentrations were measured after the first haul using a handheld YSI water quality sampler.

Catch Rates

Within the York River system, except for 2003 and 2012, the juvenile index values based on the seine survey are consistently higher on the Mattaponi River than they are on the Pamunkey River (Table 198-Table 199). In the time series, recruitment is highest (>7.0 on the Mattaponi River and >3.0 on the York River) in 1982, 1984-85, 1996, 2003 and 2004. Recruitment was low (<0.10) on both of these rivers in 2009; there was no measureable recruitment in the Pamunkey River in 1986-1989, 1992-1993, 1999, and 2007-2009.

3.12.6 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance, mean length, and mean length-at-age. Total mortality estimators were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Details for these methods are provided in Section 2.

3.12.7 Results

3.12.7.1 Abundance Trends

3.12.7.1.1 Power Analysis

Data from four fishery-independent surveys were examined as indices of American shad abundance in the York River system, all of which had associated PSEs: the York River Adult Gill Net Survey (standardized, number-based index), the York River Juvenile Seine Survey (Mattaponi River Stations), the York River Juvenile Seine Survey (Pamunkey River Stations), and the York River Juvenile Seine Survey (York River Stations). Of these surveys, only the York River Adult Gill Net Survey, which possessed a median PSE of 0.163, exhibits sufficient power to detect a 50% decrease in American shad abundance in 10 years, while all three seine surveys, with their large median PSEs, exhibits very little power to detect a 50% change in abundance over 10 years (Table 25). Currently, there is no SFMP for this system so none of these surveys are used for sustainability targets and monitoring.

3.12.7.1.2 Mann-Kendall Analysis

York River Juvenile Seine Survey data from the Mattaponi, Pamunkey, and York rivers was provided for 1980-2017. When plotted, there were obvious peaks over the time series at each, but the years varied by location, with all having some elevated levels in 1982, 1984, 1996, and 2003 (Figure 248 - Figure 250). Mann-Kendall trend analysis detected only an increasing trend in the period after 2005 in the Pamunkey River, but failed to detect any other trend for the two time periods examined in the three surveys. The York River Adult Gill Net Survey (standardized, number-based index) supplied data on female American shad from 2002-2017 and when plotted showed a general decline over the time series (Figure 251). Mann-Kendall trend analysis found a declining trend for both the full time series, but not for the period after 2005.

3.12.7.2 Mean Length Trends

The York River American shad population is one of three primary spawning runs in Virginia. This population migrates to two adjacent tributaries (the Pamunkey and Mattaponi rivers). American shad length data was provided from the York River Adult Gill Net Survey. Length data was examined for females for 1998 to 2017. A plot of the mean total lengths showed peaks in 1999, 2003/2004, and 2014, but no significant trends over time (Figure 252). This was supported by the Mann-Kendall analysis which found no significant trend in mean length of females over time.

3.12.7.3 Mean Length-at-age Trends

Mean length-at-age data using scales were provided from the York River Adult Gill Net Survey. Only female samples were included in the analysis, and fish aged ranged between ages 3 and 11. Mann-Kendall Trend analysis failed to detect any change in mean length-at-age over time for most ages, but did detect a decrease in mean length-at-age in age 8 and age 9 females (0).

3.12.7.4 Total Mortality Estimates

Age composition data tabulated from scales collected randomly or by census during the York River Adult Gill Net Survey were used for mortality estimates. Data met all criteria (see Section 2.6) for 20 years between 1998 and 2017 for females; data were not available for males (Table 32). Female mortality decreased through the early 2000s, increased in the late 2000s, and decreased again in recent years (Table 33 and Figure 253). The three-year average female estimate in 2017 (0.53) was below the threshold ($Z_{40\%}$ = 1.07) and the average standard error for this estimate was 0.30.

3.12.7.5 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the York system, current unobstructed habitat area represents 87.42% of the historical habitat extent (23.26 of 26.61 square kilometers).

3.12.8 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. Adult mortality status is sustainable as the three-year average female total mortality in 2017 was 0.53 which is below the $Z_{40\%}$ threshold (1.07).

There were no trends in female mean length detected (1998-2017). There were increasing trends detected in YOY abundance since 1980 (three data sets), but inconsistent trends since 2005 (one increasing trend, no trend in other two data sets).

Abundance
Abundance status is unknown. There have been conflicting trends in YOY abundance since 2005, with an increasing trend detected from the York River Juvenile Seine Survey (Pamunkey River Stations) and no trend detected from the York River Juvenile Seine Survey (York River Stations) and York River Juvenile Seine Survey (York River Stations), further confounding assessment of YOY abundance conditions in recent years. There were no trends in adult female abundance detected since 2005.

3.12.9 Research Recommendations

3.12.9.1 Progress on 2007 Stock Assessment Research Recommendations

- Mixed-stock composition has been evaluated using genetics (Aunins 2010)
- A stock-specific validation study for the York River has been completed using isotopes as a natural tag (Upton 2008; Upton et al. 2012)
- Recruitment variability has been monitored via seine survey; also see Tuckey (2009)

2007 Recommendations yet to be completed:

- Estimates of fishing rates and harvest by the Native American fishery
- Estimates of natural mortality have not been calculated
- Monitoring of bycatch fishery is ongoing

3.12.9.2 Additional Research Recommendations

- Continuing to estimate larval and juvenile abundances and sources of mortality
- Evaluate reliability of bycatch fishery as an estimate of fishing mortality
- Calculate natural mortality using bycatch fishing mortality and estimates of total mortality
- Evaluate pound net bycatch, including assessment of mixed-stock composition
- Continue juvenile recruitment studies to include habitat use and migration patterns
- Evaluate efficiency of seine survey for production of JAI

3.13 James

3.13.1 Habitat Description

The James River forms at the junction of Cowpasture and Jackson rivers (rkm 580), and its drainage is the largest watershed in Virginia, totaling 26,164 km2 (Jenkins and Burkhead, 1994). Average annual spring discharge on the James River is 294.2 m3/s (Tuckey 2009). Prior to damming, which began in the colonial period, American shad were reported to reach these headwaters and far into the major tributaries of the James River (Loesch and Atran, 1994). The two primary tributaries of the James River below the fall line at Richmond are the Appomattox River, which joins at the city of Hopewell (rkm 112), and the Chickahominy River, which joins at rkm 65. The extent of salt water is variable, but brackish conditions are observed as far up as the mouth of the Chickahominy River on a seasonal basis. Tidal water reaches Boshers Dam in Richmond (rkm 182).

3.13.2 Fishery and Management History

The management area on the James River system extends from the James River Bridge at Newport News, Virginia upstream to the extent of spawning and includes all drainage areas of the Chickahominy, Appomattox, Willis, Rivanna, Slate, Hardware, Type, and Piney rivers.

Prior to 1991, there were no restrictions on the American shad commercial fishery in Virginia rivers and the Chesapeake Bay. A limited season (February 4-April 30) was established for 1991 by the VMRC, and kept in place in 1992. In 1993, a further limitation to the season was established (March 15-April 15, 1993). However, due to bad weather conditions, the season was extended through April 30. A complete moratorium was established in 1994. The current regulation states that: “On and after 1 January 1994 it shall be unlawful for any person to catch and retain possession of American shad from the Chesapeake Bay or its tidal tributaries” [VMRC Regulation 450-01-0069]. The prohibition applied to both recreational and commercial fishers. The moratorium was imposed at a time when commercial catch rates of American shad in Virginia's rivers were experiencing declines.

In 2006, a proposal by the VMRC to the ASMFC for the initiation of a limited bycatch fishery was approved by the Shad and River Herring Management Board. Since this date, bycatch allowances have been continually approved by the Management Board, and are managed by VMRC Chapter 4VAC20-530-31. In the James River, the bycatch area is restricted to the tidal waters of the James River from the James River Bridge upstream to a line connecting Dancing Point and New Sunken Meadow Creek. Additionally, number of permits available for entry into this fishery is limited. There is a 10 shad-per-vessel-per-day bycatch limit during the striped bass season, and the fisher must possess at least an equal number of fish of only the following food-grade species: spot, croaker, bluefish, catfish, striped bass or white perch. American shad must be harvested only as bycatch by anchored gill nets and staked gill nets Every fisherman permitted for the American shad bycatch fishery shall contact the commission's interactive voice response system once weekly to report the following for the preceding weekly period: name, registration number, number of fishing trips taken, water body fished, number of nets set, number of American shad caught and number retained.

Currently, monitoring of American shad stocks and fisheries in Virginia is conducted cooperatively by the VMRC, the USFWS, the VDGIF and the Virginia Institute of Marine Science (VIMS).

3.13.3 Anthropogenic Sources of Mortality and Productivity

Bycatch; Habitat loss and alteration.

In spring 1994, the VDGIF and the USFWS began a hatchery-restocking effort in the James River. Native adult shad from the Pamunkey River were used as brood stock, eggs were stripped and fertilized in the field, and larvae reared in the VDGIF hatchery at Stephensville, Virginia and the USFWS hatchery at Harrison Lake. Prior to release the larvae were immersed in an OTC solution to mark otoliths with a distinctive epifluorescent ring. The VIMS Adult Monitoring Program surveys otoliths to determine hatchery origin. Abrupt increases in the prevalence of OTC-marked adult shad on the James River coincided with higher catch rates by the staked gill nets at the river mouth in 2000-2002 (Olney et al. 2003). The age composition of the hatchery-released adults corresponded to the ages that were expected to return to the river in appreciable numbers following the first large releases of fry. In most years since 2000, the prevalence of hatchery fish in the James River has been high (>20%); in 2006 and 2009 there were lower proportions of fish with hatchery tags (10.3% and 8.9% respectively); in 2013 the hatchery percentage of fish with hatchery marks was 60.5% on the James. A correlation analysis among the from the VIMS Adult Monitoring Program catch index and hatchery prevalence from 1998-2017 was statistically significant ($r = 0.53$, df = 18, $p = 0.02$; Hilton et al. 2018). In most years, fish with hatchery tags from rivers other than the James River were detected in the monitoring sample. These strays were not included in the estimates of hatchery prevalence. Due to budget constraints and absence of brood stock, stocking efforts of American shad on the James River ended in 2018.

3.13.4 Fishery-Dependent Data Sources

There is a bycatch fishery but this data source does not provide catch data that can be analyzed as a CPUE; it does provide additional biological data on the stock (e.g., sex, age, length, weight, hatchery origin, and reproductive condition).

3.13.5 Fishery-Independent Data Sources

3.13.5.1 Adult Fishery-Independent Data Sources

3.13.5.1.1 VIMS James River Adult Gill Net Survey

Survey Methods

The current monitoring program for American shad employs methods that have been consistent for the entire time series (1998-2019), with the exception that effort was reduced from two to one day per week in 2015; similar catch indices were found with one or two days per week of effort. In 1998, a sentinel fishery was developed that was as similar as possible to traditional shad fishing methods in the middle reaches of Virginia's rivers. When the in-river fishing moratorium was imposed in 1994, commercial fishermen who held permits for existing stands of staked gill nets (SGNs) were allowed to retain priority rights for the locations of those stands in the various rivers. VIMS has records of the historic fishing locations, and one of these locations on each river (the James, York and Rappahannock) was used to monitor catch rates by SGNs in this monitoring program. Three commercial fishermen were contracted to prepare and set SGN poles, hang nets, replace or repair poles or nets, and set nets for each sampling event during the monitoring period. Two of these commercial fishermen were authors of the historical logbooks on the York and James Rivers. Scientists accompanied commercial fishermen during each sampling trip and all catches were returned to the laboratory for analysis.

The current spawning stock monitoring program yields catch rate information that is comparable with historic catch records recorded in commercial logbooks from the 1950s and the 1980s. However, multifilament gill nets were used in the 1950s and monofilament nets were used in the 1980s (as well as in the current monitoring program). A Latin square design was employed to test the differences in relative fishing power of the two gear types over two years of seasonal sampling on the York River (Maki et al. 2006). Estimates suggest that monofilament nets are roughly twice as efficient as the multifilament nets. Reported catch rates in the 1950s and 1980s are roughly equivalent. However, when adjustments are made for differences in fishing gear, catch rates for the 1950s are twice as high as during the 1980s. The data collected with this gear may not collect data robust for male American shad as the commercial gear used was designed to target the more economically valuable female shad.

Potential Biases and Uncertainty

- Because the gear being fished mimic a historical row fishery, the catches of males and younger (i.e., <age 3) females are not reliable.
- Influence of unpredictable environmental factors that affect catch efficiency (e.g., bycatch of Blue Catfish, turbidity, discharge, etc.)
- Possibility of variability reflecting run timing (e.g., short bursts missed).

Biological Sampling Methods

One SGN, 900 ft (approximately 274 m) in length, was set on the James River (Figure 254). James River sets were located in the lower James River near the James River Bridge at river mile 10 (36° 50.0' N, 76° 28.8' W). To insure that catch rates in the current monitoring program were comparable to logbook records, nets on the James River was constructed of 4 7/8" (12.4 cm) stretched-mesh monofilament netting. Panel lengths were consistent with historical records (30 ft [9.14 m] each on the James River). Each week, nets were fished for one day (i.e., a 24-h set) and then hung in a non-fishing position until the next sampling episode. Occasionally, weather or other circumstances prevented the regularly scheduled sampling on Sunday, and sampling was postponed, canceled or re-scheduled for another day.

Individual American shad collected from the monitoring sites were measured and weighed on an electronic fish measuring board interfaced with an electronic balance. The board recorded measurements (fork length (FL) and total length (TL)) to the nearest mm, received weight input to the nearest g from the balance, and allowed manual input of additional data (such as field data and comments) or subsample designations (such as gonad tissue and otoliths) into a data file for subsequent analysis.

Ageing Methods

See section 1.1.4.2.12.

CPUE Estimation Methods

Area Under The Curve (Weight-Based Index)

Catch data from each river are used to calculate a standardized catch index (the area under the curve of daily catch rate versus time of year); because the gear is biased to larger individuals (being mimicked on a roe fishery), only females are included in the catch index. The catch index, the duration of the run in days, the maximum daily catch rate in each year and the mean catch rate in each year are compared to summaries of historical logbook data to provide a measure of the relative size of the current shad runs.

In monitoring years 1998-2014, catches on two successive days were separated by up to five days in each week of sampling. From 2015-2017, catches were made once per week and separated by up to six days in each week of sampling. In some rare cases, catches are separated by more than six days. To compute the catch index during all monitoring years, catches on skipped days was estimated using linear interpolation between adjacent days of sampling.

Index Standardization (Number-Based Index)

Each gill net fished was treated as an independent observation and effort was defined as soak days. There were twenty years of data with averages of 17.7 positive observations per year and 88% positive observations per year (Table 203).

A negative binomial GAM was used to estimate a standardized index of abundance accounting for variability in annual catchability effects. The final model included count of pre-sawn female shad as the response variable and year and day of year as covariates. This survey uses mesh sizes that mimic the historical commercial fishery that targeted females with roe, so the survey does not reliably index male relative abundance. The number of soak days was included as an offset variable. A smoothing functions with basis dimension (i.e., k) of eight was estimated for day of year. AIC was used to select the final model type (GLM vs. GAM), covariates, and basis dimensions for smoothing functions. The final model converged with a dispersion statistic of 1.10, indicating the data were not over-dispersed relative to model expectations. In addition to a number-based index of abundance, a weight-based index of abundance was also provided for the assessment.

Catch Rates

Area Under The Curve (Weight-Based Index)

For the James River, a restoration target of 6.40 (the geometric mean of the catch index values observed in 1980-1992) is established. However, American shad abundance in the 1980s was insufficient to support the fishery.

Catches on the James River for the period 1980-1992 is reported in Table 201, and those for the current monitoring program (1998-2017) are reported in Table 202. On the James River, the 2017 index (3.81) was just below the geometric mean of the current monitoring data (4.03). This value is well below the peak catch index observed in the 1980s (29.20) (Figure 255). The geometric mean of the historical data during the 1980s on the James River is 6.40. Hatchery cohorts are believed to be recruiting in high proportions to the population. Prevalence of hatchery fish on the James River reached an all-time high of 60.5% in 2013 (Figure 255). The overall trend for American shad in the James River suggests that the stock remains at historically low levels and is dependent on hatchery inputs. Due to budget constraints and absence of brood stock, stocking efforts of American shad on the James River was reduced in recent years, and ended in 2018.

Index Standardization (Number-Based Index)

Catch rates are predicted to decrease during the earliest part of the sampling period, though this trend is uncertain, increase at approximately 50 days into the year (late February), peak at approximately 90 days into the year (early April), and then decline through the remainder of the sampling period. The standardized index follows the same trend as geometric mean catch rates, but there are notable differences in 1998, 2000-2001, 2010-2012, and 2014. The index increases to the highest point in the time series in 2003, declines to lowest point on the time series in 2008, increases and remains at relatively high levels in the early 2010s, and then decreases to the second lowest point of the time series in 2016. There was an uptick in the index in 2017. Annual CVs average 0.18 over the time series (Table 203). The weight-based index also follows the same trend as the modeled index.

Catch/Length/Weight-at-Age

Average catch-at-age for female American shad in the James River is given in Table 204. In the James River, ages 3 to 11 are represented in the time series, with only ages 4-7 captured in every year (age 8 was only not caught in 2009). On all rivers, age-5 fish are the largest average component of the catch, followed by age 6 and then by age 4.

Mean lengths-at-age for female American shad from the James River are shown in Table 205. On average, fish from the James and Rappahannock are largest. Ages 5-10, and in particular age 8 fish, on the York tend to be smaller than same-age fish from both the James and Rappahannock rivers, whereas age 3-9 fish from the James and Rappahannock rivers are similar in length-at-age. Age 10 and 11 fish tend to be larger in the Rappahannock River than in the James River.

Mean weight at age for female American shad from the James River is shown in Table 206. For almost all ages, fish from the Rappahannock River are heavier at age than both the York and James rivers. The only exception is that age 11 fish tend to be heavier on the James River than on the Rappahannock River. Fish from both the James and Rappahannock rivers are heavier at age than the York River for all ages.

Evaluation for Hatchery Origin

Occurrence of hatchery origin American shad in the James River is shown in Table 207. In most years since 2000, the prevalence of hatchery fish in the James River has been high (>20%); in 2006 and 2009 there were lower proportions of fish with hatchery tags (10.3% and 8.9% respectively); in 2013 the hatchery percentage of fish with hatchery marks was 60.5% on the James. The strength of the James River catch index continues to rely on the prevalence of hatchery fish. A correlation analysis among the catch index and hatchery prevalence from 1998-2017 was statistically significant (*r* = 0.53, df = 18, *p* = 0.02). In most years, fish with hatchery tags from rivers other than the James River were detected in the monitoring sample (Table 208). These strays were not included in the estimates of hatchery prevalence. Most hatchery-reared adults taken on the James River are 4-6 years old (Table 207).

3.13.5.1.2 VDGIF James River Boat Electrofishing Survey

Survey Methods

Weekly boat electrofishing for adult anadromous fishes is conducted from March to June. Each river reach contains several sampling stations to cover the area. The inter-annual trend of catch per unit effort (CPUE) is used as a measure of relative run strength.

The James River is sampled in the tidal/non-tidal interface area at the lower end of the fall zone and other fall zone areas such as just below Boshers Dam. The Chickahominy River is sampled above and below Walkers Dam.

Potential Biases and Uncertainty

- Uncertainties that are inherent in electrofishing surveys (e.g., dipnetter efficiency and experience, variation in field of shocking)
- Unknown variation in passage efficiency due to discharge and flow
- Influence of unpredictable environmental factors that affect dipnetter efficiency (e.g., turbidity, discharge, etc.)
- Possibility of variability reflecting run timing (e.g., short bursts missed).
- Difficulty in evaluation of CPUE due to lack of standardized sampling plan over time and space

Biological Sampling Methods

At each station, sex, fork and total lengths, and weight are recorded for a subsample of 25 of American shad.

CPUE Estimation Methods

A seasonal cumulative CPUE (fish/hour) for each sampling area is determined and used as a measure of run strength for comparative purposes.

Catch Rates

Each electrofishing collection was treated as an independent observation and effort was defined as minutes of active electrofishing. There were 18 years of data with averages of 32 positive observations per year and 43.6% positive observations per year. Variables available for potential inclusion in the standardization model included sampling year (discrete), sampling location (discrete or random effect), and water temperature (continuous). Electrofishing effort, in minutes, was used as an offset term in all models to account for variability in sampling effort on catches of adult American Shad. Model types considered included NB GLM, NB GLMM, NB GAM, NB GAMM, ZINB GLM, ZINB GLMM, ZINB GAM, and ZINB GAMM. All GAM models were fit assuming cubic regression splines for continuous variables and with a gamma penalty of 1.4 for all models (NB GAM & NB GAMM) and sub-models (ZINB GAM, ZINB GAMM). Mixed models included sampling location as a random effect, either through specification in the GLM modeling framework or by modeling as a smoother and invoking the random effect basis function in GAM models; in non-mixed models, all full models included sampling location as a main effect. AIC was used to select the final model type, covariates, and basis dimensions for smoothing functions. Prior to model fit, the data was constrained by 1) excluding the years 1994-1996 from the analysis, 2) excluding collections that didn't catch any of the reported species since after 2001 the survey managers did not record 0 tows if they didn't catch any of the priority species, and 3) excluded any collections missing any considered covariate data.

The best fit model, based on AIC, was a ZINB GAMM. The final model included the catch of adult American Shad as the response variable and the variables sampling year (count sub-model only) and water temperature (binary (EDF = 1.97) and count (EDF = 4.62) sub-models) as main effects and sampling location (binary (EDF = 17.79) and count (EDF = 15.64) sub-models) as a random effect; the log of effort in minutes was included as an offset term in both sub-models.

The final model suggests the catchability of adult American Shad is affected by sampling location and water temperature. Catches of adult American Shad increase as water temperature increases to approximately 17.0°C before declining at higher temperatures. Catches also vary by fixed station location, with the highest catch occurring at the Belle Isle and Bosher's stations.

The standardized index follows the same trend as the arithmetic mean catch rates for most years, with the notable exception of the first two years of the survey; the standardized index suggests low relative abundance during this period while the arithmetic mean relative abundance suggests above average abundance. The standardized index is stable, with noise, from survey inception through the terminal year, though there is an indication of below average abundance from 2004-2007 and in 2016-2017. Annual CVs averaged 0.17 over the time series (Table 211).

3.13.5.1.3 VDGIF Bosher's Dam Fishway Count

Survey Methods

The vertical slot fishway at Boshers Dam on the James River (river mile 113) near Richmond, Virginia, was completed in early 1999 and first operated and monitored in the spring of 1999. Videos are collected during the entire spring spawning run at the fishway viewing window.

Potential Biases and Uncertainty

- Unknown variation in passage efficiency due to discharge and flow
- Influence of unpredictable environmental factors that affect viewer efficiency (e.g., turbidity, discharge, etc.)

- Possibility of variability reflecting run timing (e.g., short bursts missed).
- Viewer experience

Count Methods
During 1999, live counts were obtained during six hour periods on 3 to 4 randomly selected days. In 2000 mostly live counts were obtained and the use of VHS recordings was first employed. All useable video is reviewed. In 2001 and 2002 all counting has been done by reviewing time-lapse VHS recordings. Starting in 2003 all counting has been done by reviewing digital video collected during the migration season. The digital equipment has evolved over time and currently a surveillance DVR and digital camera is used to collect passage video. Beginning in 2010, a 15-minute portion of every hour of video has been randomly selected and reviewed, and all American shad are counted. Hourly estimates are made by multiplying by four and then tallied for daily and full season results. Prior to switching to subsampling, from 2005 to 2010, 15-minute increments were recorded in order to simulate subsampled estimates for comparing to the full hour/day/season counts; statistical analyses were conducted and the estimation method accurately reflects the full hour counts. From 2010-2015, the first 15 minutes for each hour of video were analyzed. In 2016 the 15 minute per hour sub-sampling approach was modified to randomly select the 15-minute increment. The total number of a given species is estimated by multiplying the 15-minute count by four to arrive at an hourly estimate.

Catch Rates
The passage estimates are shown in Table 212. Over the time series, an average of 178 American shad are passed per year, although there are distinct peaks in 2003 (n=751) and 2011 (n=696). American shad passage numbers are less than one percent of the 500,000 shad goal that was set more than 20 years ago, which were based on population size and the available habitat upstream of Boshers Dam (137 main stem miles to the next dam plus over 150 miles of unimpeded large James tributaries).

3.13.5.2 Young-of-Year Fishery-Independent Data Sources

3.13.5.2.1 VIMS James River Juvenile Seine Survey

Survey Methods
Field sampling is conducted during five biweekly periods (rounds) from June or July through August. During each round, seine hauls were conducted at 18 index stations and 21 auxiliary stations in the James, York and Rappahannock river systems (Figure 239). The Index stations have been sampled annually from 1967 to 1973, and from 1980 to the present. Auxiliary sites were added to the survey in 1989 to provide better geographic coverage and increase sample sizes within each river system.

Collections were made by deploying a 100 ft (30.5 m) long, 4 ft (1.2 m) deep, and 0.25 in (6.4 mm) mesh minnow seine perpendicular to the shoreline until either the net was fully extended or a depth of approximately 4 ft (1.2 m) was encountered and then pulling the offshore end down-current and back to the shore. During each round, a single haul was completed at each auxiliary station, and duplicate hauls, with an interlude of at least 30 minutes, were completed at each index station. Even with a 30-minute interlude between hauls at index stations, second hauls cannot be considered independent samples and their use violates a key assumption necessary for making inferences from a sample mean (Rago et al. 1995); only the first haul at each index station is used to calculate the annual index of American shad.

From 1999-2015, the VIMS seine survey used a net comprised of 0.25 inch knotless oval mesh. However, this netting was no longer available from the manufacturer in 2015, so a new net was constructed from 0.25 inch knotless rhomboid mesh material. To test if the mesh material influenced the relative catch efficiency of the net, paired hauls of old and new nets were conducted during the 2015-2017 sampling seasons; the estimated calibration factors were not significantly different from 1 for either Striped Bass and White Perch, so there is no adjustment prior to estimation of abundance indices.

Potential Biases and Uncertainty

- Inherent biases of seine surveys (e.g., escapement issues)
- Influence of unpredictable environmental factors that affect catch efficiency (e.g., bycatch of Blue Catfish, turbidity, discharge, etc.)
- Unknown misidentification of American shad (vs. other sympatric alosines)

Biological Sampling Methods

Every fish collected during a haul was removed from the net and placed into a water-filled bucket. A sub-sample of American shad of up to 25 individuals was measured to the nearest mm FL. Sampling time, tidal stage, and weather conditions were recorded at each sampling location. Salinity, water temperature, and dissolved oxygen (DO) concentrations were measured after the first haul using a handheld YSI water quality sampler.

Catch Rates

The seine survey data on the James River (Table 209 and Table 210; Figure 258) showed no measurable recruitment of American shad in 2000, 2001, 2002, 2005, 2013, and 2017; all other years show very little detectable recruitment. In 2010, James River indices for all years were recalculated to include additional seine survey stations located in the upper James and Chickahominy rivers. Independent results from the Chickahominy River are also reported, although it is unknown whether fish captured in this river form a unique stock (i.e., distinct from that of the James River). Stocking of American shad took place on Chickahominy Lake in 2000 and on the Chickahominy River in 2004. Results from an independent survey below Boshers Dam on the James River depict no measureable recruitment in most years (VDGIF, T. Gunter, pers. comm.).

3.13.6 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance, mean length, and mean length-at-age. Total mortality estimators were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Details for these methods are provided in Section 2.

3.13.7 Results

3.13.7.1 Abundance Trends

3.13.7.2 Power Analysis

Three fishery-independent abundance indices for American shad were developed for this system that contained estimates of PSE: the James River Boat Electrofishing Survey, the James River Adult Gill Net Survey (VIMS; standardized, number-based index), and the James River Juvenile Seine Survey. Of these surveys, the first two exhibit sufficient power to detect a 50% decrease in American shad abundance in 10 years, while the James River Juvenile Seine Survey, with its large median PSE, exhibits very little power to detect a 50% change in abundance over 10 years (Table 25). Currently, there is no SFMP for this system so none of these surveys are used for sustainability targets and monitoring.

3.13.7.2.1 Mann-Kendall Analysis

Fishery-Independent Indices

Data from three fishery-independent surveys were examined as indices of American shad abundance in the James River. The James River Boat Electrofishing Survey provided data for 2000-2017, and when plotted showed consistent fluctuation of the time series with peaks in 2003, 2009, 2011, and 2013 (Figure 256). Index values from the James River Adult Gill Net Survey (VIMS; standardized, number-based index) showed an increase in values from 1999-2003, followed by decline and increase again from 2008-2011 and subsequent decline (Figure 257). Index values from the James River Juvenile Seine Survey showed no trend (Figure 258). Mann-Kendall trend analysis failed to detect a trend in any of the three fishery-independent indices for either of the time periods examined.

Run Counts

Bosher's Dam Fishway Counts on the James River were available for analysis for the period between 1999 and 2017. A plot of the run counts versus year showed that there was an initial increase from 1999 through 2005, a steep decline to a low level that continued until anther peak in 2011, followed by a quick decline through the end of the time series (Figure 259). Mann-Kendall trend analysis failed to detect a trend for either the full time series or the period after 2005.

3.13.7.3 Mean Length Trends

Lengths were available for 1995-2017 from the James River Boat Electrofishing Survey and for 1998-2017 from the James River Adult Gill Net Survey (VIMS). Plots of mean lengths (Figure 260 - Figure 261) and Mann-Kendall trend analysis of both surveys found no trend in mean lengths of either sex.

3.13.7.4 Mean Length-at-Age Trends

Mean length-at-age data using scales were provided from the James River Adult Gill Net Survey (VIMS). Only female samples were included in the analysis, and fish aged ranged between ages 3 and 10. Mann-Kendall Trend analysis failed to detect any change in mean length-at-age over time for most ages, but did detect a decrease in mean length-at-age in age 8 females (Table 213).

3.13.7.5 Total Mortality Estimates

Age composition data tabulated from scales collected randomly or by census during the James River Adult Gill Net Survey were used for mortality estimates. Data met all criteria (see Section 2.6) for 15 years between 2002 and 2017 for females; data were not available for males (Table 32). Female mortality varied without trend in the early 2000s and early 2010s, but declined in the late 2000s and recent years (Table 33 and Figure 262). There were no female data available for 2016 precluding estimation of a three year average for females in 2017, though point estimates from 2015 and 2017 suggest Z was below threshold levels.

3.13.7.6 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the James system, current unobstructed habitat area represents 72.77% of the historical habitat extent (71.90 of 98.80 square kilometers).

3.13.8 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. The adult mortality status is also unknown as there was no estimate of female total mortality in 2016. The most recent three-year average female total mortality was 0.76 in 2015 which is below the $Z_{40\%}$ threshold (1.07).

There were no trends in female mean length detected from two sets (1998-2017, 2003-2017). There were no YOY abundance trends detected since 1980 or 2005.

Abundance

Abundance status is unknown. There have been no trends in YOY abundance or adult abundance (3 data sets) since 2005.

3.13.9 Research Recommendations

3.13.9.1 Progress on 2007 Stock Assessment Research Recommendations

- Mixed-stock composition has been evaluated using genetics (Aunins 2010)

- Passage efficiency at Boshers Dam is evaluated by ongoing monitoring
- Recruitment variability has been monitored via seine survey; also see Tuckey (2009)

2007 Recommendations yet to be completed:

- A stock-specific validation study has not been completed; such a study using isotopes as a natural tag has been completed for the York River system
- Estimates of natural mortality have not been calculated
- Monitoring of bycatch fishery is ongoing

3.13.9.2 Additional Research Recommendations

- Continuing to estimate larval and juvenile abundances and sources of mortality
- Evaluate reliability of bycatch fishery as an estimate of fishing mortality
- Calculate natural mortality using bycatch fishing mortality and estimates of total mortality
- Evaluate pound net bycatch, including assessment of mixed-stock composition
- Continue juvenile recruitment studies to include habitat use and migration patterns
- Evaluate efficiency of seine survey for production of JAI

3.14 Albemarle Sound

3.14.1 Habitat Description

The Albemarle Sound area includes Albemarle Sound, all of its tributaries, Currituck, Roanoke, and Croatan sounds, and all of their tributaries. The Albemarle Sound, including the tributaries, occupies more than 212,055 hectares (ha) of open water as well as extensive bordering swamps in northeastern North Carolina (Figure 263). The Albemarle Sound measures 88.5 km long by 4.8 to 22.5 kilometers (km) wide. Shoals generally extend 0.8 km from shore, sloping to a central basin 5.5 to 7.6 meters (m) depth. The bottom consists mostly of sand in the central basin with some mud and detritus on the shoals. The shoreline in eastern Albemarle Sound consists mostly of cypress swamps and a few small beaches, while beaches and low bluffs become more frequent to the west (Street 1975). Croatan and Roanoke sounds are estuarine with salinities ranging from 1 part per thousand (ppt) to 28 ppt, depending on tide, wind, and rainfall. Salinities of 2 to 4 ppt sometimes occurred in eastern Albemarle Sound, while salinities of 1 to 2 ppt were occasionally recorded from the downstream portions of the North, Pasquotank, Alligator, and Little Rivers. North, Pasquotank, and Alligator Rivers and eastern Albemarle Sound serve as channels of the Atlantic Intracoastal Waterway (Street 1975).

3.14.1.1 Tributaries

Currituck Sound joins the Albemarle Sound from the northeast, and Croatan and Roanoke sounds join from the southeast. Ten rivers drain into Albemarle Sound, which joins Pamlico

Sound through Croatan and Roanoke sounds, and in turn, empties into the Atlantic Ocean via Oregon Inlet. Most of the rivers originate in coastal swamps and do not function as spawning areas for American shad. Moving across the Albemarle Sound drainage rivers from east to west, the North River joins the Albemarle Sound from the northeast. The North River originates in coastal swamps and occupies about 6,475 ha and is about 34 km in length (Baker and Smith 1965, as cited by Street 1975, p. 7). The Pasquotank River, covering about 13,468 ha, is the main southern outlet for the Great Dismal Swamp, and is about 64 km in length (Baker and Smith 1965, as cited by Street 1975, p. 7). The Little River originates in the Great Dismal Swamp, occupies about 2,849 ha, and flows approximately 30.6 km south to the Albemarle Sound (Baker and Smith 1965, as cited by Street 1975, p. 8). The Perquimans River also originates in the Great Dismal Swamp and flows approximately 50 km to the Albemarle Sound and occupies about 5,180 ha (Baker and Smith 1965, as cited by Street 1975, p. 8). The Yeopim River (including Yeopim Creek) originates in local swamps and is about 16 km long and occupies approximately 1,554 ha (Baker and Smith 1965, as cited by Street 1975, p. 8).

The Roanoke and Chowan Rivers are the principal tributaries of the Albemarle Sound, and areas of these rivers are known to function as American shad spawning areas (Street et al. 1975; Johnson et al. 1981; Winslow et al. 1983; Winslow et al. 1985; Hightower and Sparks 2003). The last river to join the Albemarle Sound from the north is the Chowan River. It occupies approximately 15,540 ha and extends 80.5 km from the North Carolina-Virginia border to the Albemarle Sound. Three rivers drain into the Chowan River: Meherrin, Nottoway, and Blackwater. The Meherrin and Nottoway rivers are the major tributaries of the Chowan and begin in the Piedmont Plateau of Virginia (Smith 1963, as cited by Street 1975, p. 8). The Blackwater River, a smaller tributary, originates as a coastal plain swamp in Prince George County, Virginia (VDGIF 2019). All three rivers function as a spawning area for American shad.

The Roanoke River and Cashie River join the Albemarle Sound from the west, via a shared delta. The Cashie River originates in local swamps, occupies approximately 777 ha, and flows 48.3 km to enter the Albemarle Sound (Carnes 1965, as cited by Street 1975, p. 8). The Roanoke River flows 220.5 km from the Roanoke Rapids Dam (Roanoke Rapids, North Carolina) to the Albemarle Sound. The river begins in the foothills of Virginia's Blue Ridge Mountains and crosses the Fall Line just below Roanoke Rapids Dam (Carnes 1965, as cited by Street 1975, p. 9). American shad spawning occurs in the Roanoke River near Weldon and Roanoke Rapids, North Carolina.

Two rivers join the Albemarle Sound from the south, the Scuppernong River and Alligator River. The Scuppernong River joins the Albemarle Sound from the southwest. It originates in local swamps and receives additional water via a network of canals from Lake Phelps, a 6,478 ha pocosin located in Washington and Tyrrell counties in North Carolina (NCWRC 2011). The Scuppernong River occupies approximately 1,295 ha and is about 43.5 km in length (Baker and Smith 1965, as cited by Street 1975, p. 9). The Alligator River occupies approximately 25,900 ha and flows 120.7 km to the Albemarle Sound (Baker and Smith 1965, as cited by Street 1975, p. 9).

3.14.1.2 Spawning Habitat Descriptions

Anadromous fish spawning areas (AFSAs) are defined in NCDMF rule NCAC 03N .0106 and NCWRC rule 15A 10C .0602 as those areas where evidence of spawning of anadromous fish has been documented through direct observation of spawning, capture of running ripe female or capture of eggs or early larvae (Figure 264 and Figure 265; NCDMF and NCWRC 2014). The areas are delineated in North Carolina Marine Fisheries Commission (NCMFC) rule 15A NCAC 03R .0115 and NCWRC rule 15A 10C .0603. AFSAs cover 17% and 10% of streams/shorelines and water bodies, respectively, in coastal plain portions of North Carolinas Coastal Habitat Protection Plan regions (Deaton et al 2010). Most AFSAs are located in the Albemarle region (70%) and include the Chowan River, main stem Roanoke River, Alligator River, and Phelps Lake.

The NCDMF conducted American shad spawning area surveys between 1973 and 1984 in the major coastal tributaries of North Carolina. Physical characteristics of the spawning grounds vary somewhat between systems. Shad may spawn anywhere within a given spawning area but prefer shallow flats composed of sand, gravel, or a combination of the two bordering the rivers (Smith 1907; Walburg and Nichols 1967; Beasley and Hightower 2000; Hightower and Sparks 2003). Water conditions may vary from clear to very turbid, water depth ranges from 3 to 30 ft, and temperatures may range from 8 to 26°C (Walburg and Nichols 1967; Winslow 1990).

Shad eggs are non-adhesive and slightly heavier than water, so they gradually sink and are carried along by currents (Ulrich et al. 1979). Sufficient water current is required to keep eggs suspended in the water column for successful development (Cheek 1968; Sholar 1977). This requirement may explain why American shad spawning was found only in the Nottoway, Blackwater, Meherrin, Roanoke, Tar, Neuse and Cape Fear rivers, all of which have relatively strong currents compared to other coastal rivers in the state. All American shad spawning areas have been documented either by capture of eggs or larvae, or direct observation of spawning.

Numerous miles of spawning and nursery area habitat have been eliminated due to lock or dam systems that exist on the Cape Fear, Neuse, Tar, Roanoke, Meherrin, and Nottoway rivers. These “blockages” have greatly reduced the historical spawning runs of American shad in North Carolina. In general, recent cost-benefit evaluations of these impediments have revealed that some dams are more costly to operate and maintain than to remove (Hart et al. 2002). As such, recent and ongoing studies are documenting the effects of dams on anadromous fish migrations and spawning in North Carolina.

Removal of dams may enhance the migration of anadromous fish. On the Neuse River, the potential spawning habitat available to anadromous fish increased by a total of 127 main stem river kilometers (rkm) after the removal of the Quaker Neck Dam in 1998 (Beasley and Hightower 2000) and an additional 10 km after the removal of Milburnie Dam in 2017 (White and McCargo 2018). Bowman and Hightower (2001) documented significant migration of American shad in the main stem beyond Quaker Neck Dam location. In addition, Burdick and Hightower (2006) observed spawning activity of American shad during sufficient instream flow in the enhanced barrier-free stretch of the Neuse River.

Some dams must remain in place, but alternate measures are being studied to decrease their negative ecological effects. Currently, the Roanoke River is unimpeded for 221 rkm from the mouth to the hydroelectric dam at Roanoke Rapids (Hightower et al. 1996). In addition, there are two dams upstream of the Roanoke Rapids Dam: Gaston Dam and Kerr Dam. With the recent Federal Energy Regulatory Commission (FERC) relicensing of the Roanoke Rapids and Gaston dams, provisions have been made to include a trap and transport program to relocate adult American shad above Kerr Dam. During the relicensing period, Read (2004) estimated that there was over 300 rkm of potential spawning habitat available to American shad above Kerr Dam. The proposed trap and transport program may be an alternative means of re-connecting historic, but currently inaccessible, shad spawning habitats. Since 2010, Dominion Energy (with support of state and federal partners) has annually petitioned the FERC for a delay of the design and construction of American shad fish passage facilities at Roanoke Rapids Dam (White and McCargo 2018). Cooperative management teams consisting of state and federal government agency biologists, non-governmental partners and Dominion Power staff continue to meet and evaluate the status of the Roanoke Rapids Dam FERC license agreement, including provisions for passage of American shad (White and McCargo 2016). Refer to section 1.A.4.c. for more information on the Roanoke River trap and transport program.

3.14.1.3 Hydropower Projects

Near the North Carolina-Virginia border, John H. Kerr Reservoir, Lake Gaston, and Roanoke Rapids Lake impound the Roanoke River. The U.S. Army Corps of Engineers (USACOE) operates Kerr Dam for flood control and hydropower generation, whereas Dominion Energy operates Gaston and Roanoke Rapids dams primarily for hydropower generation. Roanoke Rapids Dam, the first upstream impediment, was constructed in 1955 at Roanoke Rapids, North Carolina, 220.6 km (137 miles) from the mouth of the Roanoke River (Carnes 1965). This dam does not have facilities for fish passage and is therefore the upper limit of American shad migration. American shad accumulate in the Roanoke Rapids area, and newly spawned American shad eggs have been collected there (Knutzen 1997; Hightower and Sparks 2003; Thomas and Kornegay 2004; Harris and Hightower 2007). Downstream of Roanoke Rapids Lake, flows in the Roanoke River are highly regulated by discharges from the dams. From the Roanoke Rapids Dam, the Roanoke River flows 221 km (137 miles) through an expansive area of bottomland hardwood wetlands to its confluence with Albemarle Sound.

State and federal fisheries management agencies in North Carolina and Virginia finalized negotiations with Dominion Energy with regards to relicensing of the Gaston and Roanoke Rapids hydroelectric dams through a FERC settlement agreement approved in 2005. Among the mitigation measures agreed to as a condition of relicensing is a long-term, well-funded, and coordinated program to restore American shad in the Roanoke River basin. Measures outlined to be included in this effort are improvements in hatchery production of fry, continued intensive monitoring of fry stocking success upstream and downstream of the main stem reservoirs, experimentation with radio-telemetered spawners trapped and hauled to upstream reservoirs, and finally, assessment of the feasibility of providing upstream passage facilities. Since the license was issued, Dominion purchased and assembled an American shad hauling tank, continued stock assessment sampling in the bypassed reach, funded hydroacoustic-based population estimate research, completed an American shad turbine mortality study, developed a bypassed reach flow management and monitoring plan, implemented a recreation plan, and funded studies of lower river erosion and the biological effects of hydropower peaking. Coordination of American shad and other diadromous species restoration efforts is conducted through periodic meetings of the Diadromous Fisheries Restoration Technical Advisory Committee consisting of state and federal agency biologists as well as non-governmental agency, university, and Dominion Energy stakeholders.

In the Chowan River basin, a small hydropower facility is located on the Meherrin River near Emporia, VA. A fish lift is operated at the dam to provide anadromous fish passage, but it is ineffective at passing American shad (Eric Brittle, Virginia Division of Game and Inland Fisheries, personal communication). Thus, American shad migrations on the Meherrin River are impeded by Emporia Dam.

3.14.2 Fishery and Management History

3.14.2.1 Regulatory History

Since the early 1900s various commercial regulations have governed the American shad fisheries in North Carolina. Gear and area restrictions were adopted, as well as a closed season for American shad harvest from May through June, during 1955 to 1965. No recreational restrictions were in place during these years.

Commercial and recreational harvest of American shad is regulated by NCDMF in Coastal Waters of North Carolina and by NCWRC in Inland Waters. Prior to 1987, few limits were placed on commercial fishing (e.g., no mesh size or yardage limits, seasons, or closed areas). In 1988, the NCMFC instituted an area closure for a portion of Albemarle Sound, along with gill net mesh restrictions in other areas. In 1995, a closed season for American shad was enacted, making it unlawful to take American shad for commercial purposes by any method from April 15 through December 31 [15A NCAC 3M. 0513]. In 2008, shad (American and Hickory) was separated from 15A NCAC 3M. 0513 and 15A NCAC 3M. 0519 was implemented, maintaining the same seasons. The season has greatly reduced the harvest, since historically a large portion of the American shad harvest occurred after April 15 and into May. Area closures to gill nets, as well as yardage and mesh size restrictions, occur and vary between management units. In addition, fishing restrictions for striped bass prohibited shad fishing in some years. No quotas exist for American shad in North Carolina. North Carolina’s ocean fishery for American shad was closed in 2005. In Inland Waters, commercial harvest and sale of American shad was made illegal when American shad was designated as an inland Game Fish in 1996.

Prior to 1995, no recreational restrictions existed for American shad in either jurisdiction. In 1995, it became unlawful to take American shad and hickory shad by any method except hook-and-line from April 15 through December 31 in Coastal Waters. Additionally, from 1995 through 1998, the recreational season was January 1 through April 14. In 1999, it became unlawful to possess more than 10 American shad and hickory shad in the aggregate in Coastal Waters and

Inland Waters [1999 to 2007 15A NCAC 3M. 0513; 2008-2017 15A NCAC 3M. 0519]. NCWRC implemented a 1-fish American shad limit within the 10-fish aggregate creel limit for American and hickory shad in the Inland Waters of the Roanoke River in 2008 and in the Inland Waters of the Neuse River in 2012 (NCDMF and NCWRC 2012). In 2013, NCWRC implemented a 5-fish American shad limit within the 10-fish aggregate creel limit in the Inland Waters of the Cape Fear River and its tributaries. Also in 2013, creel limits were made consistent within both jurisdictions and commercial seasons were established with the implementation the NC SFMP for American shad (see section I.A.2.c.1.a.).

3.14.2.2 Assessment History

Regional assessments were conducted by Winslow (1990) and Hightower et al. (1996), and coastwide assessments were completed by Gibson et al. (1988), ASMFC (1998), and ASMFC (2007).

Gibson et al. (1988) provided an assessment of selected Atlantic coast rivers that included the Chowan, Tar, Neuse, and Cape Fear rivers. North Carolina river systems were found to be more resilient to higher exploitation rates than other Atlantic coast systems. However, Fmsy estimates were subject to bias from measurement errors in CPUE and stock-recruitment data, poor precision about Fmsy estimates, and random variability about stock-recruitment models related to environmental effects on recruitment. The assessment recommended that *F* not exceed 0.50 for extended periods of time for all Atlantic coast rivers.

Winslow's 1990 assessment focused primarily on Albemarle Sound. Winslow (1990) found that shad resources in Albemarle Sound, North Carolina continued to be depressed despite slight increases during previous years. Winslow (1990) stated that American shad and "civilization" are probably not compatible, and it is doubtful they can ever be restored to the status of the late 19th century. Changes have occurred in the spawning and nursery areas as a result of the encroachment of man, from reduction in size in some areas to complete elimination in others.

At the time, anadromous fish studies in Albemarle Sound did not yield sufficient information to evaluate the reason for the decline. One of the major deficiencies identified was a lack of catch-effort data. Once catch and effort statistics have been obtained for several years, studies could proceed to determine population sizes, trends, and factors responsible for fluctuations in abundance, and appropriate management measures could be developed. In addition, information on harvest and use was desperately needed; without it the shad population could never be adequately evaluated.

Winslow (1990) recommended that action be taken to reduce or eliminate pollution and habitat destruction. With needed biological data, reliable harvest data, and productive habitat, there was no reason why the American shad population in the Albemarle Sound area, as well as throughout eastern North Carolina, could not again support significant fisheries.

Hightower et al. (1996) examined catch-per-unit-effort (CPUE) data from a haul seine fishery that operated on western Albemarle Sound from 1845 through 1907. The authors fit a biomass-based model to the data and estimated a population growth rate (r) of 0.5 to 0.9. Estimated maximum sustainable yield was 0.9-1.8 million kg. The authors noted that recent harvest has been well under this level and recommended that current estimates of fishing rates be obtained for the stock.

ASMFC (1998) completed an assessment of American shad stocks along the Atlantic coast. Systems assessed in North Carolina included Albemarle Sound, Pamlico River, Neuse River, and Cape Fear River.

ASMFC (1998) found that landings in Albemarle Sound had been relatively stable from 1982 to 1990 but had declined in the last few years and suggested a serious decline in overall abundance. However, there were no estimates of fishing effort available. ASMFC (1998) also noted that total mortality estimates from Albemarle Sound and landings of coastal shad had remained relatively stable for more than a decade, which suggests that the decline in landings was likely due to a decrease in effort and not due to an actual decline in stock abundance.

Downward trends were also noted in landings from the Pamlico, Neuse, and Cape Fear rivers from 1987 to 1996. However, fishing mortality could not be estimated. Therefore, it could not be determined whether the decline in in-river commercial landings indicated an actual decline in the stock or if it was caused by a reduction in fishing effort.

ASMFC (2007) completed a benchmark assessment of American shad stocks along the Atlantic Coast from Maine through Florida. Systems assessed in North Carolina included Albemarle Sound-Roanoke River, Tar-Pamlico River, Neuse River, and Cape Fear River. ASMFC (2007) found that North Carolina American shad landings had remained relatively stable from 1973 to 2005, with the Albemarle Sound fishery contributing to a significant portion of the statewide landings since the late 1980s. ASMFC (2007) determined the abundance of American shad in the Albemarle Sound and its tributaries was well below the historic potential for these stocks, and current landings were much less than the maximum sustainable yield estimated for these stocks by Hightower et al. (1996). Catch-per-trip in the commercial fishery since the mid-1990s and CPUE from more recent fishery-independent sampling programs had all increased slightly, suggesting a recent improvement in stocks of Albemarle Sound and the Roanoke River. High mortality rates may have affected stocks in the 1970s and 1980s, but the recent stock increase suggested that mortality levels had not affected stock levels in the last 15 years; however, these improvements may have been a result of artificial enhancement via the ongoing stocking program in the Roanoke River. Harvest and presumably stock levels remained very low in the historical context.

3.14.2.3 SFMP summary

North Carolina’s first SFMP for American shad was approved by the ASMFC Shad and River Herring Management Board in May 2012 for 2013-2017 management (NCDMF and NCWRC 2012). Sustainability parameters were developed for the primary American shad spawning areas; Albemarle Sound-Roanoke River, Tar-Pamlico River, Neuse River, and Cape Fear River, based on relative abundance and relative fishing mortality rate. Sustainability parameters are based on the female segment of the stock because the commercial fishery targets roe (female) American shad. Relative abundance was calculated using available fisheries-independent survey data that were considered appropriate for measuring the abundance of American shad and were expressed in terms of CPUE. The standard deviations of the annual CPUE index values were also calculated to demonstrate the variability of these values. Environmental conditions on the spawning grounds, especially flow rates, are a major source of variability associated with these indices.

Relative fishing mortality rate (relative F) was calculated by dividing catch by a fisheries-independent index of relative abundance. Relative *F* was computed by dividing commercial landings by a centered 3-year average of a survey index. Using a centered 3-year average means the first and last year index value will be based on only two years of data, therefore the threshold value would fluctuate annually. For each monitored system, the survey data used in the calculation of relative *F* were subset to reflect conditions in the commercial fishery (open harvest seasons).

Indices of relative abundance and estimates of relative *F* were calculated for each system using available data through 2011 and updated annually. At a minimum one abundance index and one series of relative *F* estimates were selected to serve as sustainability parameters for each system.

3.14.2.3.1 Albemarle Sound 2013-2017 SFMP

Three sustainability parameters selected for Albemarle Sound were female CPUE based on NCDMF Albemarle Sound Independent Gill Net Survey (Albemarle Sound IGNS), female CPUE based on the NCWRC Roanoke River Adult Spawning Area Electrofishing Survey, and female relative *F* based on the Albemarle Sound IGNS. Exceeding the threshold for female CPUE (Albemarle Sound IGNS) or female relative *F* (Albemarle Sound IGNS) will trigger management action. Female CPUE (NCWRC Roanoke River Adult Spawning Area Electrofishing Survey) will be used in conjunction with a second index for triggering management action but cannot trigger management action alone (NCDMF and NCWRC 2012).

Female CPUE (NCWRC Roanoke River Adult Spawning Area Electrofishing Survey): The female CPUE index based on the NCWRC Roanoke River Adult Spawning Area Electrofishing Survey was calculated as the number of fish per minute using data collected from March through May. Data from the 2000 electrofishing survey were not able to be used for analysis due to database construction issue. Initial time series included data from 2001 to 2011 to calculate the 2012 threshold. Values were updated annually through 2017. The annual threshold was calculated as the 25th percentile (where 75% of all values are greater) of the female CPUE index. Management is triggered following three consecutive years of values below the 25th percentile (NCDMF and NCWRC 2012).

Female CPUE (NCDMF Albemarle Sound IGNS): The female CPUE index based on the NCDMF IGNS was calculated as the number of fish per haul using data collected January through May. The initial time series included data from 2000 to 2011 to calculate the 2012 threshold.

Although the Albemarle Sound IGNS has been conducted since 1991, use of the 2000 to 2011 time series allowed for more consistent comparison with the female CPUE index from the Roanoke River electrofishing survey, which has been conducted annually since 2000. Values were updated annually through 2017. The annual threshold was calculated as the 25th percentile (where 75% of all values are greater) of the female CPUE index. Management is triggered following three consecutive years of values below the 25th percentile (NCDMF and NCWRC 2012).

Female Relative *F* (NCDMF Albemarle Sound IGNS): Female relative *F* based on the NCDMF Albemarle Sound IGNS was calculated using commercial gill net landings of roe shad in Albemarle Sound and a female index derived from data collected in the 5.0, 5.5 and 6.0 inch stretched mesh sizes of the Albemarle Sound IGNS. The mesh sizes selected most accurately reflect those used by the commercial fleet. The fishery-independent index for the Albemarle Sound-Roanoke River was truncated to represent the commercial season, February through April for 2013. When the commercial season was reduced to March 3 through March 24 in 2014, the Albemarle Sound IGNS was subset to the month of March for female relative *F* calculation from 2014 to 2017. Truncating the data to March, increased the variability in the point estimates for relative *F* and reduced the sample size used in the Albemarle Sound IGNS index. The initial time series included data from 2000 to 2011 to calculate the 2012 threshold. Values were updated annually through 2017. The annual threshold was calculated as the 75th percentile (where 25% of all values are greater) of the female relative *F* index. Management is triggered following three consecutive years of values above the 75th percentile (where 25% of all values are greater; NCDMF and NCWRC 2012).

In 2013, under the first year of the SFMP, a commercial season from 15 February to 14 April was established for the Albemarle Sound, Tar-Pamlico River, Neuse River, and all other areas of the state. The Cape Fear River commercial season was set from 20 February to 11 April, due to the ASMFC Shad and River Herring Technical Committee request to reduce commercial harvest so that female relative *F* was below the threshold. Thresholds for the Albemarle Sound were triggered following the evaluation of the 2012 and 2013 data (thresholds for two parameters were exceed from 2011-2013) and therefore, commercial harvest reductions were needed in that system. In 2014, a commercial season from 3 March to 24 March was established for the Albemarle Sound and has remained in place through 2019. No additional management measures were required in the Albemarle Sound system following the implementation of the reduced season. Additionally, management was not triggered in any of the other systems for the duration of this plan, 2013 to 2017. Commercial seasons from 2012 (prior to SFMP) through 2017 are described in Table 214 (NCDMF and NCWRC 2017).

Recreational creel limits, within a 10-fish shad aggregate, established in the first year of the SFMP remained unchanged for the duration of the plan and are listed in Table 215.

3.14.2.3.2 Albemarle Sound 2018-2022 SFMP

In 2017, the original SFMP underwent a mandatory 5-year review and survey data was updated through 2017. The objective of the review was to refine the calculations of the abundance indices and relative *F* estimates. The new plan was approved for management for 2018 through 2022 in October of 2017. The plan includes the same sustainability parameters of relative *F* and abundance indices, with two main changes to the calculations. Relative *F* is now computed by dividing commercial landings by a hind cast 3-year average of a survey index, whereas the previous plan used a centered 3-year average. Using a hind cast 3-year average was determined more appropriate, with the addition of 5-years of data, as it ensures the value of the final year in the time series (which can trigger management action) remains unchanged once calculated. The next change was that thresholds, for all sustainability parameters, are fixed using the time series for the available survey data through 2017. In the 5-year review of the original plan, there were concerns that the thresholds could slowly decline to extremely low levels without ever being exceeded because, thresholds were recalculated annually with the addition of another year of data. The following sustainability parameters and thresholds were approved for the Albemarle Sound area and are in effect through 2022 (NCDMF and NCWRC 2017).

Female CPUE (NCWRC electrofishing survey): The female CPUE index based on the NCWRC electrofishing survey was calculated as the number of fish per minute using data collected from March through May from 2001-2017. The threshold was calculated as the 25th percentile (where 75% of all values are greater) of the female CPUE index for 2001-2017. Management is triggered following three consecutive years of values below the 25th percentile (NCDMF and NCWRC 2017).

Female CPUE (NCDMF Albemarle Sound IGNS): The female CPUE index based on the NCDMF Albemarle Sound IGNS was calculated as the number of fish per haul using data collected during January through May from 2000-2017. Although the Albemarle Sound IGNS has been conducted since 1991, use of the 2000–2017 time series will allow for more consistent comparison with the female CPUE index from the Roanoke River electrofishing survey, which has been conducted annually since 2000. The threshold was calculated as the 25th percentile (where 75% of all values are greater) of the female CPUE index for 2000-2017. Management is triggered following three consecutive years of values below the 25th percentile (NCDMF and NCWRC 2017).

Female Relative *F* (NCDMF Albemarle Sound IGNS): Female relative *F* based on the NCDMF Albemarle Sound IGNS was calculated using commercial gill net landings of roe shad in Albemarle Sound and a female index derived from data collected in the 5.0, 5.5 and 6.0-inch mesh sizes of the Albemarle Sound IGNS from 2000-2017. The mesh sizes selected most accurately reflect those used by the commercial fleet. In the development of the 2013-2017 SFMP, the fishery-independent index for the Albemarle Sound-Roanoke River was truncated to represent the commercial season, February through April. When the commercial season was reduced to March 3 through March 24, the Albemarle Sound IGNS was subset to the month of March for female relative *F* calculation from 2014 to 2017. This has increased the variability in the point estimates for relative *F* and reduced the sample size used in the IGNS index. Relative *F* point estimates are computed by dividing commercial landings by a hind cast 3-year average of a survey index; data for 2000-2002 is contained in the first point estimate for 2002. Each consecutive point estimate in the time series is calculated from 3-years of data. The annual threshold was calculated as the 75th percentile (where 25% of all values are greater) of the female relative *F* index from the fixed time series 2000-2017. Management is triggered following three consecutive years of values above the 75th percentile (where 25% of all values are greater; NCDMF and NCWRC 2017).

The Albemarle Sound IGNS index of female relative abundance for Albemarle Sound has shown slight variation over time and was below the threshold starting in 2011 for three consecutive years, triggering management action in 2014. The female abundance index derived from the electrofishing survey was above the threshold throughout most of the time series, except for 2006, 2010, and 2016. This index demonstrated an increase from 2006 to 2008 but decreased in 2009 and dropped below the threshold in 2010. The index increased through 2014 to the highest value of the time series, before declining to below the threshold in 2016, and increasing again in 2017 (NCDMF and NCWRC 2017).

Estimates of female relative *F* derived from the Albemarle Sound IGNS also varied with time. The index exceeded the threshold in 2011 through 2014 and remained below the threshold through 2017 (NCDMF and NCWRC 2017).

Commercial seasons (Table 214) and recreational creel limits (Table 215) from the terminal year of the first SFMP, 2017, were maintained, with the exception of the recreational creel limit in inland waters of the Albemarle Sound. The inland waters of the Albemarle Sound creel limit remained at 10-fish for American shad, whereas the Albemarle Sound was reduced to 1-fish in joint and coastal waters. This inconsistency was corrected on 1 August 2019 (15A NCAC 10C .0313) when NCWRC amended the statewide shad rule to 10-fish per day in the aggregate with only one American shad.

3.14.3 System-Specific Life History

American shad in Albemarle Sound show a slightly different life history strategy than stocks found in other systems in North Carolina and closely mirror those systems to the north. American shad populations in North Carolina river systems south of Albemarle Sound form a region where stocks transition from the iteroparous stocks in the north to the semelparous stocks seen in the south. In addition, American shad take slightly longer to mature in Albemarle Sound than in the rest of the state. American shad are fully mature at age-7 and 8 in Albemarle Sound, while shad in other North Carolina systems reach full maturity at age-6 and 7 (ASMFC 2007b). It should be noted that conclusions of life history traits based on ages, such as maturity and growth, are subject to errors due to differences in readers determining ages from scales across systems (ASMFC 2007b).

American shad spawning has been documented in the Roanoke River (Johnson et al. 1978; Hightower and Sparks 2003; Harris and Hightower 2007), Chowan River (Meherrin, Blackwater, and Nottoway rivers) (Street et al. 1975; Johnson et al. 1981; Winslow et al. 1983; Winslow et al. 1985), Tar-Pamlico River (Hawkins 1980a; Winslow et al. 1983), Neuse River (Baker 1968; Hawkins 1980b; Burdick and Hightower 2006), and Cape Fear River systems (Sholar 1977; Fischer 1980; Winslow et al. 1983). Shad begin entering the sounds and rivers as early as

February. Spawning of American shad normally occurs from early April to late May, depending on the water temperature and the system. There is generally a south to north progression in the systems.

3.14.3.1 Maturity and Fecundity

Holland and Yelverton (1973) reported that the fecundity of American shad age 5–9 off the North Carolina coast ranged from 197,323 to 457,530 with a mean of 281,137. There are no known fecundity estimates for American shad from the internal waters of North Carolina.

3.14.4 Anthropogenic Sources of Mortality and Productivity

The fluctuations of landings of the 1800s indicated that there was a problem with the American shad population; overfishing was thought to be the primary reason for the decline in harvest. To compensate for this, the federal government began artificial propagation of shad in New Bern, North Carolina in 1873. Fry that hatched were released into local waters. In 1877, the state began fish culture operations of its own on the Neuse River at several locations above New Bern (Smith 1907). The shad hatching of 1878 was noteworthy because it was conducted jointly with representatives from the U.S. Fish Commission, Virginia, Maryland, and North Carolina. The operation was sited at Salmon Creek at the head of Albemarle Sound and, having produced a million fry, the production was the most successful up to that time (Smith 1907). The federal government continued shad hatching in 1879 at the mouth of the Chowan River. In 1880, the state constructed a shad hatchery in Avoca, North Carolina and used eggs furnished by the Capehart seine fisheries at Sutton Beach and Scotch Hall. The MacDonald hatching jar was adopted in 1882, and North Carolina was the first state to employ this important device (Smith 1907). The state continued to operate the hatchery in Avoca until 1884, but all culture work ended in 1885.

Records indicate landings doubled from 1880 to 1887 through 1890, then doubled again by 1897. After this period of massive harvest, landings declined precipitously in spite of continued stocking. In 1943, the federal government decided artificial propagation as practiced was of little value in maintaining the shad population; consequently, stocking was discontinued (Walburg and Nichols 1967).

3.14.4.1 Restoration Program

Stocking of American shad in the Albemarle Sound region resumed in 1998, when the NCWRC initiated the Roanoke River American Shad Restoration Program in response to aquatic habitat damages and availability of mitigation funds resulting from highway bridge construction by the North Carolina Department of Transportation. Permanent funding for the restoration program was secured through the FERC relicensing settlement of Dominion Energy’s Roanoke Rapids and Gaston dams finalized in 2005. Sportfish Restoration Program funding has also been used to finance the restoration program. The goals of the restoration program are to use annual fry stocking to restore a viable, self-sustaining spawning population of American shad in the Roanoke River and to evaluate downstream passage of fry stocked upstream of the John H. Kerr, Gaston, and Roanoke Rapids dams.

The Roanoke River American Shad Stocking Program has used various sources and numbers of broodfish throughout the duration of the program. Following protocols of other states involved in American shad restoration efforts, broodfish were obtained from nearby rivers with adequate shad stocks during early years of the restoration program; however, only endemic broodfish from the Roanoke River spawning grounds were used for fry production in 2011–2017 (Table 216). American shad broodfish were collected by electrofishing and upon collection were placed in circular tanks with continuously circulating, oxygenated water onboard. Broodfish were transferred to large circular, trailer-mounted tanks for transport to USFWS's Edenton National Fish Hatchery (ENFH) and NCWRC's Watha State Fish Hatchery (WSFH). Hormone injection (LHRHa pellets) was used to induce spawning from 1998–2008, but improvements to hatchery techniques allowed for spawning without hormone injection in later years. As spawning occurred, eggs were siphoned into a collection vessel and transferred to McDonald hatching jars for incubation. Hatched fry were fed brine shrimp until stocking between 3 to 12 days old post-hatch.

Annual American shad fry production has resulted in stocking of 75.4 million fry into the Roanoke River basin from 1998 through 2017. Numbers of fry stocked and stocking locations have varied throughout program history (Table 217). Fry have been stocked downstream of the dams at Weldon, NC, in each year of the program for a total stocking contribution of 45.3 million fry to the lower Roanoke River. Stocking in the Staunton River at Altavista, VA, (approximately 125 rkm upstream of Kerr Reservoir) occurred from 2003 to 2010. The upriver stocking location of Clover Landing, VA, (approximately 16 rkm upstream of Kerr Reservoir) was used from 2011 through 2015. Stocking in the upper end of Lake Gaston occurred from 2013–2016, and Roanoke Rapids Lake was stocked in 2016 and 2017. Stockings upstream of the reservoirs between 1998 and 2017 totaled 27.7 million. Additional details regarding hatchery production and protocol can be found in Evans 2017.

3.14.4.2 Hatchery Evaluation

Stockings at Weldon were anticipated to rebuild the Roanoke River American shad population, whereas reservoir stockings were intended to determine rates of fry escapement through the dams and evaluate whether trap and transport of adult American shad is a viable option for population enhancement. Annual contribution of hatchery-origin American shad to the Roanoke River population was evaluated for multiple cohorts of returning adults during the spring spawning run and for out-migrating juveniles during fall of the stocking year. Evaluation of hatchery contribution to the Roanoke River American shad population was conducted using OTC marks from 1999–2009. Subsequent testing proved OTC marking procedures and analyses were unreliable, and the NCWRC initiated use of genetic microsatellite markers for parentage-based tagging (PBT) methods in 2010. With the PBT method, each spawning tank contains a genetically discrete batch of broodfish, from which the progeny can be uniquely identified. Fin clips from all American shad broodfish were stored in numbered vials containing non-denatured, spectrophotometric grade ethanol to later be referenced for determining hatchery origin of at-large fish. Otoliths or fin clips were collected from adult American shad during spawning stock surveys, and broodfish were also evaluated for potential hatchery contribution of stockings from previous years. Juvenile American shad were collected at night in the lower Roanoke River near Plymouth, NC, from September to November using boat-mounted electrofishing gear. Examination of otoliths for OTC was conducted by NCWRC staff using fluorescence compound microscopy, and all PBT analyses were conducted by the genetics laboratory at the North Carolina Museum of Natural Sciences (Evans and Carlson 2018).

3.14.4.3 Trap and Transport

Article 401 of Dominion Energy's FERC license to operate Roanoke Rapids and Gaston hydropower facilities outlines a multi-phase plan to trap adult American shad for transport upstream of John H. Kerr dam to provide upstream passage. Prior to implementation of trap and transport operations, Dominion Energy funded a research project that evaluated upstream and downstream movement of a small number of telemetered American shad that were released in the upper end of Kerr Reservoir. Results indicated that transported fish spent little time in upper basin river habitat, exhibited low levels of downstream migration through all three dams, and may have reduced effective fecundity and survival compared with fish that spawn in the lower Roanoke River (Harris and Hightower 2011). Based on these results, Dominion Energy (with support of state and federal partners) has annually petitioned the Federal Energy Regulatory Commission (FERC) for a delay of the design and construction of American shad fish passage facilities at Roanoke Rapids Dam since 2010.

3.14.5 Fishery-Dependent Data Sources

Historically, American shad were abundant in all major rivers along the North Carolina coast. Shad fisheries became important around 1869, with the greatest development coming in the next 25 years (Walburg and Nichols 1967). In 1896, the American shad harvest from Albemarle Sound was among the most important on the Atlantic coast. Historically, Virginia ranked first and North Carolina second (Walburg and Nichols 1967), but by 1960, the landings in North Carolina ranked third along the East Coast. Landings over the years have fluctuated widely but have shown a continued decline since the late 1800s.

Historically, four principal commercial fishing gears have been used in North Carolina to capture shad: anchored floating gill nets, stake gill nets, pound nets, and haul seines in internal coastal waters. These gears were essentially the same as those of the late 1800s although the length of these gears has changed and more modern materials are used for the manufacture of cordage.

During the late 1970s, an ocean-intercept fishery for American shad developed along the Outer Banks and in the southern part of the state. The major gears for these fisheries were beach haul seines, gill nets, and trawls. Beginning in 1986, a significant ocean gill net fishery for shad developed along the southern coast off the Cape Fear River area and accounted for up to 96 percent of the total ocean landings in the state (1986-2001).

In recent decades, gill nets have become the primary gear used in the commercial fishery for American shad. Individual nets average 40 to 100 yards in length, and mesh sizes range from 4.0 to 5.75 inch stretch mesh (ISM). Historically, commercial operations could fish up to 6,000 yards of gill net per operation. Over the years the maximum limit of gill net allowed per operation has decreased. In 1991, the NCMFC enacted a rule establishing a maximum length of 3,000 yards for gill nets five inches or greater, per operation (15A NCAC 03J .0103). Since 2010 this rule has been regularly suspended to reduce the maximum limit to 1,000 yards in specific areas of the state, Albemarle Sound and tributaries and the Pamlico Sound Gill Net Restricted Area (PSGNRA) from January to August. The gill net restrictions were implemented in order to comply with the statewide incidental take permit from NOAA Fisheries under Section 10 of the Endangered Species Act.

In 1995, the NCMFC enacted a rule establishing a closed season for American shad making it unlawful to take American shad by any method except hook and line from April 15 through December 31. This season is in line with “historical” seasons that existed prior to 1960.

In 1999, NCMFC and NCWRC enacted a recreational hook and line creel limit of 10 fish per person per day in their respective jurisdictions. Substantial recreational fisheries occur within the Cape Fear, Neuse, and Tar rivers. In 2000, North Carolina began a phase out program for the American shad ocean-intercept fishery. Annual total allowable catch (TAC) rates were set and dealers had to obtain permits, adhere to permit conditions, and report landings daily to NCDMF to monitor the TAC. Effective January 1, 2005, the ocean-intercept fishery for American shad was closed.

Currently, commercial American shad fisheries continue to occur in Albemarle Sound, Pamlico Sound, and the Pamlico, Neuse, and Cape Fear river systems. Prior to 2013, the commercial fishery operated under a set season of January 1-April 14 and the recreational hook and line creel limit was 10 fish per person per day. Starting in 2013, system specific commercial seasons and recreational creel limits were implemented under the SFMP (see section I.A.2.c). Mesh size and yardage restrictions exist but vary by area.

3.14.5.1 Commercial Fishery

3.14.5.1.1 Commercial Gear Restrictions

Beginning in 1987, western Albemarle Sound (also referred to as Batchelor Bay) has been closed to the use of gill nets from February through mid-November. While the purpose of the closure is Striped Bass conservation, this measure has also afforded protection for American shad. From 1988 through 1990, limits of 1,000 to 2,000 yards were implemented for 5.25-inch stretched mesh and larger gill nets in Albemarle Sound, and nets could only be set 5 days per week. In April 2016, the MFC adopted a permanent rule implementing yardage restriction for nets with a mesh length of 4.0-inch stretched mesh or greater, the maximum length of gill net shall not exceed 2,000 yards per vessel in all Internal Coastal Waters regardless of the number of individuals involved (NCDMF and NCWRC 2017).

Since 1998, commercial restrictions in Albemarle Sound have been consistent and include a prohibition on the use of gill nets with a mesh size of 3.5–5.0 inches stretched mesh and a limit of 1,000 yards on the use of 5.25-inch and greater (floating) stretched mesh during the open shad season. When the season closes, these nets are removed from the water. The Albemarle Sound is the only system for which mesh size restrictions and yardage limits exist during the shad season.

The Roanoke River has been closed to the use of anchored gill nets since 1991 and drift gill nets since 1993 which greatly reduced harvest of American shad.

3.14.5.1.2 Commercial Landings

In North Carolina, commercial landings of American shad have been reported sporadically since 1880 and consistently since 1950. From 1950 to 1978, North Carolina landings data were collected by NOAA Fisheries. From 1978 to 1993, commercial landings in North Carolina were acquired via an NCDMF and National Marine Fisheries Service cooperative statistics program on a monthly basis from licensed seafood dealers; however, reporting was not mandatory at that time. In 1994, NCDMF implemented a mandatory commercial harvest data collection system known as the Trip Ticket Program. The Trip Ticket Program is a dealer-based reporting program that obtains a trip-level census of commercial landings in North Carolina and continues to the present day (NCDMF 2018).

3.14.5.1.3 Commercial Catch Rates

Estimates of fishery-dependent CPUE are only available after the inception of the North Carolina Trip Ticket Program (Table 218, 1994 to 2017). CPUE is calculated as total catch, in pounds, divided by the total number of directed shad trips. Directed trips are those trips landing at least 100 pounds of shad. This method assumes that effort was relatively uniform among trips with respect to net yardage and soak time. Exact estimates of yardage used are not available from the Trip Ticket Program. Estimates based on maximum yardage allowed are unrealistic and would over-inflate the amount of effort actually expended.

3.14.5.2 Recreational Fishery

Prior to 1999, there were neither harvest restrictions on nor any directed fishery-dependent surveys of the American shad recreational fishery in the Albemarle Sound region. Beginning in 2000, North Carolina was required to monitor the recreational harvest of American shad in one coastal river system each year on a rotating basis. To comply with ASMFC regulations, the annual Roanoke River Striped Bass Creel survey, which began in 1988, is used to monitor recreational harvest of American shad in the Roanoke River. The creel survey is a non-uniform probability, stratified access-point creel survey design (Pollock et al. 1994) conducted only on boat anglers; bank anglers are not interviewed due to budgetary restrictions and survey design constraints. Very few American shad have been encountered in the Roanoke River creel survey, primarily due to lack of targeted effort for American shad; therefore, survey estimates are not entirely representative of the American shad recreational fishery in the Roanoke River. However, very little recreational harvest of American shad is believed to occur in the Roanoke River. Likewise, little to no recreational hook-and-line effort or harvest of American shad is thought to occur in the Albemarle Sound or its tributaries in North Carolina. A low level of harvest could be occurring in the Virginia tributaries of the Chowan River. Neither North

Carolina nor Virginia resource agencies conduct regular creel surveys to detect recreational harvest of American shad in the Meherrin, Blackwater, or Nottoway rivers.

3.14.5.3 Recreational Commercial Gear Fishery

The North Carolina Fisheries Reform Act of 1997 required the NCMFC to establish limits on recreational use of commercial fishing gear. The Recreational Commercial Gear License (RCGL) allows the use of limited amounts of specified commercial gear to catch seafood for personal consumption or recreational purposes. The holder of the RCGL must comply with the recreational size and creel limits, and RCGL catch cannot be sold. From 2002 to 2008, monthly surveys were conducted to collect data necessary for the production of RCGL catch and effort estimates. The monthly survey questionnaires were designed to determine the number of trips taken and type and quantities of gear used during the month of survey. Participants are also requested to provide estimates for the numbers and pounds of each species caught and retained as well as the number of each species discarded. A sub-sample of the entire RCGL population is randomly selected to participate in monthly surveys. The population of RCGL holders for the monthly surveys includes all individuals who purchased a license within a year prior to each month sampled. Due to budgetary constraints the RCGL survey was discontinued in 2008, and harvest data have not been collected since. (White and McCargo 2019).

3.14.6 Fishery-Independent Data Sources

3.14.6.1 Adult Fishery-Independent Data Sources

3.14.6.1.1 NCDMF Albemarle Sound Independent Gill Net Survey

Since 1991, NCDMF has conducted a stratified-random, multiple-mesh independent gill net survey throughout the Albemarle Sound area to monitor the Albemarle/Roanoke striped bass population. The survey was designed for striped bass data collection; however, American shad are captured in the survey and size, age, and sex data are collected. Gill net mesh sizes from 2.5 through 7.0 ISM in half-inch increments, and 8.0 and 10.0 ISM in whole mesh increments, are used. The Albemarle Sound IGNS is conducted from November through May, but results for American shad are only reported for January through May (from Zone II) because catches of these fish at other times are rare. The Albemarle Sound (with the exception of Currituck and Roanoke Sounds) is divided into six sample zones and each sample zone is divided into one-mile square quadrants (Figure 266). Quadrants within each zone are selected randomly. The sampling year is divided into two segments: November through February (fall/winter) and March through May (spring). Sampling methods remained the same during each sampling segment; however, areas fished, sampling frequency, and sampling effort were altered between the two segments.

During the fall/winter segment, two survey crews each fish one set of 12 nets (2.5 through 7.0, 8.0, 10.0 ISM) each sampling day. Each crew sampled each of the six zones once a month, providing 24 fishing days per month (12 per crew), and 96 days for the segment. A fishing day is defined as one crew, fishing the full set of nets, after a 24-hour soak time. Total gear soak time for each quadrant was 48-hours. Each 40-yard net, fished for 24-hours, equates to one unit of effort. Monthly effort for all mesh sizes was equal, except when nets are damaged or hampered by debris or weather. The maximum number of units of effort for the Fall/Winter segment is 2,304 units.

During the spring segment, gill net effort is concentrated to one zone, Zone II (Figure 267), in the western Albemarle Sound, near the mouth of the Roanoke and Chowan rivers. The shift to this zone was designed to increase the chance of intercepting the Albemarle/Roanoke striped bass migration to their spawning grounds on the Roanoke River. During the Spring segment, Zone II is sub-divided into northern and southern areas. The southern area, adjacent to the Roanoke River, receives effort at a 2:1 ratio south to north, based on the historical season abundance of mature striped bass (Harris et al. 1985). Quadrants sampled were randomly selected and fishing effort was conducted continuously, seven days a week, with two fishing days per quadrant. Total gear soak time for each quadrant was 48-hours. Only one set of nets was fished instead of two, for maximum daily effort of 24 units, and a maximum effort for the Spring segment of 2,208 units.

Index Development

The number of net panels at different mesh sizes (due to logistics, not design) and depths (8, 9, or 10 feet) varied within sampling days and potential catchability covariates (depth, weather conditions) varied among nets, so each net was considered an observation instead of all nets fished during a sampling day. Effort was defined as the product of the panel area and the total days fished (square foot net days). There was no spring sampling in 1990, so data from this year were dropped from the data set. Survey design was standardized in 1992 to fish equal number of mesh sizes during each sampling day, so data from 1991 were also dropped. There was relatively unbalanced sampling across mesh sizes in 1992, so these data were also dropped from the data set. Sampling occurs year round, but the data were subset to the months of January through May to capture the spawning run. The data were also subset to quadrant 2, the only quadrant sampled throughout the months of January through May. Quadrant 2 is subdivided into two strata, North and South, which are further subdivided into 10 (north) and 12 (south) 1-square mile spatial grids, respectively. There were twenty five years of data with averages of 1,141.5 positive observations per year and 61% positive observations per year.

A negative binomial GAM was used to estimate a standardized index of abundance accounting for variability in annual catchability effects. The final model included count of shad as the response variable and year, spatial grid, weather conditions, depth, and surface water temperature as covariates. The number of square foot net days was included as an offset variable. A smoothing function with basis dimension (i.e., k) of sixty was estimated for surface water temperature. AIC was used to select the final model type (GLM vs. GAM), covariates, and basis dimensions for smoothing functions. The final model converged with a dispersion statistic of 3.17, indicating the data were over-dispersed relative to model expectations. Given the over-dispersion, the stratified geometric mean catch rates were used for an index of abundance.

Abundance Index Trend
The index generally follows an increasing trend though the time series. Annual CVs average 0.11 over the time series (Table 220).

3.14.6.1.2 NCWRC Roanoke River Adult Spawning Area Electrofishing Area

NCWRC has sampled American shad on the Roanoke River spawning grounds (rkm 225) near Roanoke Rapids, NC, since 2000. Sampling is typically conducted once per week from March–June when American shad are on the spawning grounds. In 2000, however, catch and electrofishing effort data were combined for the year because sample date and site information were not available. A boat-mounted electrofishing unit (Smith-Root 7.5 GPP, 500–1,000V, 3.8–4.0A) was used to capture fish during daylight hours. In most years, two dip-netters were used, but only one dip-netter was used 2000–2004 and 2010–2011. Electrofishing samples have been conducted in the same area throughout the time series, but sampling protocols have changed over time. From 2000–2012, weekly sampling was concurrent with striped bass sampling and was typically conducted along two, approximately 1-km shoreline sites. In 2013–2017, however, American shad sampling was separated from striped bass sampling activities and protocol was changed to include random selection of nine 500-m sample sites in the study area. These 500-m sites are located along the shoreline as well as in the mid-channel of the river. This change occurred in order to sample more of the available habitat and better characterize the spawning population. At each site, staff recorded electrofishing effort (seconds), water temperature (Celsius), dissolved oxygen saturation (%), dissolved oxygen concentration (mg/L), specific conductivity (µS/cm), salinity (ppt), pH, and Secchi depth (m). American shad were held in an aerated live well, measured for total length (TL mm), weight (g), and sex. Scales were taken from a subsample of fish and used for ageing during 2000–2010. Due to inaccuracies of scale ages determined through a joint workshop with NCDMF, NCWRC changed to otoliths for ageing American shad in 2011. Thus, otoliths were taken from a subsample of American shad of up to 10 males and 10 females per 1-cm length bin from 2011–2017. Additionally, otoliths were also taken in 2004 for comparison with scale ages of the same fish. In most years, otoliths used for ageing came from broodfish that were collected independently from the spawning stock survey to reduce the number of fish sacrificed for ageing. These broodfish were collected from the same sampling area as the weekly electrofishing and should be considered part of the same spawning stock. Lastly, known ages of hatchery-origin American shad as determined by PBT analysis are available for 2013–2017.

Index Development
Each electrofishing collection was treated as an independent observation and effort was defined as minutes of active electrofishing. There were 17 years of data with averages of 30 positive observations per year and 90.8% positive observations per year. Variables available for potential inclusion in the standardization model included sampling year (discrete), number of netters on the vessel (discrete), water temperature (continuous), day of year (continuous), and seven day average daily discharge at USGS Station 02080500 (Roanoke River at Roanoke Rapids, NC; https://waterdata.usgs.gov/nc/nwis/inventory/?site_no=02080500&agency_cd=USGS; continuous). Electrofishing effort, in minutes, was used as an offset term in all models to

account for variability in sampling effort on catches of adult American Shad. Model types considered included NB GLM, NB GAM, ZINB GLM, and ZINB GAM. All GAM models were fit assuming cubic regression splines for continuous variables and with a gamma penalty of 1.4 for all models (NB GAM & NB GAMM) and sub-models (ZINB GAM, ZINB GAMM). AIC was used to select the final model type, covariates, and basis dimensions for smoothing functions. Prior to model fit, we excluded any collections missing covariate data and made prior to January 1, 2000.

The best fit model, based on AIC, was a ZINB GAM. The final model included the catch of adult American Shad as the response variable and the variables sampling year (count sub-model only), water temperature (binary (EDF = 3.60) and count (EDF = 2.70) sub-models), average daily discharge (binary (EDF = 1.00) and count (EDF = 3.14) sub-models), and day of year (count (EDF = 3.39) sub-model only); the log of effort in minutes was included as an offset term in both sub-models.

The final model suggests the catchability of adult American Shad is affected by day of year, water temperature, and average daily discharge of the Roanoke River. Catches of adult American Shad increase as water temperature increases to approximately 15.0^{o}C, though catches decline steeply at higher temperatures. There is also evidence average daily discharge of the Roanoke River, as measured at Roanoke Rapids, NC, strongly influences the catchability of adult American Shad in the survey, with catches showing a parabolic relationship with daily discharge, being maximized when daily discharges are approximately 10,000 to 20,000 ft^{3}second^{-1}. Catches also exhibit a parabolic relationship with day of the year, being maximized around day 125-130.

Abundance Index Trend

The standardized index follows the same trend as the arithmetic mean catch rates for most years. The standardized index generally remains stable to slightly increasing, with noise, from survey inception through the early-2010s; since around 2012 there is a decreasing trend in relative abundance of American Shad as measured by this survey. Annual CVs averaged 0.20 over the time series (Table 221).

3.14.6.2 Young-of-Year Fishery-Independent Data Sources

3.14.6.2.1 NCDMF Albemarle Sound Beach Seine/Chowan River Juvenile-Seine Survey

The NCDMF conducts two juvenile beach seine surveys in the Albemarle Sound area (Figure 268); although the surveys were designed to monitor river herring and striped bass, both surveys capture American shad. The river herring beach seine survey has been conducted in the Chowan River and Albemarle Sound area to monitor blueback herring (*Alosa aestivalis*) and alewife (*Alosa pseudoharengus*) abundance since 1972. This survey was designed to index annual relative abundance of juvenile blueback herring and alewife; however, American shad captured in the survey are also recorded. Eleven stations are sampled bimonthly from June through October, with an index of abundance historically only being calculated from the first pull. The eleven stations are designed to specifically sample juvenile river herring habitat and may not be suitable for juvenile American shad. Adequate sampling of the areas used by juvenile American shad has not occurred, nor the specific areas determined. The ASFMC (2007) benchmark assessment for American shad considered these data for a relative abundance index for American shad, but, due to the consistently low level of catch since 1972, the authors felt that the survey did not adequately reflect the true abundance of juvenile American shad and should not be used for management.

The striped bass (*Morone saxatilis*) beach seine survey has been conducted in the western Albemarle Sound to monitor juvenile striped bass since 1993. This survey was designed to determine the critical point (egg, larval, or early juvenile stage) that was limiting spawning success resulting in near zero catches in the juvenile trawl surveys for striped bass. The survey established nine stations in the near-shore nursery areas of the western Albemarle Sound, where early stage juvenile striped bass would be settling after larval metamorphosis from spawning grounds on the Roanoke River. The stations are sampled once a week, for six weeks (starting the first week in June). American shad captured are recorded but not consistently until 1995. Following the six weeks of sampling, the stations are sampled bimonthly through October. Previous to this assessment, this survey had not been evaluated as a potential data source for relative abundance of American shad in the Albemarle Sound.

Biological and Environmental Sampling

Seine stations are sampled with a 60-foot bag (18.5 m) seine with 0.25-inch mesh bag, with a single haul considered one catch-per-unit-of-effort (CPUE). Samples are sorted to species, and up to 30 individuals of each alosine species present were measured to the nearest millimeter FL and TL. Other species are subsampled and length measurements recorded or species documented. Environmental parameters for prevailing weather and water quality such as Secchi depth (m), air temperature (C), water temperature (C), salinity (ppt), dissolved oxygen (mg/L), conductivity (mU), and pH are also recorded. Reporting of environmental parameters oxygen were not consistent until 1997.

Evaluation of Survey Data

The histroical, nominal index of abundance for shad YOY is an arithmetic mean catch per haul from the 11 river herring core stations in Albemarle Sound and Chowan River. Beginning in 1993, two of these stations were sampled more than once per month and after 2007, all stations were sampled at least twice a month. To account for the sampling discrepancy, only the first haul of each month has been used in the annual arithmetic mean calculation. As mentioned in the 2017 Sustainable Fishery Plan, this survey index is deemed an unreliable indicator of juvenile American shad abundance by the state of North Carolina. It has not been used in any previous stock assessment.

In this assessment, the entire Albemarle seining data set from the river herring and striped bass surveys was refined to include the best stations and timeframes where YOY shad have been observed. Then it was investigated if all but the first haul of the month for index calculations should be dropped. Finally, it was evaluated if generalized linear modeling methods can provide reliable estimates of relative abundance to use in the stock assessment.

In an evaluation of catch rates and percent positive tows in all seining stations provided in the data set (76 different stations), different patterns emerged. First, four of the 11 traditional river herring stations are not great stations to index shad YOY. These stations are all located east of the Albemarle Sound Bridge, and each has less than 3% positive hauls over the entire time series. Catch rates of the seven-remaining core 'herring' stations range between 0.3 and 1.67 shad per haul, and all have over 7% positive hauls in the time series.

A summary by station analysis also showed there to be seven non-core 'striped bass' sites west of the bridge that encounter shad YOY at equal or higher rates than the seven core 'herring' stations. These stations are in the western portion of Albemarle Sound and added to the seining schedule in 1993 to supplement core sampling and to specifically target striped bass YOY. Catch rates at these striped bass YOY stations range from 0.43 to 7.7 shad per haul and percent positive tows range from 9.4% to 20.7%. The inclusion of these stations requires a tradeoff. On one hand, adding more representative areas in the region doubles annual sample size. On the other, it cuts the time series in half. For an index standardization that incorporates covariates, the decision to include these new stations is an easy one as many of the environmental variables such as salinity, prevailing weather, and dissolved oxygen were not consistently reported until 1997. Moving forward, the seven 'herring' and seven 'striped bass' stations starting in 1996, due to the availability of covariate data used in GLMs (see below), are considered the best stations for an index of American shad abundance.

To calculate an index of abundance, it needs to be determined which monthly hauls to include. As mentioned earlier, the traditional index only includes the first haul of every month. An evaluation of catch per monthly haul for the three herring sites with the highest catch rates showed minimal patterns. There did not appear to be a relationship between catches in the first haul of the month versus the ensuing hauls, and more importantly, the removal of other monthly hauls removed some large catches from the data set. The additional monthly hauls in the data set were included and, because number of hauls differs by month, 'MONTH' was kept as a factor in the initial GLM models.

Other initial covariates examined in generalized linear model development were year, water temperature, salinity, and cloud cover (less than 50% or more than 50%). This full list of covariates was initially run through the following models: Poisson GLM, a negative Binomial GLM, and a Zero-Inflated Negative Binomial GLM. Generalized additive models were not examined due to the high number of zero hauls (85%). The Zero-inflated Negative Binomial GLM model was determined the best initial model based on comparisons of the dispersion parameter and AICs. A step-wise evaluation of covariates was then performed for the zero-inflated negative binomial model. Water temperature, salinity, month and cloud cover were all shown to significantly impact catch rates and presence. The best performing model was Counts ~ Year + water temperature + salinity | salinity + cloud cover + month. Based on the importance of the final model covariates on catch and presence, as well as model CVs lower than the nominal index, this ZINB modeled index was considered to be the best index of relative abundance for this survey. However, this index should be used with caution as annual model CVs and proportions of zero hauls remain large.

Abundance Index Trend

The catch rates from 1996 to 2017 are variable with a slight increasing trend (Table 219, Figure 269). Of note, is the exceptionally high catch rate in 2016 due to large catches of shad in the striped bass stations. Because catch rates were consistent among stations and monthly hauls, these catches are likely to accurately reflect the relative abundances in that year.

3.14.6.2.2 NCWRC Roanoke River Juvenile-Electrofishing Survey

NCWRC staff has conducted annual juvenile American shad sampling in the lower Roanoke River since 1999. The sampling objective during the initial four years was to collect as many juveniles as possible to evaluate hatchery contribution by looking for OTC marks. In 2004, methods were standardized to allow calculation of a potential juvenile index. Weekly boat-electrofishing is conducted in the lower Roanoke River near Plymouth from September to November each year. One fixed station adjacent to a paper mill is sampled each night of the survey period for 6–12 weeks each year. Sampling begins 30 minutes after sunset so that juvenile American shad are concentrated around the lights from the paper mill facility.

These catch rate data are not considered representative of interannual abundance changes and were not used in the assessment for abundance trend analyses (Table 16).

3.14.7 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance, mean length, and mean length-at-age. Total mortality estimators were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. A statistical catch-at-age model was also used to evaluate abundance and mortality. Details for all methods except the statistical catch-at-age model are provided in section 2. Details for the statistical catch-at-age model are provided below.

3.14.7.1 Statistical Catch-at-Age Model

An Age Structured Assessment Program (ASAP) statistical catch-at-age model was developed for American shad in the Albemarle Sound. ASAP is an age-structured model that uses forward computations, assuming separability of fishing mortality into year and age components, to estimate population sizes given observed catches, catch-at-age, and indices of abundance. Various components of the catch may be treated as separate fleets. The separability assumption is partially relaxed by allowing for fleet-specific computations and by allowing selectivity-at-age to change in blocks of years. Weights are inputted for different components of the objective function, which allows for configurations ranging from relatively simple age-structured production models to fully parameterized statistical catch-at-age models. The objective function is the sum of the negative log-likelihood of the fit to various model components. Fishery and survey age compositions are modeled assuming multinomial distributions, while most other model components are assumed to have lognormal error distributions. Specifically, lognormal error is assumed for: total catch in weight by fleet, aggregate survey indices, and annual deviations in fishing mortality. Recruitment deviations are also assumed to follow a lognormal distribution, with annual deviations estimated as a bounded vector to force them to zero. Additional technical details can be found in the technical manual (Legault 2012).

3.14.7.1.1 Input data

The ASAP model tracked age-specific, but sex-aggregated, abundance at annual time steps from 2000-2017. Prior to 2000, age data were not available. The model incorporated ages 0-8$^+$ with age-8 considered a plus group. Across the time series, the plus group represented 3.8% of the total catch.

All age length keys (ALKs) were constructed using multinomial logistic regression (Gerritsen et al. 2006; Stari et al. 2010, Weakfish Stock Assessment Subcommittee 2015, Black Sea Bass Stock Assessment Subcommittee 2016) using the multinom function in the nnet package for R (Ripley 2016). ALKs were constructed whenever sample size for a given year and sex combination exceeded 30. This was based on exploratory work conducted during the 2016 black sea bass stock assessment. All ALKs were based on fork length and scales. When fork length was not available, total length was converted to fork length (see section 1.1.3.1). All available data from NCDMF surveys was used to create keys. Scale age-length keys (ALKs) for both males and females were constructed for each year from 2000-2017.

Fishery catches

Total commercial landings were assumed to be representative of total catch. Recreational harvests are thought to be low, and it was further assumed that discards and oceanic catches are minimal. This assumption could bias estimates of abundance and fishing mortality if unknown removals are not negligible.

Commercial fishery landings-at-length was provided directly by North Carolina. These catch-at-length data are based on length sampling from the gill net fishery only for 2000-2017; pound nets generally represented a relatively small proportion of the landings. Therefore, it was assumed that the observed length proportions were representative of individuals caught in both gill nets and pound nets, and that selectivity of American shad to these gears are the same.

Fishery catch-at-age (CAA) was calculated by applying the sex and year-specific ALK to sex and year-specific commercial catch number-at-length provided directly by North Carolina. Catch weight-at-length was then calculated by multiplying calculated weight-at-length, from NCDMF commercial data, by catch number-at-length. Catch weight-at-length was then multiplied by the appropriate year and sex-specific ALK to determine catch-at-age in weight (CAW). Weight-at-age was then determined by dividing the CAW matrix by CAA. This time series of empirical weight-at-age estimates represented the weight-at-age of the catch in the model.

Indices

Available indices for potential incorporation into the ASAP model included the Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey index, Albemarle Sound Commercial CPUE, Albemarle Sound IGNS index, and Roanoke River Adult Spawning Area Electrofishing Survey index. The Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey index, Albemarle Sound Commercial CPUE and Albemarle Sound IGNS index were included in the final model. The Roanoke River Adult Spawning Area Electrofishing Survey index was not included because it does not capture fish spawning on the Chowan River, and was therefore thought to not be fully representative of the Albemarle Sound. In contrast, the Albemarle Sound IGNS intercepts individuals from both spawning rivers.

Length composition data were available for the Albemarle Sound IGNS and sex composition data were available for 2004 onward. Accordingly, catch-at-age proportions from the Albemarle Sound IGNS survey were developed for 2004 onward using available survey length samples to calculate sex-specific catch-at-length, and then the developed age-length keys to convert catch-at-length to catch-at-age for each sex.

The Albemarle Sound IGNS is completed from November through May, but beginning in March all effort occurs in one quadrant located at the mouth of the Roanoke and Chowan Rivers; this is the primary quadrant used in NC's sustainability plan. Accordingly, the timing of this survey was set to March in the ASAP model. The Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey occurs annually from June-October; therefore, survey timing was set to August. The timing of the CPUE index was set to March because 69% of the landings occurred in March from 2000-2017 with 30% from adjacent months (February and April). Since 2014, the commercial season for the Albemarle Sound has been constrained to March 3-24, due to triggers being exceed in the sustainability plan.

Biological assumptions

Sex-specific Von Bertalanffy growth and length-weight parameters for the southern iteroparous region were used to develop time-invariant estimates of weight-at-age for each sex (Sections 1.1.5 and 1.1.3.2). The Von Bertalanffy growth parameters were estimated from age data derived from scale ageing and were: t_0=-0.322, K=0.440, and L_∞=495 mm for females, and t_0=-0.344, K=0.459, and L_∞=453 mm for males. The resulting female weight-at-age estimates were inputted as spawning stock weight-at-age in the ASAP model. An average of sex-specific weight-at-age estimates were inputted as the stock (combined sexes) weight-at-age.

Natural mortality was assumed to be both time- and age-invariant and set to 0.47, which represented the southern iteroparous estimate derived using the approach of Then et al (2015) (Section 1.1.8).

A female maturity-at-age ogive estimated from the mortality-based method for southern iteroparous fish (Section 1.1.7) was used to calculate spawning stock biomass. Spawning was assumed to occur April 1 and resulting spawning stock biomass estimates represented females only.

3.14.7.1.2 Model configuration

To develop the final ASAP model, multiple model configurations were explored. Configurations examined fell into two general categories: 1) investigation of alternative configurations to evaluate whether model diagnostics and fits to input data improved, and 2) sensitivity analyses to evaluate robustness of model outputs to varying assumptions. For each configuration, the annual CVs associated with each index were iteratively adjusted to match the specified uncertainty of the index with the level of precision estimated by the model. In particular, the annual CVs were iteratively adjusted until the resulting root mean square error (RMSE) approached the confidence bounds associated with a N(0,1) distribution for the index's sample size. These CVs were adjusted by adding a constant to each year to preserve interannual variation in the CVs. Likewise, effective samples sizes (ESS) for age composition data sets were iteratively adjusted using the RMSEs and comparisons between pre-specified and estimated ESSs (Francis 2011, McAllister and Ianelli 1997). Across all configurations, the use of likelihood penalties for fishery or survey selectivity, deviation in first year abundance or recruitment deviation parameters were minimized.

The final ASAP model assumed:

- One fishing fleet
- Time-invariant fishery selectivity for ages 3-8$^+$ that followed a logistic function
- Flat-topped Albemarle Sound IGNS selectivity with age-8$^+$ selectivity fixed at 1, age-0 and age-1 selectivity fixed at 0, and remaining age-specific selectivity parameters freely estimated
- Selectivity of the fishery-dependent CPUE index was linked to that of the fishing fleet
- Recruitment parameterized as a mean plus annual deviations with steepness fixed at 1 and was therefore not a function of a stock recruitment relationship

Alternative configurations explored to examine model sensitivity included:

- Likelihood profile across varying assumed time- and age-invariant natural mortality rates
- Maturity estimates derived from the cumulative proportions and Maki methods
- 2016 Albemarle Sound Beach Seine/Chowan River Juvenile-Seine Survey index estimate replaced with 5-year average (replaced observed value of 19.78 with the 2011-2015 average value of 1.45)
- Two fishery selectivity blocks with second block beginning in 2013
- Time and age-invariant natural mortality corresponding to minimum of likelihood profile
- Leave one out analysis where each index was sequentially dropped from the model

MCMC simulations were completed to estimate the posterior distributions of total biomass, spawning stock biomass and fishing mortality; simulations were conducted using a chain of an initial length of 2,000,000 with every thousandth value saved to result in a final chain length of

2,000. From the MCMC distributions, 90% posterior probability intervals (PIs) were calculated to provide a measure of uncertainty associated with the point estimates.

A retrospective analysis was conducted to examine the stability of model estimates as years of data were removed from the end of the time series. Retrospective peels were made for five years in total, the 2013-2017 terminal years.

3.14.8 Results

3.14.8.1 Abundance Trends

3.14.8.1.1 Power Analysis

Three abundance indices for American shad were developed for this system that contained estimates of PSE, the Albemarle Sound IGNS (median PSE = 0.112), the Roanoke River Adult Spawning Area Electrofishing Survey (median PSE = 0.167), and the Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey (median PSE = 0.430). The first two are currently used for sustainability targets and monitoring in the SFMP, while the latter is not.

Of these surveys, the Albemarle Sound IGNS exhibits sufficient power to detect a 50% change in American shad abundance in 10 years, while the Roanoke River Adult Spawning Area Electrofishing Survey is only able to detect a 50% decrease at the desired 0.80 power level (Table 25). The Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey, with its large median PSE, exhibits very little power to detect a 50% change in abundance over 10 years.

3.14.8.1.2 Mann-Kendall Analysis

Albemarle Sound (JAI)

JAI values in the Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey remained fairly stable since 1996, with noticeable peaks in 2003 and 2016, the latter being considerably higher than all other observed values (Figure 269). Mann-Kendall analysis found an increasing trend over the entire time series and for the years since 2005.

Albemarle Sound (FI CPUE)

Two fishery-independent indices were provided for the Albemarle Sound system. When plotted, the Albemarle Sound IGNS showed a general increase from 1993 forward, with peaks in 1997, 2002, 2008, and 2013 (Figure 270). Mann-Kendall trend analysis found an increasing trend over the full time series, but no trend for the period from 2005 forward. A plot of the Roanoke River Adult Spawning Area Electrofishing Survey showed no apparent trend over time (Figure 271) and Mann-Kendall analysis did not detect a trend for either time period.

Albemarle Sound (FD CPUE)

North Carolina submitted data for a Commercial CPUE survey for the Albemarle Sound for the years between 1994 and 2017. A steady increase in index values over the time series were apparent when plotted over time (Figure 272). Mann-Kendall trend analysis detected an increasing trend in the index for both the full time series and the period from 2005 forward.

3.14.8.2 Mean Length Trends

3.14.8.2.1 Albemarle Sound

Plot of the mean total length for female and male American shad from a fishery-dependent commercial sampling program showed similar inter-annual changes in mean length of both sexes (Figure 273) and the Mann-Kendall test found a significant decline for both sexes since the 1970s. A plot of the fishery-independent data from the Albemarle Sound IGNS showed no discernable trend of a change in mean length of American shad since 2004 (Figure 274) and the Mann-Kendall test was not significant. Four additional data programs were submitted, but excluded from analysis because the time series was too short.

3.14.8.2.2 Roanoke River

The NCWRC submitted American shad length data from the Roanoke River Adult Spawning Area Electrofishing Survey. Lengths are available from 2000-2017. A plot of mean lengths (Figure 275) and Mann-Kendall trend analysis found no trend in mean lengths of either sex.

3.14.8.3 Mean Length-at-Age Trends

3.14.8.3.1 Albemarle Sound

Mean length-at-age data using scales were provided from three sampling programs, Albemarle Sound commercial sampling program, the Albemarle Sound IGNS, and the Roanoke River Adult Spawning Area Electrofishing Survey (Table 227). Aged fish ranged between ages 3 and 9 for both sexes and only males were present in the Roanoke survey. Mann-Kendall Trend analysis detect a decrease in mean length-at-age over time for multiple ages of males in females in both sampling programs in the Albemarle Sound. A single increase in mean length-at-age occurred for age 7 male American shad in the Roanoke River.

3.14.8.4 Total Mortality Estimates

Age composition data from length compositions and age-length keys derived from scales collected during the Roanoke River Adult Spawning Area Electrofishing Survey, Albemarle Sound IGNS, and fishery-dependent commercial sampling program were used for mortality estimates. The Roanoke River Adult Spawning Area Electrofishing Survey age composition data were developed from survey-specific age-length keys while the Albemarle Sound IGNS and fishery-dependent commercial sampling program age composition data were initially developed for the SCAA model using shared age-length keys. There were some limited otolith-derived data available from the Roanoke River Adult Spawning Area Electrofishing Survey, but these data did not meet all criteria for any period of three consecutive years and were therefore dropped from the analysis. Data from the Roanoke River Adult Spawning Area Electrofishing Survey met all criteria (see Section 2.6) for 6 and 10 years between 2000 and 2010 for females and males, respectively (Table 32). Data from the Albemarle Sound IGNS met all criteria for 14 years between 2004 and 2017 for both sexes (Table 32). Data from the fishery-dependent commercial sampling program met all criteria for 16 and 5 years between 2001 and 2017 for females and males, respectively (Table 32).

Mortality estimates vary between monitoring programs, particularly between the Roanoke River Adult Spawning Area Electrofishing Survey and the other programs for females and among all programs for males (Table 33 and Figure 276). Female mortality estimates from the Albemarle Sound IGNS and fishery-dependent commercial sampling program were generally similar, varying without trend through the early 2010s before declining to lower levels in recent years. There was an uptick in mortality in 2017. The three-year average female estimates from both monitoring programs in 2017 (0.65 and 0.83 for the fishery-dependent commercial sampling program and Albemarle Sound IGNS, respectively) were below the threshold (Table 33 and Figure 276). The average standard errors for these estimates were 0.58 (fishery-dependent commercial sampling program) and 0.48 (Albemarle Sound IGNS). Female mortality estimated from the Roanoke River Adult Spawning Area Electrofishing Survey was generally lower than estimated from the other monitoring programs in the early 2000s and is unavailable in recent years. Male mortality estimated from the Roanoke River Adult Spawning Area Electrofishing Survey and fishery-dependent commercial sampling program was generally higher than mortality estimated from the Albemarle Sound IGNS. Male mortality estimated from both the Roanoke River Adult Spawning Area Electrofishing Survey and Albemarle Sound IGNS follow similar declining trends through the late 2000s. Male mortality estimated from the Albemarle Sound IGNS is relatively stable in the most recent years and unavailable from the other monitoring programs.

3.14.8.5 Statistical Catch-at-Age Model

3.14.8.5.1 Final ASAP model

The contribution of each data set to the total likelihood is detailed in (Table 222). Aggregate fishery catches predicted by the model closely followed observed catches (Figure 277). RMSEs for all indices fell close to the confidence bounds associated with a N(0,1) distribution for the corresponding sample size of the index (Figure 278). For the Albemarle Sound IGNS and Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey indices, the final RMSEs were achieved by inputting the annual empirical CVs plus constants of 0.15 and 0.45, respectively, in each year. Empirical CVs were not available for the CPUE index; therefore, an annual CV of 0.25 was assumed. Accordingly, index values predicted by the model generally followed observed temporal trends and strong patterning of the residuals was not apparent (Figure 279-Figure 281). For the fishery age composition data, some patterning in the residuals of ages 3, 4, 6 and 7 was evident, especially for 2013 onward (Figure 282). While large residuals were apparent for some year/age combinations, strong patterning in the Albemarle Sound IGNS residuals was not apparently (Figure 283).

Over the modeled time series, spawning stock biomass increased from a low of 25.1 metric tons in 2000 to a high of 63.3 metric tons in 2009, and has averaged 50.6 since 2010 (Table 223, Figure 284). Terminal year SSB was estimated to be 49 metric tons with a corresponding 90% confidence interval of 39.6-66.0 metric tons. Recruitment estimates indicated a very strong year class in 2016 (Table 224, Figure 285); however, this 2016 year class is driven entirely by the 2016 YOY index value because this cohort will not become even partly vulnerable to the IGNS until 2018 and to the fishery until 2019 (Table 225). Accordingly, ages 1-2 abundance and the strong increase in total stock biomass in 2017 should not interpreted (Table 224, Figure 286).

Estimated fully-recruited fishing mortality generally decreased over the time series, ranging from a high of 3.96 in 2003 to a low of 0.35 in 2016 (Table 226, Figure 287). Terminal year fishing mortality was estimated to be 0.48 with a corresponding 90% confidence interval of 0.30-0.67. While fishing mortality estimates were very high in some years, only the plus group (age-8^+) experienced the full mortality because it was the only age-class estimated to be fully recruited to the fishery (Table 225, Figure 288). A comparison of estimated fishery selectivity and inputted maturity values indicated that with the exception of the plus group, the proportion vulnerable to the fishery was less than the proportion mature (Figure 288). Across all ages, the proportion vulnerable to the Albemarle Sound IGNS was greater than the proportion vulnerable to the fishery.

A retrospective analysis indicated a tendency to underestimate fishing mortality and overestimate spawning stock biomass as the terminal four years were omitted (Figure 289). However, the fifth peel switched directions and exhibited an overestimation in fishing mortality and an underestimation in SSB. The 5-year Mohn's rho value for SSB, average fishing mortality and recruitment were -0.18, 0.10 and 0.73, respectively.

3.14.8.5.2 Sensitivity analyses

The final ASAP model was rerun with alternative, constant natural mortality values ranging from 0.10 to 1.60 to assess the consequences of assuming a natural mortality rate of 0.47. The minimum value of the likelihood profile corresponded to a natural mortality of 0.90 (Figure 290). Accordingly, an additional sensitivity run was completed assuming M = 0.90.

Sensitivity runs for alternative model assumptions of maturity, natural mortality, fishery selectivity blocks and the 2016 YOY index value indicated similar temporal trends in SSB; however, the scale of SSB varied considerably (Figure 291). Alternative fishery selectivity blocks and use of an assumed average value for the 2016 YOY index resulted in SSB estimates within the 90% probability intervals of the final ASAP run. However, the magnitude of estimated SSB increased as the cumulative proportion and Maki estimates were assumed for maturity and as natural mortality was increased to 0.90.

With the exception of the run with the alternative 2016 YOY index value, all runs indicated a strong increase in January-1 biomass at the end of the time series (Figure 292). Accordingly, this sensitivity analysis further supports that the predicted increase in total biomass at the end of the time series is driven solely by the YOY index. Therefore, this increase should not be interpreted because these fish have not recruited to the fishery and the strong year class suggested by the 2016 YOY index value is not yet apparent in the adult data sets.

As with SSB, temporal trends in fishing mortality were generally consistent across sensitivity runs (Figure 293). Because the ASAP model did not assume a relationship between spawning stock biomass and subsequent recruitment, fishing mortality estimates did not change with alternative maturity assumptions. Assuming an average value for the 2016 YOY index or creating two temporal blocks for fishery selectivity generally increased the magnitude of fishing mortality estimates, where assuming a natural mortality of 0.9 generally decreased the magnitude of estimated fishing mortality. However, fishing mortality estimates from all sensitivity runs fell within the 90% probability intervals of the final ASAP model.

A 'leave-one-out' analysis was completed to demonstrate the influence of each individual index on resulting estimates of SSB and fishing mortality (Figure 294). The ASAP model did not converge when the YOY index was omitted; this result was to be expected because the YOY index was the only time series that provided information on the youngest age classes. Temporal trends in SSB and F were generally robust to omission of the Albemarle Sound IGNS or commercial CPUE indices, and resulting estimates from these sensitivity runs generally fell within the 90% probability intervals of the final ASAP model. However, omission of the Albemarle Sound IGNS index eliminated the increasing trend in SSB at the end of the time series.

3.14.8.5.3 Reference points

The stock assessment subcommittee selected the SBPR reference point of 40%. Accordingly, $F_{40\%}$ was estimated to be 1.71 using the final ASAP model. Similar to estimated fishing mortality rates, the comparatively high value for this $F_{40\%}$ reference point is a function of the low selectivity on most age classes; when fishing at $F_{40\%,}$ the realized fishing mortality on ages 0 through 7 would be notably less than 1.71.

Long-term projections were completed to estimate the spawning stock biomass associated with $F_{40\%}$. Projections were made from 2000 estimates of numbers-at-age that resulted from the MCMC analysis of the final ASAP model. One hundred population simulations, each of 100 years, were completed for each of the 2000 numbers-at-age estimates resulting from the MCMC.

Recent five-year averages for catch weight-at-age estimates were used for projection inputs; other weight-at-age inputs were time-invariant. Because the final model was parameterized with only one time block for fishery selectivity, the point estimates from the final ASAP model were used in projections. The harvest scenario for all years was set to $F_{40\%}$. Time-invariant natural mortality and maturity were both set to the values assumed in the final ASAP model.

Recruitment was modeled by sampling from an empirical cumulative density function derived from the 2000-2014 recruitment estimates of the final ASAP model. Accordingly, estimated reference points are reflective of recent productivity and not potential historical productivity that may have occurred prior to the first modeled year (2000). The recruitment estimates from the final three years of the modeled time series (2015-2017) were not included because they had high CVs and were not informed by fishery catches. The average spawning date was specified as April 1st.

An average of the final 10 years of predicted stock biomass estimates from the long- term projections was used to define the spawning stock biomass biological reference point ($SSB_{40\%}$) associated with the $F_{40\%}$ of 1.71. The final estimate of $SSB_{40\%}$ (with 90% confidence intervals) equaled 42 metric tons (30 – 59 metric tons). A phase plot of temporal trends in SSB and fishing morality in relation to these reference points is presented in Figure 295. The Albemarle Sound stock was considered overfished if the SSB in the terminal year of the model (2017) was below the $SSB_{40\%}$ reference point of 42 metric tons. Likewise, overfishing was considered to be occurring if the fishing mortality in the terminal year was above the $F_{40\%}$ reference point of 1.71.

3.14.8.6 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Albemarle Sound System, habitat estimates were based on information from the Chowan River and Roanoke River. Current unobstructed habitat area for the Albemarle Sound System represents 58.92% of the historical habitat extent (66.85 of 113.46 square kilometers).

3.14.9 Stock Status and Conclusions

The SAS selected the SCAA model as the preferred method (over total mortality estimators) due to its use of integrated data sets on relative abundance, fishery removals and age proportions in both the fishery and gill net survey.

Mortality

The stock is not experiencing overfishing, as the terminal year fishing mortality in 2017 was 0.49 (90% CIs of 0.30-0.67), which is below the $F_{40\%}$ threshold (1.71).

There was a declining trend in female mean length from a long-term data set (1970-2017), but no trend from two additional short-term data sets (2001-2017, 2004-2017) was detected. There were positive trends detected in YOY abundance since 1998 and since 2005.

Abundance

The stock is not overfished, as the terminal year spawning stock abundance in 2017 was 49 metric tons (90% CIs of 39.6-66.0 metric tons) which is above the $SSB_{40\%}$ threshold (42 metric tons).

3.15 Tar-Pamlico

The Tar-Pamlico watershed is the fourth largest in North Carolina encompassing 14,090 square km (Figure 263) and resides entirely in North Carolina. From its headwaters in Person County, the Tar-Pamlico watershed is drained by 3,790 km of tributaries along its 290 km main-channel length to Pamlico Sound near the confluence of the Pungo River (NCDWQ 1999). River reaches upstream of Washington, North Carolina are designated as the Tar River and are primarily freshwater, while the reach below Washington, referred to as the Pamlico River, has characteristics of an upper estuary. Sixteen counties and six large municipalities (Washington, Greenville, Tarboro, Rocky Mount, Henderson, and Oxford) are represented within the basin. Main stem headwater reaches and tributaries are located within the outer piedmont physiographic region and are characterized by low flows during dry seasons due to minimal groundwater discharge (NCDWQ 1999). However, since the majority of the basin is located within the coastal plain, these waters are largely characterized by slow flowing, low gradient, brown and Blackwater streams with extensive floodplains often comprised of bottomland hardwood forests and marshes.

3.15.1 Habitat Description

From its headwaters in the North Carolina Piedmont the Tar River flows 288 km in a southeasterly direction before emptying into the Pamlico River at sea level. The Tar River drainage basin is approximately 802,893 ha. The principal tributaries of the Tar River, as it is ascended, are Tranters Creek, Town Creek, Fishing Creek, and Swift Creek. The Pamlico River is actually a continuation of the Tar River with the name change occurring at the US 17 bridge near Washington, North Carolina. It flows southeasterly about 53 km and empties into the Pamlico Sound about 51 km west of Ocracoke Inlet. The Pamlico River drainage basin is approximately 315,967 ha. The principal tributaries of the Pamlico River, in addition to the Tar River, include Pungo River, Rose Bay, Swanquarter Bay, Juniper Bay, Chocowinity Bay, Broad Creek, Bath Creek, Blount Creek, Durham Creek, North Creek, Goose Creek, South Creek, and Upper Goose Creek (Marshall 1976).

3.15.1.1 Spawning Habitat Descriptions

Refer to section 3.14.1.2 for spawning habitat descriptions.

3.15.1.2 Hydropower Projects

Rocky Mount Mills Dam was constructed on the Tar River near the City of Rocky Mount in approximately 1816. The dam provided power for gristmill, sawmill, and textile industries. In 1949, hydro-electric turbines were installed, and the dam produced electricity in addition to the textile manufacturing (GEO 2019). The textile mill closed in 1996, but the hydropower operation continued through approximately 2013 (USEPA 2019). The current owners of the dam and associated hydropower facility plan to refurbish the turbines and resume power generation in the future. Operation for the benefit of fish spawning and providing fish passage will not be required because the dam is not regulated by FERC; however, the owners have been receptive to fish passage ideas and seem willing to cooperate with beneficial flows (Wilson Laney, USFWS ret., personal communication). Rocky Mount Mills Dam will continue to represent a barrier to American shad migration on the Tar River until its removal or development of fish passage.

3.15.2 Fishery and Management History

Refer to section 3.14.2 for regulatory, assessment, and SFMP summaries.

3.15.2.1 Tar-Pamlico River 2013-2017 SFMP

The two sustainability parameters selected for Tar-Pamlico River were female CPUE based on the NCWRC Tar River Adult Spawning Area Electrofishing Survey and female relative *F* based on the NCWRC Tar River Adult Spawning Area Electrofishing Survey. Exceeding the threshold for female CPUE or female relative *F* would trigger management action (NCDMF and NCWRC 2012).

Female CPUE (NCWRC Tar River Adult Spawning Area Electrofishing Survey): The female CPUE index based on the NCWRC Tar River Adult Spawning Area Electrofishing Survey was calculated as the number of fish per minute using data collected from March through May. Initial time series included data from 2000 to 2011 to calculate the 2012 threshold. Values were updated annually through 2017. The annual threshold was calculated as the 25th percentile (where 75% of all values are greater) of the female CPUE index. Management is triggered following three consecutive years of values below the 25th percentile (NCDMF and NCWRC 2012).

Female Relative *F*: Female relative *F* based on the NCWRC Tar River Adult Spawning Area Electrofishing Survey was calculated using commercial gill net landings of roe shad by all gear types from the Pamlico River and the female CPUE index from the Tar River Adult Spawning Area Electrofishing Survey. Since the electrofishing survey primarily occurs during March and April, only commercial landings from those months were used in the calculations. Initial time series included data from 2000 to 2011 to calculate the 2012 threshold. Values were updated annually through 2017. The annual threshold was calculated as the 75th percentile (where 25% of all values are greater) of the female relative *F* index. Management is triggered following three consecutive years of values above the 75th percentile (where 25% of all values are greater; NCDMF and NCWRC 2012).

3.15.2.1.1 Seasons and Creel Limits

The SFMP established an open commercial season from 15 February to 14 April for the Tar-Pamlico River, which remained unchanged for the duration of the plan (Table 214). Tar-Pamlico River recreational creel limits, 10-American shad within a 10-fish shad aggregate, established in the first year of the SFMP also remained unchanged for the duration of the plan and are listed in Table 215.

3.15.2.2 Tar-Pamlico River 2018-2022 SFMP

In 2017, the original SFMP underwent a mandatory 5-year review and survey data was updated through 2017. The objective of the review was to refine the calculations of the abundance indices and relative *F* estimates. The new plan was approved for management for 2018 through 2022 in October of 2017. The plan includes the same sustainability parameters of relative *F* and abundance indices, with two main changes to the calculations. Relative *F* is now computed by dividing commercial landings by a hind cast 3-year average of a survey index, whereas the previous plan used a centered 3-year average. Using a hind cast 3-year average was determined more appropriate, with the addition of 5-years of data, as it ensures the value of the final year in the time series (which can trigger management action) remains unchanged once calculated. The next change was that thresholds, for all sustainability parameters, are fixed using the time series for the available survey data through 2017. In the 5-year review of the original plan, there were concerns that the thresholds could slowly decline to extremely low levels without ever being exceeded because, thresholds were recalculated annually with the addition of another year of data. The following sustainability parameters and thresholds were approved for the Tar-Pamlico River and are in effect through 2022 (NCDMF and NCWRC 2017).

Female CPUE (NCWRC Tar River Adult Spawning Area Electrofishing Survey): The female CPUE index based on the NCWRC Tar River Adult Spawning Area Electrofishing Survey was calculated as the number of fish per minute using data collected from March through May from 2000-2017. The annual threshold was calculated as the 25th percentile (where 75% of all values are greater) of the female CPUE index for 2000-2017. Management is triggered following three consecutive years of values below the 25th percentile (NCDMF and NCWRC 2017).

Female Relative *F*: Female relative *F* based on the NCWRC Tar River Adult Spawning Area Electrofishing Survey was calculated using commercial landings of roe shad by all gear types from the Pamlico River and the female CPUE index from the Tar River Adult Spawning Area Electrofishing Survey. Since the electrofishing survey primarily occurs during March and April, only commercial landings from those months were used in the calculations. Relative *F* point estimates are computed by dividing commercial landings by a hind cast 3-year average of a survey index, data for 2000-2002 is contained in the first point estimate for 2002. Each consecutive point estimate in the time series is calculated from 3-years of data. The annual threshold was calculated as the 75th percentile (where 25% of all values are greater) of the female relative *F* index from the fixed time series 2000-2017. Management is triggered following three consecutive years of values above the 75th percentile (where 25% of all values are greater; NCDMF and NCWRC 2017).

Female relative abundance of American shad derived from the electrofishing survey in the Tar River has been relatively stable over the time series except for two notably high years in 2003 and 2004. The index was below the threshold in 2006, 2007 and 2009 but above the threshold in all other years (NCDMF and NCWRC 2017).

Estimates of relative *F* for female American shad derived from the electrofishing survey were below the threshold during 2003 to 2006. These estimates of female relative *F* exceeded the threshold in 2002, 2007, 2009, and 2012. The 2017 estimate is well below the threshold (NCDMF and NCWRC 2017).

3.15.2.2.1 Seasons and Creel Limits

The 2018-2022 SFMP maintained the open commercial season from 15 February to 14 April (Table 214) and recreational creel limits, 10-American shad within a 10-fish shad aggregate (Table 215), for the Tar-Pamlico River.

3.15.3 Anthropogenic Sources of Mortality and Productivity

American shad broodfish were collected from the Tar River to support the Roanoke River American Shad Restoration Program from 1998–2010. The collections resulted in mortality of

6,366 Tar River American shad that otherwise could have spawned and contributed to in-river year class production (Table 216).

3.15.4 Fishery-Dependent Data Sources

Refer to section 3.14.5 for fishery-dependent data background.

3.15.4.1 Commercial Fishery

3.15.4.1.1 Commercial Gear Restrictions

Since 2016 a statewide rule limits the amount of large mesh (4.0-inch and greater) gill net set in internal Coastal waters to no more than 2,000 yards per vessel. Prior to 2016 a former rule was suspended in the majority of internal Coastal waters as a result of sea turtle conservation measures to institute no more than 2,000 yards per vessel of 4.0–6.5-inch gill net in the Tar-Pamlico and Neuse systems. Additionally, in certain sections of the Tar-Pamlico and Neuse rivers, gill nets with a mesh size less than five inches must be attended at all times.

Also, it is unlawful to use gill nets of any mesh size in Joint Fishing Waters from midnight on Friday to midnight on Sunday each week (except for portions of Albemarle and Currituck sounds). These existing gill net measures have likely reduced American shad harvest since they have remained in effect since the spring 2012 fishing season and will remain in effect indefinitely.

3.15.4.1.2 Commercial Landings

Refer to section 3.14.5.1.2 for information on commercial landings.

3.15.4.1.3 Commercial Catch Rates

Catch rates are provided in Table 229. Refer to section 3.14.5.1.3 for information on commercial catch rates.

3.15.4.2 Recreational Fishery

A rotating creel survey occurred on the Tar, Neuse and Cape Fear rivers prior to 2012. A comprehensive creel survey was initiated in 2012 to identify and estimate recreational American and Hickory Shad effort and catch within these systems, which are collectively known as the Central Southern Management Area (CSMA). The CSMA was originally established for purposes of estuarine striped bass management and includes all internal Coastal, Joint, and contiguous Inland waters of North Carolina south of a line from Roanoke Marshes Point across to Eagle Nest Bay to the South Carolina state line. The areas surveyed in the CSMA include the Neuse, Trent, Tar-Pamlico, Cape Fear and Pungo rivers. The Neuse River basin drains over 6,200 square miles of land with over 3,000 miles of streams and rivers. The mouth of the main channel is six miles across – the widest in the United States. Over 1.3 million residents reside within this river basin. Major tributaries include Crabtree, Swift, and Contentnea creeks, along with the Eno, Little, and Trent rivers. Survey points included 45 boat ramps and fishing access points from Milburnie Park in East Raleigh to Lee's Landing on Broad Creek. The river was divided in three segments, with all access points in Goldsboro and above classified as the upper zone, sites on Contentnea Creek and downstream from Goldsboro to Core Creek were considered the middle zone, and those downstream from Core Creek, the lower zone. Prior to 2012, the Neuse River was comprised of only two zones with all sites above Contentnea Creek considered the upper.

The Tar-Pamlico River watershed drains over 5,500 square miles with over 2,400 miles of streams and rivers. Major tributaries include Cokey Swamp, Swift, Fishing, and Tranters creeks, and the 30-mile Pungo River near Belhaven, North Carolina – the main tributary in the lower basin. Access points surveyed on the Tar-Pamlico River include 19 boat ramps and access sites from Battle Park in Rocky Mount to the Quarterdeck Marina in Bath, NC. This system was divided into upper and lower zones, with sites upstream of Greenville, North Carolina considered the upper zone. The Pungo River was surveyed at the Leechville ramp (NC-264 bridge), the Belhaven NCWRC ramp, Wrights Creek NCWRC ramp, and Cee Bee Marina on Pungo Creek.

The Cape Fear River is the southernmost river within the CSMA and was included to target shad (American and hickory) beginning in 2013 (NCDMF and NCWRC 2017).

3.15.4.2.1 Sampling Procedures

Recreational fishing statistics from the CSMA were calculated through a non-uniform stratified access-point creel survey (Pollock et al. 1994). Site probabilities were set in proportion to the likely use of the site according to time of day, day of the week, and season. Probabilities for this survey were assigned based on observed effort from past years and direct observation by creel clerks. Morning and afternoon periods were assigned unequal probabilities of conducting interviews, with each period representing half a fishing day. A fishing day was defined as the period from one hour after sunrise until one hour after sunset. Monthly sampling periods for each river and zone were stratified accordingly, and all weekend and holiday dates along with two randomly selected weekdays were chosen from each week for sampling.

Tar-Pamlico River anglers in the upper zone were interviewed throughout the spring months (January-May), while anglers in the lower zone were interviewed year-round based on the evidence of a year-round fishery and no seasonal closures. Two creel clerks were assigned to this river, with one surveying the upper zone January through May and one clerk surveying the lower zone from January through December. The three zones within the Neuse River were covered with one creel clerk per zone. The lower zone was surveyed from January to December while middle zone surveys were conducted January-May and the upper zone surveys from February-May. The Pungo River was surveyed throughout the year with one creel clerk.

Returning fishing parties were interviewed by a creel clerk at the selected access point to obtain information regarding party size, effort, total number of fish harvested and/or released, primary fishing method, and location. Harvested fish were identified, counted, measured nearest mm fork length (converted to centerline length and total length for appropriate species), and weighed to the nearest 0.1 kg, while information on discarded fish was obtained from the angler to acquire the number and status of discarded individuals. The age structures were given to the Fisheries Management section of NCDMF for age determination. Creel clerks also obtained socioeconomic information from the angler, including age, state and county of residence, sex, ethnic background, marital status, number of individuals within household, and trip information and expenditures

3.15.4.2.2 Analysis

Samples were reduced to shad species effort and catch only. Results were stratified by river, access point, and time of day. Catch was defined as the sum of harvested fish and discarded fish. Discarded fish equaled the sum of fish caught in excess of creel limits (over-creel), legal-sized fish caught and released, and sub-legal fish returned to the water. Daily effort and catch for each river were calculated by expanding observed numbers by the sample unit probability (time of day probability divided by access area probability). Total catch estimates for the CSMA and catch estimates for each zone and type of day were calculated based on the Horvitz-Thompson estimator for non-uniform probability sampling as such:

$$C = \sum_{i=1}^{n} (c_i / p_i)$$

where a sample of number (n) un10-American shad within a 10-fish shad aggregate is taken, and the probability of the *i*th unit being in the sample is denoted by P_i (Pollock et al. 1994). Total effort over the CSMA and each individual zone and type of day were estimated in the same fashion, as were other extrapolated data. Approximate standard errors (SE) of the catch and effort estimates within zone and type of day were calculated according to:

$$SE = \sqrt{N^2 \left(\frac{s^2}{n} \right)}$$

where s^2 is the variance of the observations, n is the number of days sampled, and N is the number of days of that type available for sampling (Pollock et al. 1994). Estimated catch per unit effort (CPUE) values were obtained by dividing estimated catch by estimated shad spp. trips as well as angler hours (angler-h) in order to identify trends in fishing pressure and angler success. Size structure of shad spp. in harvests was described for each zone using length-frequency distributions of observed samples. Fishing party characteristics and methods used during shad spp. trips reported by anglers were documented by river and day type. The database was created using Access© and statistical analyses were performed with SAS 9.1©. Beginning in 2012, the Wildlife Resources Commission (WRC) Portal Access to Wildlife Systems (PAWS) was used to house these data and estimate effort and catch. NCDMF and NCWRC staff have been verifying calculations to ensure consistency with the previous work.

Catch rate data are not considered representative of interannual abundance changes and were not used in the assessment for abundance trend anlyses (Table 13).

The CSMA Creel Survey socioeconomic questionnaire included questions to identify characteristics of the shad spp. angling population. Demographics of anglers were reported according to age, residency, gender, ethnic background, marital status, and expressed as a percentage of the total angling population throughout the CSMA. Mean values were calculated. Results were further grouped by river and day type. Anglers were considered to be local, regional, or out-of-state residents. Local anglers resided within the county, while regional anglers resided elsewhere in North Carolina. The socioeconomic questionnaire also included questions regarding trip length, distance traveled, party size, and expenses on lodging, food, ice, bait, equipment rental, and boat fuel and oil. Mean weighted expenditures per trip were reported by river and day type. Lodging and rental expenses were rarely encountered and therefore are not included within this report. The weighted mean of each expenditure was totaled to provide an average trip cost.

3.15.4.3 Recreational Commercial Gear License Survey

Refer to section 3.14.5.3 for information on the recreational commercial gear license survey.

3.15.5 Fishery-Independent Data Sources

3.15.5.1 Adult Fishery-Independent Data Sources

3.15.5.1.1 NCWRC Tar River Adult Spawning Area Electrofishing Survey

American shad spawning area surveys have been conducted on the main stem Tar River from 2000 through 2017, and survey protocols have changed relatively little throughout the survey period. One dip netter is used to capture fish during daylight hours. Electrofishing samples are conducted weekly during March–May. Sampling begins when water temperatures approach 10oC. Sample sites are located within one of three approximately 15-km segments that encompass most of the American shad spawning habitat in the Tar River. Segment 1 contains the river stretch from Rocky Mount Mill Dam downstream to the Dunbar Boating Access Area (BAA). Segment 2 includes the river stretch from Dunbar BAA downstream to the Bell's Bridge BAA. Segment 3 continues from the Bell's Bridge BAA downstream to the Tarboro town ramp. Normally, one sample of approximately 30 minutes of electrofishing time is conducted within a segment during a sample day. Typically, only one 30-minute sample is conducted per week, yet, depending on flows, attempts are made to conduct another 30-minute sample in a different segment, or at least in a different site of the same segment, during that same week. Sample sites within a segment vary from week to week and are selected from areas that appear to have preferred American shad habitat. Angling activity is avoided. Flows and water temperature determine which segment is sampled on a particular day. Moderate to high flows and warmer water temperatures tend to cause American shad to move further upstream into segment 1. There are certain minimum river levels required to allow access to the river for electrofishing, yet the majority of American shad sampling is concentrated in segment 1 when flows are greater than 300 cfs. Flooding often prevents access to the river for sampling, but high water subsides quickly in the Tar River and at least one sample site per week is usually possible.

Abundance Index Trend

Catch rate data are not considered representative of interannual abundance changes and were not used in the assessment for abundance trend analyses (Table 16). Currently, this survey is used in the SFMP.

3.15.6 Methods

Mann-Kendall analysis was used to evaluate trends in abundance, mean length, and mean length-at-age. Total mortality estimators and delay-difference models were used to evaluate adult mortality. There were diagnostic problems with the delay-difference models, so the results are not provided. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Details for these methods are provided in Section 2.

3.15.7 Results

3.15.7.1 Abundance Trends

3.15.7.1.1 Mann-Kendall Analysis

North Carolina submitted data for a Commercial CPUE survey for the Tar-Pamlico for the years between 1994 and 2017. Index values increased slightly from 1994, consistently fluctuated around a mean until 2014, before declining to the lowest value of the time series in 2016 (Figure 296). Mann-Kendall trend analysis failed to detect a trend for either the full time series of the period after 2005.

3.15.7.2 Mean Length Trends

American shad length data was provided by the NCWRC for the Tar River Adult Spawning Area Electrofishing Survey. Lengths are available by sex for all years between 2000 and 2017. A plot of mean lengths (Figure 297) and Mann-Kendall analysis found no trend in mean lengths of either sex. NCDMF conducts sampling of American shad from fishery-dependent and fishery-independent collections in the Tar-Pamlico River. Lengths from a fishery-dependent commercial sampling program are available for years between 1975 and 1989 and 2000 and 2017 for male and female American shad. A plot of mean total length showed similar inter-annual changes for both sexes (Figure 298). Mann-Kendall analysis found a significant decline in mean length for female American shad, but failed to detect a trend for males, which had fewer data points in the time series with a minimum of 30 sampled fish within a year. Multiple additional data programs were submitted, but excluded from analysis due to small sample sizes or because the time series were too short.

3.15.7.3 Mean Length-at-Age Trends

Mean length-at-age data using scales were provided from two adult sampling programs, the Tar River Adult Spawning Area Electrofishing Survey and a fishery-dependent commercial fishery monitoring program. Fish in the Tar River Adult Spawning Area Electrofishing Survey consisted of females age 4 to 7 and males age 2 to 7. The commercial fishery monitoring program included females only and the ages ranged from age 3 to age 9. Mann-Kendall Trend analysis failed to detect any change in mean length-at-age over time in the Tar River Adult Spawning Area Electrofishing Survey, but did detect a decrease in mean length-at-age for female American shad for ages 5 through 7 (Table 230).

3.15.7.4 Total Mortality Estimates

Age composition data from length compositions and age-length keys derived from scales collected during the Tar River Adult Spawning Area Electrofishing Survey were used for mortality estimates. Data met all criteria (see section 2.6) for 6 and 7 years between 2000 and 2009 for females and males, respectively (Table 32). Female mortality followed an increasing trend since the mid-2000s while male mortality followed a declining trend throughout the time series (Table 33 and Figure 299). There were no female data available in recent years, precluding estimation of a three year average for females in 2017.

3.15.7.5 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Tar-Pamlico system, current unobstructed habitat area represents 75.68% of the historical habitat extent (26.89 of 35.53 square kilometers).

3.15.8 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. The adult mortality status is also unknown as there was no estimate of female total mortality in 2017 and the delay-difference model experienced diagnostics problems and could not be used for status determination. The most recent three-year average female total mortality was 0.87 in 2007 which is below the $Z_{40\%}$ threshold (1.07).

There was a declining trend in female mean length from a long-term data set (1979-2017), but no trend from an additional short-term data set (2000-2017) detected. There were no YOY recruitment data to compare to mean length trend analyses.

Abundance

Abundance status is unknown. There were no YOY abundance data available and no trend detected in adult abundance since 2005.

3.16 Neuse

The Neuse River is formed by the confluence of the Eno and Flat Rivers in the Piedmont region of North Carolina and flows in a southeasterly direction through the coastal lowlands discharging into Pamlico Sound 430 km from its origin (Hawkins 1980b; McMahon and Lloyd 1995; Figure 263). It has a drainage area of 1,449,869 ha. The river flows in a southeasterly direction from its origin to below New Bern where it bends to flow in an easterly direction to the Pamlico Sound. Bay River, West Bay, and a portion of the western Pamlico Sound, and Core Sound from Ocracoke Inlet to Drum Inlet are also included in the basin (Marshall 1977).

3.16.1 Habitat Description

The Neuse River and its tributaries drain all or a portion of 18 counties. The upper third of the river lies in the Piedmont Region of the state with the fall line occurring halfway between Raleigh and Smithfield, North Carolina. Flow regimes in the Neuse River downstream of Raleigh, North Carolina are regulated by Falls Lake Dam (rkm 370), which was built in 1983 by the USACOE to create an impoundment for flood control, water supply, water quality, and recreational purposes. Spawning of American shad has been documented in the main stem Neuse River up to the first dam near Raleigh and in several tributaries: Contentnea Creek, Mill Creek, Little River, Swift Creek, and Crabtree Creek (Burdick and Hightower 2006). Principal tributaries of the Neuse River as it is ascended from its mouth to New Bern are: Broad Creek, Turnagain Bay, South River, Smith and Greens Creek at Oriental, Adams Creek, Dawson Creek, Clubfoot Creek, Hancock Creek, Beards Creek, Slocum Creek, Goose Creek, Upper Broad Creek, and the largest tributary, Trent River. The Trent River is quite large and has an important tributary, Brice Creek. All of these tributaries lie within 55 km of the mouth of the river and are within 93 km of Ocracoke Inlet. Between New Bern and Goldsboro, the principal tributaries are Bachelor Creek, Swift Creek, Cove Creek, and Contentnea Creek. These creeks are all within 103 km of the mouth, and Contentnea Creek at river mile 103 is the last major tributary until Little River is reached near Goldsboro, NC (rkm 261). Further upstream tributaries include: Thoroughfare Swamp, Mill Creek, Black Creek, Swift Creek, Marks Creek, Walnut Creek, Crabtree Creek, Perry Creek, and Smiths Creek. All other tributaries are located upstream of Falls Lake Dam, which represents the uppermost limit of American shad migration in the Neuse River Basin.

3.16.1.1 Spawning Habitat Descriptions

Refer to section 3.14.1.2 for spawning habitat descriptions.

3.16.1.2 Hydropower Projects

Milburnie Dam was constructed on the Neuse River outside of Raleigh in 1901. Previous dams that powered a gristmill, papermill, and sawmill throughout their history had been at the same location since 1760. Hydroelectric production was added to the dam in 1984, but the company operating the facility ceased operation in the late 2000s. Milburnie Dam was removed in 2017, providing access to 16 km of spawning habitat for American shad and other anadromous species.

3.16.2 Fishery and Management History

Refer to section 3.14.2 for regulatory, assessment, and SFMP summaries.

3.16.2.1 Neuse River 2013-2017 SFMP

The two sustainability parameters selected for Neuse River were female CPUE based on the NCWRC Neuse River Adult Spawning Area Electrofishing Survey and female relative *F* based on the NCWRC Neuse River Adult Spawning Area Electrofishing Survey. Exceeding the threshold for female CPUE or female relative *F* would trigger management action (NCDMF and NCWRC 2012).

Female CPUE (NCWRC Neuse River Adult Spawning Area Electrofishing Survey): The female CPUE index based on the NCWRC Neuse River Adult Spawning Area Electrofishing Survey was calculated as the number of fish per minute using data collected from March through May. Initial time series included data from 2000 to 2011 to calculate the 2012 threshold. Values were updated annually through 2017. The annual threshold was calculated as the 25th percentile (where 75% of all values are greater) of the female CPUE index. Management is triggered following three consecutive years of values below the 25th percentile (NCDMF and NCWRC 2012).

Female Relative *F*: Female relative *F* based on the NCWRC Neuse River Adult Spawning Area Electrofishing Survey was calculated using commercial gill net landings of roe shad by all gear types from the Neuse River and the female CPUE index from the Neuse River Adult Spawning Area Electrofishing Survey. Since the electrofishing survey primarily occurs during March and April, only commercial landings from those months were used in the calculations. Initial time series included data from 2000 to 2011 to calculate the 2012 threshold. Values were updated annually through 2017. The annual threshold was calculated as the 75th percentile (where 25% of all values are greater) of the female relative *F* index. Management is triggered following three consecutive years of values above the 75th percentile (where 25% of all values are greater; NCDMF and NCWRC 2012).

3.16.2.1.1 Seasons and Creel Limits

The SFMP established an open commercial season from 15 February to 14 April for the Neuse River, which remained unchanged for the duration of the plan (Table 214). The Neuse River recreational creel limits, 1-American shad within a 10-fish shad aggregate, established in the first year of the SFMP also remained unchanged for the duration of the plan (Table 215).

3.16.2.2 Neuse River 2018-2022 SFMP

In 2017, the original SFMP underwent a mandatory 5-year review and survey data was updated through 2017. The objective of the review was to refine the calculations of the abundance indices and relative *F* estimates. The new plan was approved for management for 2018 through 2022 in October of 2017. The plan includes the same sustainability parameters of relative *F* and abundance indices, with two main changes to the calculations. Relative *F* is now computed by dividing commercial landings by a hind cast 3-year average of a survey index, whereas the previous plan used a centered 3-year average. Using a hind cast 3-year average was determined more appropriate, with the addition of 5-years of data, as it ensures the value of the final year in the time series (which can trigger management action) remains unchanged once calculated. The next change was that thresholds, for all sustainability parameters, are fixed using the time series for the available survey data through 2017. In the 5-year review of the original plan, there were concerns that the thresholds could slowly decline to extremely low levels without ever being exceeded because, thresholds were recalculated annually with the addition of another year of data. The following sustainability parameters and thresholds were approved for the Neuse River and are in effect through 2022 (NCDMF and NCWRC 2017).

Female CPUE (NCWRC Neuse River Adult Spawning Area Electrofishing Survey): The female CPUE index based on the NCWRC Neuse River Adult Spawning Area Electrofishing Survey was calculated as the number of fish per minute using data collected from March through May from 2000-2017. The annual threshold was calculated as the 25th percentile (where 75% of all values are greater) of the female CPUE index for 2000-2017. Management is triggered following three consecutive years of values below the 25th percentile (NCDMF and NCWRC 2017).

Female Relative *F*: Female relative *F* based on the NCWRC Neuse River Adult Spawning Area Electrofishing Survey was calculated using commercial landings of roe shad by all gear types from the Neuse River and the female CPUE index from the Neuse River Adult Spawning Area Electrofishing Survey. Since the electrofishing survey primarily occurs during March and April, only commercial landings from those months were used in the calculations. Relative *F* point estimates are computed by dividing commercial landings by a hind cast 3-year average of a survey index, data for 2000-2002 is contained in the first point estimate for 2002. Each consecutive point estimate in the time series is calculated from 3-years of data. The annual threshold was calculated as the 75th percentile (where 25% of all values are greater) of the female relative *F* index from the fixed time series 2000-2017. Management is triggered following three consecutive years of values above the 75th percentile (where 25% of all values are greater; NCDMF and NCWRC 2017).

The electrofishing index of relative abundance for female American shad in the Neuse River has been variable and remained above the threshold for the past seven years. The index was below the threshold in 2000, 2002, 2006, 2007, and 2010. Relative *F* estimates for female shad derived from the electrofishing survey have been below the threshold since 2008 (NCDMF and NCWRC 2017).

3.16.2.2.1 Seasons and Creel Limits

The 2018-2022 SFMP maintained the open commercial season from 15 February to 14 April (Table 214) and recreational creel limits, 1-American shad within a 10-fish shad aggregate (Table 215), for the Neuse River.

3.16.3 Anthropogenic Sources of Mortality and Productivity

Dams have restricted anadromous fish migrations and limited American shad productivity in the Neuse River basin for centuries. A dam has been present on the main stem Neuse River at Milburnie (rkm 352) since 1760. Quaker Neck Dam was built on the main stem near Goldsboro, NC, (rkm 225) to provide cooling water for a coal-fired power plant in 1952. Falls of the Neuse Dam (rkm 370) was built on the main stem Neuse River in 1983 by the USACOE to provide flood control and water supply. At least five dams have restricted anadromous fish migrations on the Little River, a tributary near Goldsboro, NC, (rkm 212) with known American shad spawning habitat. A tremendous amount of spawning habitat restoration has occurred since the late 1990s. Quaker Neck Dam on the main stem and Cherry Hospital Dam on Little River were removed in 1998. Rains Mill Dam and Lowell Mill Dam, also on the Little River, were removed in 1999 and 2005. A low-head dam at the Goldsboro water treatment facility on the Little River (rkm 7.9) was partially removed (notched) during the same timeframe. Lastly, Milburnie Dam was removed in 2017. These dam removals have restored access to the majority of historic spawning habitat in the Neuse River basin, and spawning success evidenced by the presence of adults as well as eggs and larvae has been documented well upstream of the former dam locations in the main stem (Burdick and Hightower 2006) and Little River (Raabe and Hightower 2014). The full extent in reduction of spawning potential as a result of the dams is not known, but the lack of migration impediments should benefit the Neuse River American shad population in the future.

3.16.3.1 Restoration Program

The NCWRC began an American shad restoration stocking program in the Neuse River in 2012. The goal of the Neuse River American shad stocking program is to supplement the wild population by stocking fry produced from one spawning tank of approximately 100 broodfish each year. American shad broodfish are collected from the Neuse River near Goldsboro, NC and are transported to Edenton National Fish Hatchery where they can spawn and fry are reared for approximately 7 days. American shad fry are stocked in the Neuse River near Goldsboro, NC. Evaluation of hatchery contribution to the Neuse River American shad population is conducted using the same PBT methods as described for the Roanoke River restoration program. A total of 4,893,186 American shad fry have been stocked in the Neuse River at the NC Hwy 117 bridge near Goldsboro, NC since 2012, and hatchery contribution to out-migrating juvenile samples has been low (0–13%; Table 228). Hatchery contribution to returning adults has also been low. In 2016, which was the first-year hatchery fish were potentially available as age-4 adults, only 9 of 411 (4%) adults tested with PBT analysis were of hatchery-origin. Contribution of stocked fish may increase slightly in the future as more hatchery cohorts will move into the spawning population, but it appears the stocking program is contributing very little to the overall American shad population in the Neuse River (NCDMF and NCWRC 2017).

3.16.4 Fishery-Dependent Data Sources

Refer to section 3.14.5 for fishery-dependent data background.

3.16.4.1 Commercial Fishery

3.16.4.1.1 Commercial Gear Restrictions

Since 2016 a statewide rule limits the amount of large mesh (4.0-inch and greater) gill net set in internal Coastal waters to no more than 2,000 yards per vessel. Prior to 2016 a former rule was suspended in the majority of internal Coastal waters as a result of sea turtle conservation measures to institute no more than 2,000 yards per vessel of 4.0–6.5-inch gill net in the Tar-

Pamlico and Neuse systems. Additionally, in certain sections of the Tar-Pamlico and Neuse rivers, gill nets with a mesh size less than five inches must be attended at all times.

Also, it is unlawful to use gill nets of any mesh size in Joint Fishing Waters from midnight on Friday to midnight on Sunday each week (except for portions of Albemarle and Currituck sounds). These existing gill net measures have likely reduced American shad harvest since they have remained in effect since the spring 2012 fishing season and will remain in effect indefinitely.

3.16.4.1.2 Commercial Landings

Refer to section 3.14.5.1.2 for information on commercial landings.

3.16.4.1.3 Commercial Catch Rates

Catch rates are provided in Table 231. Refer to section 3.14.5.1.3 for information on commercial catch rates.

3.16.4.2 Recreational Fishery

Refer to sections 3.15.4.2 and 3.14.5.2 for more information.

3.16.5 Fishery-Independent Data Sources

3.16.5.1 Adult Fishery-Independent Data Sources

3.16.5.1.1 NCWRC Neuse River Adult Spawning Area Electrofishing Survey

American shad electrofishing surveys have been conducted in the Neuse River from 2000 through 2017. Electrofishing samples are conducted weekly during March–May, and one dip netter is used to capture fish during daylight hours. Sampling begins when water temperatures approach 10oC and ends when spawning appears to be complete. Sampling is conducted near known spawning areas at Goldsboro, NC (rkm 240) and Raleigh, NC (rkm 350). Sampling begins at the downstream Goldsboro location in March, and the Raleigh location is added to the weekly sampling regime once 30–40 American shad are collected in one day at the Goldsboro location. Weekly sampling locations are contingent upon water levels because low flows limit navigability. The Raleigh location is only accessible at moderate to high flows and is dropped from weekly sampling when flows are not adequate for safe and effective sampling. When conditions improve, sampling is resumed at the Raleigh location. Sampling locations have been consistent throughout the survey period, but sampling protocols at each location have varied over time. In early years of the survey, two sample sites were sampled at each location. The sample sites were 2–3 km long and took over one hour of electrofishing time to complete. Since 2015, two or three sample sites are sampled at each location, but the sites have been shortened to around 1 km and electrofishing effort has been reduced. Nevertheless, the same areas have been consistently sampled throughout the survey.

Index Development

Each electrofishing collection was treated as an independent observation and effort was defined as minutes of active electrofishing. There were 18 years of data with averages of 28 positive observations per year and 90.8% positive observations per year (table d). Variables available for potential inclusion in the standardization model included sampling year (discrete), sampling location (discrete or random effect), water temperature (continuous), and average daily discharge at USGS Station 02087500 (Neuse River near Clayton, NC; https://nwis.waterdata.usgs.gov/nwis/inventory/?site_no=02087500; continuous).

Electrofishing effort, in minutes, was used as an offset term in all models to account for variability in sampling effort on catches of adult American Shad. Model types considered included NB GLM, NB GLMM, NB GAM, NB GAMM, ZINB GLM, ZINB GLMM, ZINB GAM, and ZINB GAMM. All GAM models were fit assuming cubic regression splines for continuous variables and with a gamma penalty of 1.4 for all models (NB GAM & NB GAMM) and sub-models (ZINB GAM, ZINB GAMM). Mixed models included sampling location as a random effect, either through specification in the GLM modeling framework or by modeling as a smoother and invoking the random effect basis function in GAM models; in non-mixed models, all full models included sampling location as a main effect. AIC was used to select the final model type, covariates, and basis dimensions for smoothing functions. Prior to model fit, we excluded any collections missing covariate data.

The best fit model, based on AIC, was a ZINB GAM. The final model included the catch of adult American Shad as the response variable and the variables sampling year (count sub-model only), sampling location (count sub-model only), water temperature (binary (EDF = 1.00) and count (EDF = 3.83) sub-models), and average daily discharge (binary (EDF = 2.06 and count (EDF = 2.14) sub-models) as main effects; the log of effort in minutes was included as an offset term in both sub-models.

The final model suggests sampling location, water temperature, and average daily discharge of the Neuse River affects the catchability of American Shad via the survey. Catches of adult American Shad increase as water temperature increases to approximately 17.0^{o}C, with catch beginning to decline at higher temperatures. There is also evidence average daily discharge of the Neuse River, as measured near Clayton, NC, strongly influences the catchability of adult American Shad in the survey, with catches showing a negative exponential relationship with daily discharge. Catches also vary substantially by fixed station location, with the highest catch generally occurring at the Milburnie Dam sampling location.

Abundance Index Trend

The standardized index follows the same trend as the arithmetic mean catch rates for most years. The standardized index remains stable, with noise from survey inception through the terminal year, though there are notable peaks in adult American Shad abundance in 2013 and 2017. Annual CVs averaged 0.17 over the time series (Table 232).

3.16.6 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance, mean length, and mean length-at-age. Delay-difference models were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Details for these methods are provided in Section 2.

3.16.7 Results

3.16.7.1 Abundance Trends

3.16.7.1.1 Power Analysis

The only abundance index for American shad in this region containing estimates of PSE was the Neuse River Adult Spawning Area Electrofishing Survey. This survey exhibited a median PSE of 0.156. Given this median PSE the power analysis suggests the survey would be able to detect a 50% decrease in abundance (power > 0.80) in 10 years, though it would not quite be able to detect a 50% increase over the same period with power exceeding 0.80 (Table 25). Currently, this survey is used in the SFMP for sustainability targets and monitoring.

3.16.7.1.2 Mann-Kendall Analysis

Neuse River (FD CPUE)

North Carolina provided fishery-dependent data from the Commercial CPUE between 1994 and 2017 as an index of American shad abundance in the Neuse River. No apparent trend was observed when the data was plotted versus time (Figure 300) and Mann-Kendall trend analysis failed to detect a trend in either time period in the analysis.

Neuse River (FI CPUE)

North Carolina provided fishery-independent data from the Neuse River Electrofishing Survey for 2000-2017 as an index of American shad abundance in the Neuse River. When plotted, index values declined from 2003-2006, followed by a gradual increase thereafter with a large peak in 2013 and subsequent decline (Figure 301). Mann-Kendall trend analysis failed to detect a trend over the full time series, but did find an increasing trend for the period from 2005 forward.

3.16.7.2 Mean Length Trends

The State of North Carolina conducts biological sampling of American shad from fishery-dependent and fishery-independent collections in the Neuse River. Lengths from a fishery-dependent commercial fishery monitoring program are available for many years between 1978 and 2017, but there is a gap in the time series from 1990-1999. A plot of mean lengths showed a similar inter-annual changes for both male and female American shad, as well as a general decrease in mean length of both sexes since 1986 (Figure 302). Mann-Kendall trend analysis confirmed the decrease, finding a significant decreasing trend in mean length over time for both sexes. Four additional data programs were submitted, but excluded from analysis due to small sample sizes or because the time series were too short.

3.16.7.3 Mean Length-at-Age Trends

Mean length-at-age data using scales were provided from a fishery-dependent commercial fishery monitoring program in the Neuse River. Analysis included females age 4 to age 8 and males age 3 to age 7. Mann-Kendall Trend analysis failed to detect any change in mean length-at-age over time for males, but did detect a decrease in mean length-at-age in females ages 5 through 7 (Table 233).

3.16.7.4 Delay-Difference Model

The delay-difference model for the Neuse River was run using the southern iteroparous life history parameters and the Neuse River fishery-independent electrofishing survey as the abundance index. Total commercial fishery catch was available for 1972 through 2017, while the abundance index was available for 2000 through 2017. Since the delay-difference model requires identical time series length for catch and index, the total catch was truncated to 2000 through 2017. Estimated biomass remained relatively constant throughout the time series (Figure 303). The ratio of estimated biomass to initial biomass indicated an initial decrease between 2000 and 2009, followed by a modest increase through 2017. The index and effort showed opposing trends throughout the time series alternating widely between 2000 and 2015, with effort indicating a marked decrease over the time series. Observed and estimated catch from the model simulations show that total catches increased from 2001 through 2007 followed by a decrease throughout the end of the time series. Median TAC over 100 simulations was estimated to be 51,600.7 lbs, with overfishing unlikely to occur within the confidence intervals at catch levels equal to the mean of the final 3 years of the time series.

3.16.7.5 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Neuse system, current unobstructed habitat area represents 90.05% of the historical habitat extent (47.61 of 52.87 square kilometers).

3.16.8 Stock Status and Conclusions

Mortality[2]

Juvenile mortality status is unknown due to lack of data to make this determination. Adult mortality status is sustainable as the three-year average catch in 2017 was less than the delay-difference model median TAC estimate.

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[2] This status determination changed following the Peer Review Workshop. See the addendum (Section 9) for final status determination.

There was a declining trend in female mean length from 1978-2017. There were no YOY recruitment data to compare to mean length trend analyses.

Abundance

Abundance status is unknown. There were no YOY abundance data available. There have been conflicting trends in adult abundance since 2005, with an increasing trend detected from the Electrofishing Survey and no trend detected from Commercial CPUE, further confounding assessment of abundance conditions in recent years.

3.17 Cape Fear

The Cape Fear River (Figure 263) forms at the confluence of the Deep and Haw rivers in the Piedmont region of North Carolina and flows approximately 274 km in a southeasterly direction to the city of Wilmington and from there, 40 km south to discharge into the Atlantic Ocean near South Port (Fischer 1980).

3.17.1 Habitat Description

The main river drainage area encompasses an area of 15,708 sq km with an additional 7,988 sq km included in the drainage areas of the Deep and Haw Rivers. It is the largest river basin lying completely within the state of North Carolina. The basin includes portions of 27 counties and 114 municipalities, and encompasses 9,984 km of freshwater streams and rivers, 36 lakes and reservoirs, and 15,864 ha of estuarine waters (NCDWQ 1995). The Cape Fear River has five major tributaries: Upper Little River, Lower Little River, Rockfish Creek, Black River, and Northeast Cape Fear River, which is the largest of the tributaries. The major tributaries which feed the Cape Fear River are dark, acidic, swamp-drainage streams; however, the waters of the Cape Fear River itself are usually very turbid (Fischer 1980).

Three navigational dams and locks were built between 1913 and 1934. The dams prevented fish from ascending the river above except during boat lockages or periods of high water. Although the dams were provided with fish ladders, anadromous fishes did not use them (Davis and Cheek 1967, as cited by Fischer 1980) and were prevented from accessing historic spawning habitat around Smiley Falls (rkm 290) and further upstream. However, through an agreement among NCWRC, USACOE, and USFWS, fish are locked upstream through all three locks during the spawning run of anadromous fishes in the spring (Nichols and Louder 1970, as cited by Fischer 1980). In 2012, a rock arch fishway was constructed at the base of Lock and Dam 1 (rkm 97) to provide continuous, volitional fish passage, and USACOE halted locking operations for fish passage at Lock and Dam 1 after the fishway was completed. Buckhorn Dam (rkm 316) prevents further migrations to potential upstream spawning habitat except during extreme flood events.

3.17.1.1 Spawning Habitat Descriptions

Refer to section 3.14.1.2 for spawning habitat descriptions.

3.17.1.2 Hydropower Projects

There are no hydropower projects affecting American shad in the Cape Fear River basin.

3.17.2 Fishery and Management History

Refer to section 3.14.2 for regulatory, assessment, and SFMP summaries.

3.17.2.1 Cape Fear River 2013-2017 SFMP

The two sustainability parameters selected for Cape Fear River were female CPUE based on the NCWRC Cape Fear River Adult Spawning Area Electrofishing Survey and female relative *F* based on the NCWRC Cape Fear River Adult Spawning Area Electrofishing Survey. Exceeding the threshold for female CPUE or female relative *F* would trigger management action (NCDMF and NCWRC 2012).

Female CPUE (NCWRC Cape Fear River Adult Spawning Area Electrofishing Survey): The female CPUE index based on the NCWRC Cape Fear River Adult Spawning Area Electrofishing Survey was calculated as the number of fish per minute using data collected from March through May. Initial time series included data from 2001 to 2011 to calculate the 2012 threshold. Values were updated annually through 2017. The annual threshold was calculated as the 25th percentile (where 75% of all values are greater) of the female CPUE index. Management is triggered following three consecutive years of values below the 25th percentile (NCDMF and NCWRC 2012).

Female Relative *F*: Female relative *F* based on the NCWRC Cape Fear River Adult Spawning Area Electrofishing Survey was calculated using commercial gill net landings of roe shad by all gear types from the Cape Fear River and the female CPUE index from the Neuse River electrofishing survey. Since the electrofishing survey primarily occurs during March and April, only commercial landings from those months were used in the calculations. Initial time series included data from 2001 to 2011 to calculate the 2012 threshold. Values were updated annually through 2017. The annual threshold was calculated as the 75th percentile (where 25% of all values are greater) of the female relative *F* index. Management is triggered following three consecutive years of values above the 75th percentile (where 25% of all values are greater; NCDMF and NCWRC 2012).

3.17.2.1.1 Seasons and Creel Limits

The SFMP established an open commercial season from 20 February to 11 April for the Cape Fear River, which remained unchanged for the duration of the plan (Table 214). The Cape Fear River recreational creel limits, 5-American shad within a 10-fish shad aggregate, established in the first year of the SFMP also remained unchanged for the duration of the plan and are listed in Table 215.

3.17.2.2 Cape Fear River 2018-2022 SFMP

In 2017, the original SFMP underwent a mandatory 5-year review and survey data was updated through 2017. The objective of the review was to refine the calculations of the abundance indices and relative *F* estimates. The new plan was approved for management for 2018 through 2022 in October of 2017. The plan includes the same sustainability parameters of relative *F* and abundance indices, with two main changes to the calculations. Relative *F* is now computed by dividing commercial landings by a hind cast 3-year average of a survey index, whereas the previous plan used a centered 3-year average. Using a hind cast 3-year average was determined more appropriate, with the addition of 5-years of data, as it ensures the value of the final year in the time series (which can trigger management action) remains unchanged once calculated. The next change was that thresholds, for all sustainability parameters, are fixed using the time series for the available survey data through 2017. In the 5-year review of the original plan, there were concerns that the thresholds could slowly decline to extremely low levels without ever being exceeded because, thresholds were recalculated annually with the addition of another year of data. The following sustainability parameters and thresholds were approved for the Cape Fear River and are in effect through 2022 (NCDMF and NCWRC 2017).

Female CPUE (NCWRC Cape Fear River Adult Spawning Area Electrofishing Survey): The female CPUE index based on the NCWRC Cape Fear River Adult Spawning Area Electrofishing Survey was calculated as the number of fish per minute using data collected from March through May from 2001-2017. The annual threshold was calculated as the 25th percentile (where 75% of all values are greater) of the female CPUE index for 2000-2017. Management is triggered following three consecutive years of values below the 25th percentile (NCDMF and NCWRC 2017).

Female Relative *F*: Female relative *F* based on the NCWRC Cape Fear River Adult Spawning Area Electrofishing Survey was calculated using commercial landings of roe shad by all gear types from the Cape Fear River and the female CPUE index from the Cape Fear River Cape Fear River Adult Spawning Area Electrofishing Survey. Since the electrofishing survey primarily occurs during March and April, only commercial landings from those months were used in the calculations. Relative *F* point estimates are computed by dividing commercial landings by a hind cast 3-year average of a survey index, data for 2001-2003 is contained in the first point estimate for 2003. Each consecutive point estimate in the time series is calculated from 3-years of data. The annual threshold was calculated as the 75th percentile (where 25% of all values are greater) of the female relative *F* index from the fixed time series 2001-2017. Management is triggered following three consecutive years of values above the 75th percentile (where 25% of all values are greater; NCDMF and NCWRC 2017).

Relative abundance of female American shad from the electrofishing survey in the Cape Fear River was low from 2005 through 2011, and values were below the threshold from 2006 to 2011 (NCDMF and NCWRC 2017). Since 2011, relative abundance of female American shad has been above the threshold and continued to increase through 2015. Estimates of female relative *F* have remained below the threshold since 2012 (NCDMF and NCWRC 2017).

3.17.2.2.1 Seasons and Creel Limits

The 2018-2022 SFMP maintained the open commercial season from 15 February to 14 April (Table 214) and recreational creel limits, 1-American shad within a 10-fish shad aggregate (Table 215), for the Cape Fear River.

3.17.3 System-Specific Life History

Refer to Section 3.14.3 for life history information.

3.17.4 Anthropogenic Sources of Mortality and Productivity

Collaborative habitat enhancement projects that focus on fish passage and increasing spawning habitat have been implemented on the Cape Fear River in recent years. Each year, NCWRC recommends a locking schedule to the USACE to pass anadromous fishes upstream of locks and dams during the spring spawning run. In 2012, a rock arch fishway was constructed below Lock and Dam 1 (LD-1) to facilitate volitional, upstream fish passage. Telemetry studies conducted to evaluate American shad usage of the rock arch fishway indicate American shad passage efficiency at the LD-1 fishway ranged 53–65% and was consistent with prior estimates from locking procedures (Raabe et al. 2019). Electrofishing surveys corroborate the telemetry studies, as electrofishing catch rates have increased at the upper two locks and dams and decreased at LD-1 over the last five years. These results indicate American shad are readily passing LD-1. With presumed historic spawning grounds, upstream of Lock and Dam 3 (LD-3), substrate was strategically placed below Lock and Dam 2 (LD-2) in 2013 to increase the potential spawning habitat for anadromous fish that pass the rock arch fishway but fail to navigate the lockage system. Locking at LD-1 has ceased at this point but continues for LD-2 and LD-3 to facilitate fish passage. American shad spawning activity has been observed by Commission staff (Bennett Wynne, NCWRC retired, personal communication), and American shad eggs have been collected just downstream of LD-2 (Dawn York, Cape Fear River Partnership, personal communication). Therefore, fish that migrated to LD-2 but failed to migrate farther upstream could reproduce and benefit from the habitat enhancement efforts. In 2016, NCWRC staff documented higher egg densities below LD-3 compared to other locks and dams (Morgeson and Fisk 2018). The Cape Fear River Partnership, including local, state, and federal agencies, as well as private groups, continues to plan fish passage enhancement projects on the remaining locks and dams on the main stem Cape Fear River.

Based on the construction efforts and changing conditions, NCDMF and NCWRC recommended a two-year review of the 75th percentile threshold for female relative F in the 2013-2017 SFMP as calculation of this parameter was likely to be heavily influenced by drought, floods, and changes in fish passage. There was also concern that restoration efforts might influence electrofishing catch rates due to improvements in fish passage with completion of the rock arch fishway. After review in 2015, no changes were recommended for the Cape Fear system. North Carolina will continue to evaluate American shad relative abundance and sustainability metrics in the context of improvements in habitat and passage benefiting anadromous fishes in the Cape Fear River.

3.17.5 Fishery-Dependent Data Sources

3.17.5.1.1 Commercial Gear Restrictions

There are different gill net restrictions than described above for the Tar-Pamlico and Neuse systems (i.e. mesh lengths, spacing, set/retrieval days and times) for the Cape Fear system. Nets can be set in lengths no greater than 100 yards and must have at least a 25-yard space between each individual length of net. Only single overnight sets are allowed; nets can be set one hour prior to sunset and must be retrieved within one hour of sunrise, with no sets allowed Friday, Saturday or Sunday evenings, and the maximum yardage allowed is a 1,000-yard limit per vessel.

It is unlawful to use gill nets of any mesh size on weekends in the Cape Fear system. This measure will remain in effect indefinitely.

3.17.5.1.2 Commercial Landings

Refer to section 3.14.5.1.2 for information on commercial landings.

3.17.5.1.3 Commercial Catch Rates

Catch rates are provided Table 234. Refer to section 3.14.5.1.3 for information on commercial catch rates.

3.17.5.2 Recreational Fishery

Refer to section 3.15.4.2 for more information.

3.17.6 Fishery-Independent Data Sources

3.17.6.1 Adult Fishery-Independent Data Sources

3.17.6.1.1 NCWRC Cape Fear River Adult Spawning Area Electrofishing Survey

Sampling for American shad has occurred in the Cape Fear River from 2001 through 2017. In most years, one dip netter was used to collect American shad, but two dip netters have been used 2015–2017 to avoid gear saturation caused by increases in American shad abundance. In all survey years, sampling occurred at three fixed sample sites adjacent to the base of each of three locks and dams found on the river. Since 2010, sampling efforts have been standardized by electrofishing for 30 minutes downstream of each lock and dam—15 minutes from the middle of each dam down each shoreline. Sampling at each site is attempted weekly when water temperatures approach 10oC and is ended when spawning appears complete. Prior to 2010, however, sampling was more sporadic and did not always occur at each site every week. Other areas in the Cape Fear River upstream of the locks and dams (Buckhorn Dam and Smiley's Falls) are also sampled, but data from sites other than the locks and dams are not included in annual relative abundance analyses. Sampling at the locks and dams is possible under most flow conditions, but flood events can periodically prevent sampling.

Index Development

Each electrofishing collection was treated as an independent observation and effort was defined as minutes of active electrofishing. There were 17 years of data with averages of 20 positive observations per year and 88.2% positive observations per year. Variables available for potential inclusion in the standardization model included sampling year (discrete), sampling location (discrete or random effect), water temperature (continuous), and average daily discharge at USGS Station 02105769 (Cape Fear River at Lock #1; https://waterdata.usgs.gov/nwis/inventory/?site_no=02105769; continuous). Electrofishing effort, in minutes, was used as an offset term in all models to account for variability in sampling effort on catches of adult American Shad. Model types considered included NB GLM, negative binomial generalized linear mixed models (NB GLMM), NB GAM, negative binomial generalized additive mixed models (NB GAMM), ZINB GLM, zero-inflated negative binomial generalized linear mixed models (ZINB GLMM), ZINB GAM, and zero-inflated negative binomial generalized additive mixed models (ZINB GAMM). All GAM models were fit assuming cubic regression splines for continuous variables and with a gamma penalty of 1.4 for all models (NB GAM & NB GAMM) and sub-models (ZINB GAM, ZINB GAMM). Mixed models included location as a random effect, either through specification in the GLM modeling framework or by modeling as a smoother and invoking the random effect basis function in GAM models; in non-mixed models, all full models included sampling location as a main effect. AIC was used to select the final model type, covariates, and basis dimensions for smoothing functions. Prior to model fit, any collections missing covariate data were excluded from the analysis.

The best fit standardization model, based on AIC, was a ZINB GAM. The final model included the catch of adult American Shad as the response variable and the variables sampling year (count sub-model only), sampling location (count sub-model only), water temperature (binary (EDF = 2.28) and count (EDF = 4.02) sub-models), and average daily discharge (count (EDF = 1.00) sub-model only); the log of effort in minutes was included as an offset term in both sub-models.

The final model suggests the catchability of adult American Shad is affected by sampling location, water temperature, and average daily discharge of the Cape Fear River. Catches of adult American Shad increase as water temperature increases to approximately 20.0^{o}C; at higher temperatures catches begin to decline slightly. There is also evidence average daily discharge of the Cape Fear River, as measured at Lock #1, strongly influences the catchability of adult American Shad in the survey, with catches being inversely related to daily discharge. Catches also vary substantially by fixed station location, being generally higher at locations near locks.

Abundance Index Trend

The standardized index follows the same trend as the arithmetic mean catch rates for most years. The standardized index suggests a decreasing trend from survey inception through the mid-2000s, followed by a period of below average catches through 2011. Since 2011 relative abundance initially increased, with a recent peak in 2014, followed by a slight decline through the terminal year. Annual CVs averaged 0.25 over the time series (Table 235).

3.17.7 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance, mean length, and mean length-at-age. Delay-difference models were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Details for these methods are provided in Section 2.

3.17.8 Results

3.17.8.1 Abundance Trends

3.17.8.1.1 Power Analysis

The only abundance index for American shad in this region containing estimates of PSE was the Cape Fear River Adult Spawning Area Electrofishing Survey. This survey exhibited a moderate median PSE (0.223). Given this median PSE the power analysis suggests the survey would be able to detect a 50% decrease in abundance (power > 0.80) in 10 years, though it would not be able to detect a 50% increase over the same period (Table 25). Currently, this survey is used in the SFMP for sustainability targets and monitoring.

3.17.8.1.2 Mann-Kendall Analysis

Cape Fear River (FD CPUE)

North Carolina submitted data for a Commercial CPUE survey for the Cape Fear River for the years between 1994 and 2017. A steady increase in index values over the time series were apparent when plotted over time, with the peaks occurring around 2003 and 2014 (Figure 304). Mann-Kendall trend analysis detected an increasing trend in the index for both the full time series and the period from 2005 forward.

Cape Fear River (FI CPUE)

North Carolina submitted data for a fishery-independent Cape Fear River Adult Spawning Area Electrofishing Survey for the years between 2001 and 2017. Values were highest in 2002 before declining and remaining low through 2011 and slowly increasing afterwards (Figure 305). Mann-Kendall trend analysis failed to detect a trend over the entire time series, but did find an increasing trend for the period from 2005 forward, which could be a result of fish passage improvements at Lock and Dam 1 in 2012.

3.17.8.2 Mean Length Trends

Plot of the mean total length for female and male American shad from a fishery-dependent commercial sampling program showed similar inter-annual changes in mean length of both sexes (Figure 306). Mann-Kendall analysis found a significant decline in mean length of female American shad since the 1980s, but no trend for males. Plot of a fishery-independent electrofishing survey from the Cape Fear River showed no discernable trend in mean lengths of either sex since 2000 (Figure 307) and the Mann-Kendall test was not significant. Three additional data programs were submitted, but excluded from analysis due to sample size or because the time series was too short.

3.17.8.3 Mean Length-at-Age Trends

Mean length-at-age data using scales were provided from two sampling programs, the fishery-dependent commercial fishery monitoring and the Cape Fear River Adult Spawning Area Electrofishing Survey. Data were only provided for females for the fishery-dependent program and ages ranged from 3 to 8 years. In contrast, the electrofishing survey provided length-at-age data for only male American shad ages 3 to 7. Mann-Kendall Trend analysis failed to detect any change in mean length-at-age over time in the Cape Fear River Adult Spawning Area Electrofishing Survey, but did detect a decrease in mean length-at-age for females ages 5 through 7 in the commercial fishery monitoring (Table 236).

3.17.8.4 Delay-Difference Model

The delay-difference model for the Cape Fear River was run using the semelparous life history parameters and the Cape Fear River Adult Spawning Area Electrofishing Survey as the abundance index. Total commercial fishery catch was available for 1972 through 2017, while the abundance index was available for 2000 through 2017. Since the delay-difference model requires identical time series length for catch and index, the total catch was truncated to 2000 through 2017. Estimated biomass declined over the time series from a median estimate of 112,680 lbs in 2000 down to a low of 48,443 lbs in 2011 before rising to a final estimate of 70,205 lbs in 2017 (Figure 308). The ratio of estimated biomass to initial biomass indicated an initial decrease between 2000 and 2012, followed by a modest increasing trend through 2017. The index and effort showed opposing trends throughout the time series alternating widely between 2000 and 2015, with both ending the time series with a decreasing trend. Observed and estimated catch from the model simulations show that total catches varied widely throughout the time series, with the largest harvest occurring in 2014 followed by a decrease through 2017. Median TAC over 100 simulations was estimated to be 27,615.6 lbs, with overfishing unlikely to occur within the confidence intervals at catch levels equal to the mean of the final 3 years of the time series.

3.17.8.5 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Cape Fear system, current unobstructed habitat area represents 46.59% of the historical habitat extent (32.46 of 69.67 square kilometers).

3.17.9 Stock Status and Conclusions

Mortality[2]

Juvenile mortality status is unknown due to lack of data to make this determination. Adult

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[2] This status determination changed following the Peer Review Workshop. See the addendum (Section 9) for final status determination.

mortality status is sustainable as the three-year average catch in 2017 was less than the delay-difference model median TAC estimate.

There was a declining trend in female mean length from a long-term data set (1984-2017), but no trend from an additional shorter-term data set (2001-2017) detected. There were no YOY recruitment data to compare to mean length trend analyses.

Abundance
Abundance status is unknown. There were no YOY abundance data available. There was an increasing trend in adult abundance (two data sets) detected since 2005.

3.18 Winyah Bay

The Winyah Bay complex has supported South Carolina's largest commercial shad fishery in the last few years. Fisheries were centered in the lower 64 km (40 miles) of the Waccamaw River. Both drift and anchored nets are used throughout this area. The concentrated amount of fishing effort within tidal freshwater and estuarine portions of the system complicates management of unit stocks or sub-stocks within the Waccamaw River. Drift nets were used in limited areas above the Winyah Bay, as winding channels, rapid currents, and water of variable depth with bottom obstructions are typical of most inland portion of these waterways.

3.18.1 Habitat Description

The Winyah Bay and its tributaries (Figure 309) constitute the northern most system that SCDNR monitors for American shad. Winyah Bay extends nearly 24 km inland and has six tributaries that have spawning runs of American shad (Sampit, Lynches, Pee Dee, Bull Creek, Black, and Waccamaw Rivers). From 1979 to 2005, shad had to bypass the Winyah Bay ocean-intercept fishery before entering their natal rivers to spawn. The Sampit is a small, tidal river that becomes unnavigable inland at about rkm 64. The mouth of the Black River is near the junction of the Great Pee Dee River and upper Winyah Bay and has approximately 40 km of navigable waters. The downstream section of the Great Pee Dee River merges with the Black River and they diverge about 16 km upriver. The Pee Dee River continues until it merges with

Bull Creek at rkm 96. The Little Pee Dee River extends about 96 km to the North Carolina state line. The only dam located on the Pee Dee River is at Blewett Falls, North Carolina (320 km inland) (Post et al. 2004). The Lynches River remains navigable for over 113 km after separating from the Great Pee Dee River. Bull Creek extends 24 km and borders the Waccamaw River to the south and the Great Pee Dee River to the north. The Waccamaw River fishery begins at rkm 0 and continues for 64 km upriver.

3.18.2 Fishery and Management History

South Carolina manages its shad fisheries using a combination of seasons, gear restrictions, and catch limits implemented over several management units: Winyah Bay and Tributaries (Waccamaw, Great Pee Dee, Little Pee Dee, Lynches, Black, and Sampit Rivers).

Beginning with the 1998 commercial shad-netting season, all licensed fishermen are required to report their daily catch and effort to SCDNR. In 2000, Act #245 of the 2000 South Carolina General Assembly was passed in response to the perceived population status of shad populations in each of the state's river systems supporting an American shad fishery.

Significant changes in shad and herring regulations became effective with the 2001 passage of the Marine Resources Act of 2000, giving SCDNR authority to implement a permit program for the State's shad and herring fisheries. All commercial shad and herring fishery license holders were issued permits that could be used to "restrict the number of nets for taking shad…in any body of water where the number of nets or fishermen must be limited…to prevent congestion of nets or watercraft, or for conservation purposes." The number and conditions of permits can be controlled "to designate areas, size, and take limits, hours, type and amount of equipment, and catch reporting requirements," and enabled SCDNR to phase out the ocean-intercept fishery by 2005. In addition, a recreational aggregate creel limit of 10 American and hickory shad per person was implemented in all state waters, except for the Santee River in which a 20 fish creel limit was set.

Additionally, with requirements initiated by Amendment 3 to the ASMFC Shad and River Herring FMP, South Carolina was required to develop a shad SFMP to demonstrate sustainability in all rivers where shad fisheries occurred. A sustainable fishery was defined as "those that demonstrate their stock could support a commercial and/or recreational fishery that will not diminish the future stock reproduction and recruitment." Acceptable measures to develop sustainability benchmarks included mark-recapture studies, enumeration at fish passage facilities, catch-per-unit-effort (CPUE) by appropriate sample gear, or other indices of abundance. If sustainability could not be demonstrated, those fisheries were to be closed. In 2012 and again in 2017, South Carolina's SFMP was approved by the ASMFC Shad and river herring Technical Committee and Shad and river herring Management Board. Measures in the SFMP required a 50 percent statewide reduction for available commercial gill nets.

3.18.2.1 Landings Data

South Carolina has monitored commercial fisheries for American shad within state waters since 1979, although historical records for South Carolina date back much farther (Figure 310). The NOAA Fisheries landings data before 1979 were collected from major wholesale outlets located near the coast; therefore, it is likely that inland landings were not completely accounted for in these years, since many shad fishermen claim not to sell their catch and keep it for personal consumption. This results in discrepancies between SCDNR and NOAA Fisheries American shad landings in South Carolina through the time series. No landings were attributed to the South Carolina ocean-intercept fishery before 1979. SCDNR has records of landings by system since 1979 for the Atlantic Ocean (i.e., the ocean-intercept fishery), Winyah Bay, Waccamaw River, Pee Dee River, and Black River. Data collected since 1979 generally include inland landings and should be considered as a separate time series.

3.18.2.2 Catch-Per-Unit-Effort

No effort data were collected for American shad fisheries before 1979; thus, it was not possible to attribute stock fluctuations to changes in fishing effort, changes in spawning stock size, or other factors. License data are available but are not useful as many shad fishermen participated on a part-time basis and the amount of gear deployed was not specified in records. In addition, approximately 80 percent of the licensed fishermen fished infrequently, precluding estimation of total effort and, therefore, CPUE (Ulrich et al. 1978).

Commercial American shad catches were sampled to collect biological data (e.g., length, weight, and age) by SCDNR from American shad fishermen at boat ramps from 1979 to 1985 for rivers with an active American shad fishery. During this time, SCDNR identified a group of “reliable” fishermen from which to collect catch and effort data. Voluntary catch records (data sheets) from these fishermen were used to develop fishery-dependent catch-per-unit-effort (CPUE) from 1979 to 2000. Starting in 1998, SCDNR instituted mandatory reporting for all commercial shad fishermen. In order to maintain consistency with previous years, mandatory reporting records from the “reliable” fishermen have been used to calculate CPUE for specific rivers since 2001. Every attempt was made to use data from the same fishermen over time, but some difficulties were encountered (e.g., one or two fishermen did not fish for the season, fishermen changed their fishing gear, or fishermen may have left the fishery). Such events might have affected the CPUE estimates, but these problems were minimal and these data constitute the only available long-term CPUE series for South Carolina American shad fisheries. Records were separated by river and in some cases by specific regions of a river and by gear: Winyah Bay (drift nets); Waccamaw River (lower drift nets); and Pee Dee River (Petersfield set nets). Not all systems were monitored each year due to personnel limitations.

For this assessment, data collected through mandatory reporting means (1999-2017) were used. Since this includes reports from all fishers and not just those fishers selected in previous data (1979-2001), data prior to 1999 is considered a separate time series and is not included in this analysis. Catch rate estimates is determined by annual landings (kg) per trips. To maintain confidentiality, landings for the Winyah Bay System (Winyah Bay, Waccamaw, Black, and Great Pee Dee Rivers) have been combined. Many variables, such as water temperature, water levels, and flow rates, affect observed CPUE values and these parameters are highly variable between seasons and might have substantial impacts on catchability, and even effort, particularly in certain rivers. Linear regressions of CPUE against year were conducted to determine the significance of any trends in these data time series.

3.18.2.3 Winyah Bay Fishery

The Winyah Bay extends nearly 24 km inland and is the point of access to spawning streams for American shad. Shad destined for the Sampit and Black Rivers had to avoid Winyah Bay fisheries from 1979 to 2005 before entering their natal rivers. The Sampit River is a small, primarily tidal river that becomes unnavigable inland at about rkm 64. Shad gill netting was sporadic and was generally limited to the first 16 km of the river above its confluence with the Winyah Bay.

The Black River branches from near the junction of the Great Pee Dee River and the upper Winyah Bay and extends inland with an additional 202 km or more of navigable waterway. Most American shad fishing occurs in the lower 97 km of Black River.

The Great Pee Dee River begins just below Highway 17 where it merges with the Black River. The rivers split about 16 km upriver and the Great Pee Dee River continues until it intercepts Bull Creek. Significant netting effort continues up to rkm 105, with activity less intensive farther upriver. Gill Netting extends upriver to at least rkm 240. The shad run continues beyond the North Carolina state line at about rkm 280 to Blewett Falls Dam located nearly 320 km from the Atlantic Ocean.

Fish migrating to the Little Pee Dee and Lynches Rivers must have successfully by-passed fisheries in the Great Pee Dee before entering their natal tributary streams at approximately rkm 72 and rkm 113, respectively. The Little Pee Dee River extends about 97 rkm to the North Carolina state line. Shad fishery activity is generally restricted to the lower 32 km of the river. The Lynches River remains navigable for over 113 km beyond its departure from the Great Pee Dee River, but the fishery is prosecuted in the lower 24 km.

3.18.3 System-Specific Life History

American shad returning to South Carolina rivers are generally believed to be semelparous. In annual compliance reports to ASMFC, SCDNR reports that no repeat spawning marks have been observed in their sampling since 2001. Approximately 200 fish were sampled each year from both river and coastal ocean locations. SCDNR compliance reports note a low degree of repeat spawning in 1985 (3% for males and 2% for females) and Walburg (1956) did not record presence of spawning marks. There are no recent studies on the growth and fecundity of South Carolina shad.

3.18.3.1 Age

Data from commercially harvested shad in the Waccamaw, Santee, and Edisto Rivers were examined to evaluate whether the age of American shad has changed within these systems over time. Sampling levels for age and length are 200 fish per year in the Waccamaw and Santee Rivers, and are taken from the first 20 fish caught on the river each day. Samples are collected throughout the season to better represent the commercial catch. From 1979 to 1985, SCDNR staff collected extensive biological information from the state's commercial shad fisheries. Beginning in 2000, SCDNR once again began monitoring commercial fisheries on individual rivers on a rotating basis (North Santee 2000 to 2002; Waccamaw 2003 to 2005). Data for the Edisto River include SCDNR biological sampling from 1979 to 1985, 1996-1997, 2006-2007, and age data from Walburg's (1956) assessment efforts.

In the Waccamaw River, the maximum observed age decreased from age 6 (males) and age 7 (females) in 1979 to 1985 to age 5 (males) and age 6 (females) in 2003 to 2005. Although the maximum age and the range of ages appear to decrease in the Waccamaw River between the two sampling periods (Figure 311), length distributions (total length) appear similar between periods for both sexes (Figure 312). The dichotomy in changes in age and consistency in length between periods is likely due to discrepancies in ageing methods and variability related to using different readers.

3.18.4 Anthropogenic Sources of Mortality and Productivity

Potential sources for anthropogenic mortality are available in the SCDNR American Shad Habitat Plan (http://www.asmfc.org/files/ShadHabitatPlans/AmShadHabitatPlan_SC.pdf). No hatchery augmentation activities occur the Winyah Bay Complex.

3.18.5 Fishery-Dependent Data Sources

3.18.5.1 Landings

Complete statewide South Carolina landings can be found in Figure 310.

Winyah Bay landings averaged 37,695 kg a year since 1979, highlighted by a period of below average landings from 1987 to 2000 (ASMFC 2007b). The highest landings of the time series were in 1981 when 114,104 kg of shad was landed. Recent peaks in landings came in 2002 and 2004 with 85,502 kg and 77,167 kg of shad landed, respectively. Landings in 2017 were below average for the time series at 5,600 kg, which is likely attributable to shifting effort from Winyah Bay to the Waccamaw, Great Pee Dee, and Santee Rivers.

There was a decline in total Winyah Bay landings; however, a few points should be noted regarding the lesser shad rivers of this system. As discussed previously, the Sampit River no longer supported a commercial shad fishery by 1960 nor were any landings reported in 2005. By 2005, no landings were reported from the Lynches River (1960 landings = 13,428 kg) and the Black River only yielded 192 kg (1960 landings = 5,168 kg).

3.18.5.2 Catch and Effort

CPUE data are available for the Winyah Bay Complex (Winyah Bay, Great Pee Dee, Waccamaw, and Black Rivers (Table 237-Table 240)) gill net fisheries from 1999 to 2017.

CPUE data are available for the Winyah Bay Complex (Winyah Bay, Great Pee Dee, Waccamaw, and Black Rivers) gill net fisheries from 1999 to 2017, but have fluctuated with trend ($p = 0.8473$, slope = -0.206, and $R^2 = 0.002$) (Table 237 - Table 240; Figure 314-Figure 315).

3.18.5.3 Tagging

No tagging data exploitation rates are presented.

3.18.6 Fishery-Independent Data Sources

3.18.6.1 Adult Fishery-Independent Data Sources

3.18.6.1.1 Waccamaw River Adult Gill Net Survey

South Carolina DNR has conducted tag-return studies on the Waccamaw River (2003 to 2005; 2010-2017) to estimate in-river relative exploitation rate (RE) for pre-spawning female American shad. In this report, data for male American shad are also presented. From 1986 to 1988, SCDNR tagged shad in the Atlantic Ocean (at North Jetty Winyah Bay) but these data are not used in this assessment because the data could not be used to calculate a river-specific RE rate. However, in the previous and current ASMFC stock assessments, these data, in conjunction with other tagging and MtDNA studies, are used to partition mixed-stock landings from the ocean-intercept fishery (ASMFC 1998).

South Carolina DNR captures shad for tagging from late January through early May of each year with most tagging effort concentrated from late February through the end of April coinciding with the primary shad migration period. CPUE data are summarized (fish per 92 m net-hour) for the Waccamaw River (2003 to 2005; 2010-2017) in McCord (2000) and Post et al. (2004-2017), along with complete descriptions of the tagging programs. The short time series of these data sets do not permit any trend analysis, but, if continued on a regular rotating basis using the same methodology, these could provide a baseline for comparison with future CPUE estimates.

Shad were captured using 12.5 and 14.0 cm stretched-mesh monofilament drifting gill nets, 92 m long and 7.5 m deep. Fishing was conducted during low-flow periods of the tidal cycle to maximize catch rates. To minimize pre-tagging mortality or injury when possible, shad are removed as soon as they are caught. Typically, fishing gear was checked or retrieved within 30 minutes of being set.

Captured shad are held on board in a flow-through tank and most fish are transported and released approximately 200 m from the capture location in order to minimize immediate recapture of tagged shad. Only shad with actively moving opercula are tagged; the tags are cannula-implanted dart tags placed on the left side immediately below the dorsal fin. Tags are fluorescent orange and are printed with return address, reward notification and tag number. Public notification of the project included news releases before the season opening and posters posted at boat landings that outline the reward payment procedures (including payments for all returned tags) and the mechanics of the lottery drawing for two rewards each of $50 and $100. Rewards for individual tag returns depended on the project budget and the number of tag returns.

The in-river relative exploitation estimates from these studies should be considered lower bound estimates of exploitation rates because they do not account for tag loss, post tagging mortalities, “fallback” of tagged shad, and non-reporting of recaptured shad (McCord 2000). Fall-back describes fish that are tagged and then do not continue their migrations upriver

(Hightower and Sparks 2003; Olney et al. 2006). In addition, the design of a high-reward component of tagging studies clearly distinguishes high-reward tags from low-reward tags. The purpose of conducting a high-reward study is to determine the difference in reporting rate between regular low-reward tags and high-reward tags that should be returned at a higher rate (approaching 100%). The lottery system, as used by SCDNR, based on a single batch of tags that did not distinguish differing reward levels does not achieve this goal. Therefore, the level of tag underreporting remains unknown. Given the concerns with the tagging data, these data are not used to evaluate stock status.

From 2003 to 2005 and 2010 to 2017 in the Winyah Bay System, CPUE data were calculated for American shad captured by SCDNR for their tag- return studies. These data are not discussed in terms of stock status, since only 3 and 7 years of data exist.

3.18.7 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance, mean length, and mean length-at-age. Delay-difference models were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Details for these methods are provided in Section 2.

3.18.8 Results

3.18.8.1 Abundance Trends

3.18.8.2 Power Analysis

For the Winyah Bay System, three separate fishery-dependent commercial CPUE indices were available for power analysis from rivers feeding Winyah Bay, one from the Waccamaw River (median PSE = 0.808), one from the Black River (median PSE = 0.986), and one from the Great Pee Dee River (median PSE = 1.631). Despite each of these surveys being currently used in the SFMP for sustainability targets and monitoring, none of exhibit sufficient power to detect a 50% change in abundance over 10 years (Table 25).

3.18.8.2.1 Mann-Kendall Analysis

Commercial CPUE of American shad from the Black, Great Pee Dee, and Waccamaw Rivers between 2001 and 2017 were submitted as fishery-dependent indices. Plots of CPUE indices showed a substantial amount of error around index values and very little change in index values for all three rivers, with the exception of a large peak in 2009 from the Black River (Figure 313-Figure 315). Mann-Kendall trend analysis found an increasing trend in the Black River for the period from 2005 forward, but failed to detect a trend over the full time series in the Black River. No significant trends over time were found in either the Great Pee Dee or Waccamaw Rivers.

3.18.8.3 Mean Length Trends

The Waccamaw River is one of four major rivers that drains into Winyah Bay, which has supported South Carolina's largest commercial shad fishery in past years. The larger shad fisheries and populations have previously been centered in the lower 64 km of the Waccamaw River. Through a fishery-dependent commercial fishery monitoring program American shad length data was provided by South Carolina DNR for the Waccamaw River. Length data is available for some years between 1979 and 2017, with a gap in the time series between 1985 and 2003. A plot of mean total length showed a general decline in mean length for females over time and a sharp decline in mean length of males from 1982-1983 (Figure 316). Mann-Kendall analysis showed a significant decrease in mean length for females and no significant trend for male American shad. Two additional programs were submitted for the Winyah Bay, but excluded from analysis due to low sample size or because the time series was too short.

3.18.8.4 Mean Length-at-Age Trends

Mean length-at-age data using scales were provided from the Commercial Fishery Monitoring program in the Waccamaw River. Only female American shad were included in the analysis and ranged between ages 3 and 7. Mann-Kendall trend analysis failed to detect any change in mean length-at-age over time in the program (Table 241).

3.18.8.5 Delay-Difference Model

Three abundance indices for American shad were developed for this system that were identified as suitable for use in the delay-difference model, the Black River Commercial CPUE index, the Great Pee Dee River Commercial CPUE index, and the Waccamaw River Commercial CPUE index. The delay-difference model was run using semelparous life history parameters and each of the indices individually.

Total commercial fishery catch was available for years between 1978 and 2017, while abundance indices developed from commercial CPUE surveys in the Black River were available for 2001 through 2017. Since the delay-difference model requires identical time series length for catch and index, the total catch was truncated to 2001 through 2017. Estimated biomass remained relatively constant throughout the time series (Figure 317). The ratio of estimated biomass to initial biomass indicated an initial decrease between 2001 and 2009, followed by a modest increasing trend through 2017. The index and effort showed opposing trends throughout the time series alternating widely, with effort showing a decline while the index indicated an increase over the time series. Observed and estimated catch from the model simulations show that total catches varied widely throughout the time series, with periods of increased harvest occurring in the early and late 2000s. Median TAC over 100 simulations was estimated to be 310,310 lbs, with overfishing unlikely to occur within the confidence intervals at catch levels equal to the mean of the final 3 years of the time series.

Total commercial fishery catch was available for years between 1978 and 2017, while abundance indices developed from commercial CPUE surveys in the Great Pee Dee River were available for 2001 through 2017. Since the delay-difference model requires identical time series length for catch and index, the total catch was truncated to 2001 through 2017. Estimated biomass decreased over the time series from a median high of 546,581 lbs in 2001 to a low of 314,290 lbs in 2017 (Figure 318). The ratio of estimated biomass to initial biomass demonstrates an exaggerated view of the difference in biomass over time, with decreasing trend over the time series. The index and effort showed opposing trends throughout the time series alternating widely, with both showing an overall decline over the time series. Observed and estimated catch from the model simulations show that total catches varied widely throughout the time series, with three periods of increased harvest followed by periods of markedly decreased harvest. Median TAC over 100 simulations was estimated to be 75,837.3 lbs, 2.5% lower than the average catch over the final 10 years of the time series.

Total commercial fishery catch was available for years between 1978 and 2017, while abundance indices developed from commercial CPUE surveys in the Waccamaw River were available for 2001 through 2017. Since the delay-difference model requires identical time series length for catch and index, the total catch was truncated to 2001 through 2017. Estimated biomass decreased over the time series from a median high of 551,331 lbs in 2001 to a time series low in 2010, then increasing to 208,216 lbs in 2017 (Figure 319). The ratio of estimated biomass to initial biomass demonstrates an exaggerated view of the difference in biomass over time, with decreasing trend over the time series. The index decreased sharply after 2001, then remained relatively low for the rest of the time series. Effort showed opposing trends to the index, with effort exhibiting an anomalously high year in 2005. Observed and estimated catch from the model simulations show that total catches varied widely throughout the time series, with three periods of increased harvest followed by periods of markedly decreased harvest. Median TAC over 100 simulations was estimated to be 73,394.2 lbs, 6% lower than the average catch over the final 10 years of the time series.

3.18.8.6 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Winyah Bay system, habitat estimates were based on information from the Waccamaw River and Great Pee Dee River. Current unobstructed habitat area for the Winyah Bay system represents 73.13% of the historical habitat extent (83.88 of 114.70 square kilometers).

3.18.9 Stock Status and Conclusions

Mortality[2]

Juvenile mortality status is unknown due to lack of data to make this determination. Adult mortality status is sustainable as the three-year average catch in 2017 was less than the delay-difference model median TAC estimate for all three models.

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[2] This status determination changed following the Peer Review Workshop. See the addendum (Section 9) for final status determination.

There was a declining trend detected in female mean length from 1981-2015, but no YOY recruitment data to compare to mean length trend analyses.

Abundance

Abundance status is unknown. There were no YOY abundance data available. There have been conflicting trends in adult abundance since 2005, with an increasing trend detected from the Black River Commercial CPUE and no trend detected from the Great Pee Dee River or Waccamaw River Commercial CPUE, further confounding assessment of abundance conditions in recent years.

3.18.10 Research Recommendations

Research recommendations should be prioritized based on the assumed magnitude of the American shad run and fisheries of a river. Comprehensive monitoring of the shad runs from two or three of South Carolina's major shad rivers to collect reliable data on age composition and relative abundance could be used to guide management for the whole state, as trends in market factors and alternative fisheries probably apply statewide. However, the danger in adopting such a strategy is that there could be loss of genetic diversity in the small or unmonitored rivers. The following recommendations are for all of South Carolina, not specific systems, unless noted.

Commercial Landings and Effort

- Continue and improve compliance with mandatory catch and effort reporting from commercial fishery for all American shad fisheries prosecuted in South Carolina waters.
- Continue the "volunteer CPUE" series to compare with CPUE series developed from comprehensive mandatory reporting database.
- Convert volunteer commercial catch and effort from field reports into digital format so raw data are available for future analysis.
- Collect age, length, weight, and spawning history information from shad caught in commercial fisheries in the Santee River, Winyah Bay system, Savannah River, and Edisto River.
- Conduct an age validation study of American shad from South Carolina rivers (especially, Santee River, Winyah Bay system, Savannah River, and Edisto River).

Tagging

- Continued monitoring of river systems (Santee River, Waccamaw River, and Edisto River) on rotating basis (yearly rather than a 3-year schedule).
- Improvements to tagging design (e.g., develop high-reward design, telemetry studies to get estimates of fall back, double tagging study to estimate tag loss, and tag-mortality study) to improve relative exploitation estimates.

- Conduct tagging studies for duration of shad migration and continue to collect effort information from sampling collections (e.g., soak time, net length, and mesh size) to permit development of CPUE calculations.

Creel Surveys

- Continue to conduct creel surveys in rivers with notable recreational fisheries (Savannah River and Cooper River). If necessary, conduct creel surveys on a rotating basis.

Fish Passage

- Develop species specific upstream and downstream passage efficiency at all rivers with priority given to Santee-Cooper system dams.
- Develop species specific counts at Pinopolis fish-lock on the Cooper River.

Juvenile Abundance Index

- Continue to develop reliable indices of juvenile abundance.

General

- Collect environmental covariates (tidal stage, flood stage, flow rate, water temperature, cloud cover, water clarity, annual precipitation, etc.) to aid development of CPUE indices.

3.19 Santee-Cooper

3.19.1 Habitat Description

The Santee River was historically one of the longest river systems on the Atlantic coast and supported spawning stocks of American shad as far as 438 km inland to Great Falls on the Wateree River and up to 602 km up the Congaree River (Figure 309; Walburg and Nichols 1967). The Cooper River likely supported a small shad stock before the creation of the lakes and rerouting of the Santee River. The South Carolina Public Service Authority (SCPSA) initiated the Santee-Cooper Diversion Project in 1938. This project included the construction of the Santee Dam for flood control on Santee River at rkm 143, which created Lake Marion and the construction of Pinopolis Dam at rkm 77, which is a hydroelectric facility and navigation lock. Pinopolis Dam formed Lake Moultrie (Cooke and Leach 2003; Figure 309). With the increased flows resulting from the Diversion, the Cooper River likely attracted larger runs of anadromous species.

Increased flows from the Santee-Cooper Diversion Project to the Cooper River led to shoaling in Charleston Harbor. The Cooper River Rediversion Project reduced shoaling in Charleston Harbor by diverting water back to the Santee River through a 15 km Rediversion Canal. The St. Stephen Dam was constructed 7 km up the Rediversion Canal to control the flow from Lake Moultrie to the Canal and has a hydroelectric facility and a fish-lift. The Rediversion Canal was completed in 1985 and approximately 75 percent of the Cooper River's flow was returned to the Santee River, increasing its flow from 63 cubic meters per second (cms) to 295 cms (Cooke and Leach 2003).

Passage efficiency at St. Stephen is unknown but believed to be less than 100 percent during the years of this assessment. It varied over years as modifications to turbine operation and flow regimes were made to improve the attraction of fish to the lift, which is considered to have generally improved efficiency since 1990. In 2017, SCDNR conducted a passage efficiency study for American shad and blueback herring. Acoustic telemetry combined with Passive Integrated Transponder (PIT) tag arrays were used in the tailrace and exit chamber of St. Stephen Dam and associated fish lift. It was determined passage was between 21 and 40% during that season. Another confounding factor is that the Santee River experiences dramatically different flow regimes dependent on annual inflows and releases from the St. Stephen Powerhouse resulting in variations of attraction flow between years.

Initially, high or intermittent discharges from the St. Stephen Dam prevented fish from entering the lock. In the 1990s, the SCPSA implemented a flow agreement to improve the fish-lift function, and a series of modifications were completed from 1995 through 2000 that increased the efficiency of the fish-lift, but in low flow years, when water levels are not adequate for turbine operation, fish may bypass the Rediversion canal and use the Santee River proper. Pinopolis and St. Stephen Dams receive priority for releases to produce electricity from their hydroelectric facilities. This leads to minimal flow releases from the Santee dam.

There are no fish passage facilities on the Santee Dam on the Santee River. The relative flow of the Santee River varies among years and can influence American shad migration and, therefore, the passage of shad through the St. Stephen fish-lock each year. The discharge of water from the St. Stephen Dam in moderate to high flow years provides an attractive flow to the Rediversion Canal for fish migrating up the Santee River. However, drought conditions, such as those experienced earlier this decade, reduce the availability of American shad at the St. Stephen fish-lift and fish may bypass the Rediversion Canal in those years.

Mortality of juvenile and adult American shad associated with cleaning and dewatering the fish-lift has decreased from the 1990s to recent years (e.g., 4,061 adult and 72,715 juvenile mortalities in 1999 to 129 adult and 200 juvenile mortalities in 2004) (Cooke and Leach 1999; Leach and Cooke 2005). These reductions are attributed to improvements in the operational protocol and increasing the size of the floor grating to reduce impingement. The relative flow of the Santee River proper compared to that of the Rediversion Canal varies among years and can influence American shad migration and, therefore, the passage of shad through the St. Stephen fish-lock each year. The discharge of water from the St. Stephen Dam in moderate to high flow years provides an attractive flow to the Rediversion Canal for fish migrating up the Santee River. However, drought conditions, such as those experienced earlier this decade, reduce the availability of American shad at the St. Stephen fish-lift and fish may bypass the Rediversion Canal in those years.

There have been no directed studies to determine turbine mortality on American shad at the St. Stephen Dam, although it is believed that turbine strike mortality is minimal, with anecdotal information indicating that passage is more problematic for larger fish. Turbine mortality studies may be conducted as part of the Federal Energy Regulatory Commission (FERC) relicensing process in the Santee-Cooper system. Blueback herring (Alosa aestivalis) may be more affected by the pressure differential than by turbine strikes during their downstream migration through the facility (William McCord, SCDNR, pers. comm.). Above Lake Marion, several impediments to migrations exist on Santee River tributaries. On the Wateree River, the Wateree Dam is the first obstruction to fish passage.

3.19.2 Fishery and Management History

South Carolina manages its shad fisheries using a combination of seasons, gear restrictions, and catch limits implemented over several management units: Santee River; Charleston Harbor (Wando, Cooper, and Ashley Rivers).

Beginning with the 1998 commercial shad-netting season, all licensed fishermen are required to report their daily catch and effort to SCDNR. In 2000, Act #245 of the 2000 South Carolina General Assembly was passed in response to the perceived population status of shad populations in each of the state's river systems supporting an American shad fishery.

Significant changes in shad and herring regulations became effective with the 2001 with the passage of the Marine Resources Act of 2000, which gave giving SCDNR authority to implement a permit program for the State's shad and herring fisheries. All commercial shad and herring fishery license holders were issued permits that could be used to "restrict the number of nets for taking shad…in any body of water where the number of nets or fishermen must be limited…to prevent congestion of nets or watercraft, or for conservation purposes." The number and conditions of permits can be controlled "to designate areas, size, and take limits, hours, type and amount of equipment, and catch reporting requirements," and enabled SCDNR to phase out the ocean-intercept fishery by 2005. In addition, a recreational aggregate creel limit of 10 American and hickory shad per person was implemented in all state waters, except for the Santee River in which a 20 fish creel limit was set.

Additionally, with requirements initiated by Amendment 3 to the ASMFC shad and river herring Fishery Management Plan (FMP), South Carolina was required to develop a shad Sustainability Fishery Management Plan (SFMP) to demonstrate sustainability in all rivers where shad fisheries occurred. A sustainable fishery was defined as "those that demonstrate their stock could support a commercial and/or recreational fishery that will not diminish the future stock reproduction and recruitment." Acceptable measures to develop sustainability benchmarks included mark-recapture studies, enumeration at fish passage facilities, catch-per-unit-effort (CPUE) by appropriate sample gear, or other indices of abundance. If sustainability could not be demonstrated, those fisheries were to be closed. In 2012 and again in 2017, South Carolina's SFMP was approved by the ASMFC Shad and river herring Technical Committee and Shad and river herring Management Board. Measures in the SFMP required a 50 %percent statewide reduction for available commercial gill nets, juvenile shad fishery independent surveys, and closure of several river systems where sustainability could not be demonstrated.

The Santee River was historically one of the largest watersheds on the Atlantic coast and supported spawning stocks of American shad as far as rkm 483. With the impoundment of the Santee-Cooper lakes in the late 1940s, this system was closed to anadromous fish migrations above rkm 121. This situation persisted through 1985, when the Santee-Cooper Rediversion Canal and fish-lift at St. Stephen Dam were completed. The fish-lift passes pre-spawning adult shad into the lakes and provides access to historical spawning grounds in portions of the Wateree and Congaree Rivers. Since completion of the Rediversion Project, the shad and river herring gill net fisheries have been restricted to protect the Santee River striped bass population and sturgeon from incidental catches. The entire Rediversion Canal and Santee channel below Santee dam are closed to gill nets. Two sections downriver of the closed area remain open to commercial fishing. The upper of the two sections extending 48 km seaward of the closed area has had the open fishing period reduced by over 80 percent compared to what it was before rediversion. This section of river is open to commercial fishing from January 15 to April 15 Tuesdays and Thursdays 0700 to 1900 hours. The lower 48 km of the river remains open to shad fishing Monday noon through Saturday noon from January 15 through April 1. The recreational fishery on the Rediversion Canal has reportedly increased in recent years; however, it was not monitored as frequently as the Cooper River recreational fishery.

3.19.2.1 Restoration Projects

The USFWS, NOAA Fisheries, and SCDNR developed a fish restoration plan for the Santee-Cooper River basin with proposed restoration targets (USFWS et al. 2001); however, river-specific goals were not established for other systems in South Carolina.

The proposed Santee-Cooper restoration goals were based on a target number of 50 fish per acre for currently available habitat and possible habitat if all upstream dams were equipped with effective fish passage. Effective fish passage at Santee-Cooper Project dams (Pinopolis, St. Stephen, and the Santee Dam) is identified as an essential requirement for restoration throughout the Basin. The plan identifies restoration priorities for upstream sub-systems of the Santee-Cooper reservoirs and main stem rivers including the Saluda River, Wateree-Catawba system, and Broad River. If all upstream dams were outfitted with adequate fish passage, the restoration target for the entire South Carolina portion of the Santee-Cooper Basin was estimated at 3.3 million American shad. However, as of preparation of this assessment (2020), the FERC license for Santee-Cooper has not been issued, so many of the measures included in the license agreement and settlement agreement have not been initiated.

3.19.3 System-Specific Life History

American shad returning to South Carolina rivers are generally believed to be semelparous. In annual compliance reports to ASMFC, SCDNR reports that no repeat spawning marks have been observed in their sampling since 2001. Approximately 200 fish were sampled each year from both river and coastal ocean locations. SCDNR compliance reports note a low degree of repeat spawning in 1985 (3% for males and 2% for females) and Walburg (1956) did not record presence of spawning marks. There are no recent studies on the growth and fecundity of South Carolina shad.

3.19.3.1 Age

In the Santee River, the maximum observed age decreased from age 6 (males) and age 7 (females) in 1979 to 1985 to age 5 (males) and age 6 (females) in 2000 to 2003. Age and total length frequency distributions (Figure 320 and Figure 321) indicate that younger and smaller fish were observed in the recent period. The change in age and length distributions could be influenced by the opening of the Rediversion Canal in 1985, as the increased flow to the Santee River has led to improved recruitment. Moreover, these changes could be attributable to increased shad attraction resultant from improved water quality and flow conditions in the river. Another explanation is that the decrease in age and length could be a function of increased fishing rate, as landings and the population increased after the completion of the Rediversion canal. Changes in gear selectivity are less likely as the same mesh size (5.5 inch) was employed in both periods but are not discountable. Similarity in direction of length and age change over time provides some support that shad ageing has been consistent over these periods but does not provide support of the accuracy of ageing data. American shad have been sampled opportunistically at the St. Stephen fish-lock since 1992 and have showed no trend in mean fork length through 2003 for both males and females (Figure 321; Leach and Cooke 2005).

3.19.4 Anthropogenic Sources of Mortality and Productivity

Potential sources for anthropogenic mortality are available in the SCDNR American Shad Habitat Plan (http://www.asmfc.org/files/ShadHabitatPlans/AmShadHabitatPlan_SC.pdf).

The St. Stephen Fish Lock located on the Rediversion Canal of the Santee River System has operated since 1985. The lock is located upstream of any recreational or commercial fishing effort, so this escapement and subsequent passage should be considered fish actively contributing to reproduction in the Santee River System. Seasonal shad mortalities associated with fish passage at this facility are minimal relative to amount of fish passed annually (<1%).

Additionally, as part of the Santee Accord stock enhancement study, adult American shad were captured 2008-2017 during spawning runs using with electrofishing methods or a trap basket at the St. Stephen fish lock. These fish are used as brood fish to produce fry to be stocked in the upper tributaries in the Santee River System. Through 2017, a total of 25,336,131 (24,000-4,292,654) fry were released.

3.19.5 Fishery-Dependent Data Sources

South Carolina has monitored commercial fisheries for American shad within state waters since 1979, although historical records for South Carolina date back much farther (Figure 311). The NOAA Fisheries landings data before 1979 were collected from major wholesale outlets located near the coast; therefore, it is likely that inland landings were not completely accounted for in these years, since many shad fishermen claim not to sell their catch and keep it for personal consumption. This results in discrepancies between SCDNR and NOAA Fisheries American shad landings in South Carolina through the time series. No landings were attributed to the South Carolina ocean-intercept fishery before 1979. SCDNR has records of landings by system since 1979 for the Atlantic Ocean (i.e., the ocean-intercept fishery), Santee, and Cooper Rivers (Figure 312). Data collected since 1979 generally include inland landings and should be considered as a separate time series.

The Cooper River supports an active recreational fishery below the Pinopolis Dam tailrace in the late winter to early spring. SCDNR has conducted a creel survey from 2001 to 2017 to estimate exploitation and catch-per-effort in this recreational fishery. SCDNR also conducted sportfishing creel surveys on the Cooper and Santee Rivers from 1981 to 1982 and 1991 to 1993 in order to evaluate the impact of the Rediversion Canal on these rivers' recreational fisheries (Cooke and Chappelear 1994). These surveys examined the total recreational fisheries on each river for each study period. For the purpose of this assessment, the Cooper River survey can indicate changes in the magnitudes over time and is presented as an abundance trend for the Cooper River shad population.

3.19.5.1 Santee River

3.19.5.1.1 Landings

The Santee River stands alone as the only South Carolina River that has experienced a consistent increase in shad harvest over the last 100 years. Walberg and Nichols (1967) reported a Santee shad harvest of 15,183 kg in 1896, which increased to 24,610 kg in 1960. Since 1979, Santee River commercial shad harvest has averaged 42,260 kg a year, with 53,788 kg landed in 2005. Note that the "modern" landings include "before and after" Rediversion landings, where annual harvest averaged 2,482 kg a year before the Rediversion canal was completed in 1985 (ASMFC 2007b).

The Santee River shad landings averaged only 2,554 kg from 1979 to 1985; however, since the completion of the Rediversion Canal in 1985 the shad run and, concurrently, landings have risen to an average of 91,286 kg a year since 1995 (ASMFC 2007b). In 2005, Santee River shad landings were 53,788 kg, the lowest since 1995. Annual fishing effort has averaged 619 trips since 1999 and the number of trips in 2017 dropped to 366 from 696 in 2004 (Table 242).

3.19.5.1.2 Catch and Effort

CPUE for this fishery indicates a stable trend for the time series (Table 243).

3.19.5.1.3 Fish Passage

From 2001 to 2017, annual American shad passage decreased compared to the previous 6 years (Table 244 and Figure 322). Counts peaked from 1995 through 2000 ranging from 306,493 to 592,321 shad passed per year. Since 2001, annual counts averaged 202,147 shad and in 2018 a total 320,092 shad were passed through the fish-lift.

3.19.5.1.4 Minimum population of American Shad on the Santee River

Count data from the Stephen fish-lift are available since 1988, but Santee River commercial gill net landings in numbers by sex are only available since 1998; however, Santee River landings by weight are available to 1988. The ratio of male to female American shad in pounds landed was calculated for the period 1999 to 2017 (males = 7%, females = 93%). This ratio was applied to the commercial gill net landings from 1988 to 1998 to partition the landings between male and female. To convert the landings in weight estimate to numbers, the landings of male and female shad were divided by the average weight of male (1.36 kg) and female (1.81 kg) shad.

A minimum population bound was calculated by summing landings and fishway counts in numbers for each year. This is considered a minimum bound because landings are known to be underreported and do not include recreational removals from the Rediversion Canal fishery, which can be significant at times. Additionally, fish passage at the St. Stephen fish-lift is known to be less than 100 percent and operational outages can also severe at times. Minimum population size ranged from 16,387 in 1988 to a high of 667,106 in 2000 with 332,659 estimated in 2018 (Figure 322).

3.19.5.2 Cooper River

3.19.5.2.1 Landings

The Cooper River supports an active recreational fishery below the Pinopolis Dam tailrace in the late winter to early spring. SCDNR has conducted a creel survey from 2001 to 2017 to estimate exploitation and catch-per-effort in this recreational fishery. SCDNR also conducted sportfishing creel surveys on the Cooper and Santee Rivers from 1981 to 1982 and 1991 to 1993 in order to evaluate the impact of the Rediversion Canal on these rivers' recreational fisheries (Cooke and Chappelear 1994). These surveys examined the total recreational fisheries on each river for each study period. For the purpose of this assessment, the Cooper River survey can indicate changes in the magnitudes over time and is presented as an abundance trend for the Cooper River shad population. Landings have been reported sporadically, with a high of 1294.1 kg in 1984 and a minimum reported value of 5 kg in 2004.

3.19.5.2.2 Cooper River Recreational Creel Survey

In the 2000 to 2016 American shad fishing seasons in the Cooper River Tailrace Canal, 11,143 surveys were conducted (mean = 655/y) over a total of 203 survey dates (mean = 41 d/y) (Table 245). Creel clerks were on duty an average of 6 hours per day. Annual estimates of the shad catch (in numbers) from 2000 to 2016 ranged from 2,158 to 16,626. Catch-per-man-hour (CPMH; Table 246) averaged 1.39 and ranged from 0.59 in 2002 to 2.86 in 2013. CPMH increased during the time series. A 10 fish per day creel limit has been in effect for the duration of this study. Twenty-two percent of the catch was released in 2005. A recreational creel survey conducted by SCDNR in the Cooper River before (1981 to 1982) and after (1991 to 1993) completion of the Rediversion Canal showed that, although effort increased slightly in the post-Rediversion survey, landings of all fish decreased over 50 percent from the earlier period (ASMFC 2007b). Additionally, in 2017 turbine operation schedule was changed to peaking rather than continuous flow. This change dramatically affected behavior of shad which resulted in a decrease in overall effort as well as CPMH. Therefore, data for 2017 are not included in this assessment.

3.19.6 Fishery-Independent Data Sources

South Carolina DNR has conducted tag-return studies on the Santee (1991 to 1992, 2000 to 2002, 2008-2010) to estimate the in-river relative exploitation rate (RE) for pre-spawning female American shad. However, tag return data were not reliable to estimate in-river RE for the time series.

3.19.6.1 Adult Fishery-Independent Data Sources

3.19.6.1.1 St. Stephen Locks Passage Count

The Cooper River Rediversion Project was completed in 1985. The Rediversion set a maximum weekly average discharge (127 cms) from Pinopolis Dam and the difference of the flows were redirected back to the Santee River primarily via the St. Stephen Dam and Rediversion Canal. The St. Stephen fish lift is located approximately mid-way on the Rediversion Canal at rkm 92. Migratory fish are attracted to the fish lift by a variable attraction flow up to approximately 21 cms. Typically, fish lift operations occur on the hour during daylight periods and every 30 minutes as required when fish densities are high. Each morning a “clearing” operation is made to pass fish collected overnight.

Fish passage at the St. Stephen Dam was monitored by hydroacoustic sampling from 1986 to 1987, real- time human counts from 1988 to 1994, and time-lapse video recording from 1994 to 2017. Since the proportion of Santee River American shad that entered the Rediversion Canal and the efficiency of the fish lift both are unknown and appear to vary among years, fish passage at this facility can only be used to document general abundance trends.

These passage data are not considered representative of interannual abundance changes and were not used in the assessment for abundance trend anlyses (Table 20).

3.19.6.1.2 Santee River Adult Gill Net Survey

Sampling conducted in the Santee River [river kilometer (rkm) 21] focuses on capturing adult American shad to establish catch data used in stock structure analysis. This location is a frequently utilized commercial netting area and is tidally influenced, with a reversal of flow upstream during flood tides. The channel width at this sampling site was 150 meters (m) with water depths at mean low tide ranging from 4–8 m. A 68.58 m drift monofilament gill net with 12.70 centimeter (cm) stretched mesh was deployed and retrieved using a 5.3 m open decked, outboard powered skiff. Depending on the tidal stage, either a 5.08 m deep or a 6.35 m deep net were used. Water temperature and salinity were recorded at the beginning and end of each sampling day using a thermometer and refractometer.

Netting effort for the purposes of this study was defined in “net hours”, where one net hour equals one 92 m drift for one hour. Captured fish were measured to the nearest fork length (FL) and total length (TL) in millimeters (mm), and an external dart tag placed in the dorsal musculature of each fish prior to release near the sample site (female tags: Model PDAT-Large, 145 mm, Hallprint; male tags: Model PDAT-Large, 110 mm, Hallprint). All tags were international orange or blue in color and inscribed with a tag number, return address, and the word “reward”, specifying an undetermined reward amount. News releases prior to the open season, and orange posters at applicable boat landings were used to publicize the project and encourage tag returns from commercially caught shad. Returns of tags encountered in the commercial shad fishery are used annually to estimate fishing mortality rates for American shad in the Santee River.

An index of abundance developed from this survey is in Table 247 and Figure 324.

3.19.6.1.3 Cooper River Fish Count

Pinopolis Dam is located approximately 77 km upstream from Charleston Harbor on the headwaters of Cooper River, South Carolina. A single-lift navigation lock, approximately 18.3 m wide by 73.2 m long, provides boat and fish passage between Cooper River and Lake Moultrie. An array of 11 upward facing, 235 KHz side-scan sonar transducers monitors fish passage. The transducers transmitted to a Bendix hydroacoustic biomass counter, which incorporates a conversion assuming an average swimming speed and mass of an adult blueback herring, 136 g. Counts were made in terms of these “herring units” and no species-specific counts are made. Using this antiquated technology is not a reliable method to assess passage at the lock, and it was discontinued in 2014. Therefore, these data are not used in this assessment.

3.19.7 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance, mean length, and mean length-at-age. Delay-difference models were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Details for these methods are provided in Section 2.

3.19.8 Results

3.19.8.1 Abundance Trends

3.19.8.1.1 Power Analysis

Three abundance indices for American shad were developed for this system that contained estimates of PSE, the Cooper River Recreational Creel Survey (median PSE = 0.062), the Santee River Adult Gill Net Survey (median PSE = 0.214), and the Santee River Commercial CPUE index (median PSE = 1.680). Each of these surveys are currently used in the SFMP for sustainability targets and monitoring.

Of these surveys, the Cooper River Recreational Creel Survey exhibits sufficient power to detect a 50% change in American shad abundance in 10 years, while the Santee River Adult Gill Net

Survey is only able to detect a 50% decrease at the desired 0.80 power level (Table 25). The Santee River Commercial CPUE index, with its large median PSE, exhibits very little power to detect a 50% change in abundance over 10 years.

3.19.8.1.2 Mann-Kendall Analysis

Data from a fishery-dependent and two fishery-independent surveys were examined as indices for American shad in the Santee-Cooper River. A plot of the Santee River Commercial CPUE showed substantial error associated with data points and no visual trend in changes over time (Figure 323). Mann-Kendall trend analysis confirmed this with no trend detected for either time period examined. The Santee River Adult Gill Net Survey provided index data from 2008-2017, and a plot showed only a slight decline over the time series with no apparent patterns (Figure 324). Data from the Cooper River Recreational Creel Survey was available for 2000-2016, and a plot showed inter-annual fluctuation through 2011, a large increase in the index value from 2011-2013 (Figure 325). Mann-Kendall trend analysis failed to detect any trends for the Santee River Adult Gill Net Survey, but found an increasing trend for both time periods in the Cooper River Recreational Creel Survey.

3.19.8.2 Mean Length Trends

3.19.8.2.1 Cooper River

South Carolina DNR collects American shad lengths as part of the Cooper River Recreational Creel Survey. Lengths are available between 2000 and 2017. A plot of mean lengths showed a general increase in mean lengths of both sexes from 2008-2017 (Figure 326). However, while Mann-Kendall analysis found a significant increasing trend in female mean lengths, no trends were found for males.

3.19.8.2.2 Santee River

The South Carolina DNR has provided American shad length data from both fishery-independent and fishery-dependent collections in the Santee River. The St. Stephen Locks Passage Count is a fishery-independent program that has given mean length data of American shad from 2000-2017. The plot shows no trend, but a distinct decline for males from 2003-2005 and females from 2004-2006 with similar fluctuations occurring through 2017 for both sexes (Figure 327). The Mann-Kendall analysis found no significant trend for either sex. The mean lengths submitted by the Santee River Recreational CPUE from 2006-2017 for male and female American shad show similar inter-annual fluctuations with no significant trends over time (Figure 328). This was supported by the Mann-Kendall analysis which found no significant trend occurring for either sex. The fishery-dependent Commercial Fishery Monitoring program has submitted a majority of data for females from 1979-2017, but very little years with sufficient samples for male American shad. The plot shows data missing from 1985-1999 as well as 2003-2007 for both sexes (Figure 329). Mann-Kendall analysis found a significant decrease in mean lengths in female American shad over the time period, but not for the few available male data points.

3.19.8.3 Mean Length-at-Age Trends

Mean length-at-age data using scales were provided from fishery-dependent Commercial Fishery Monitoring for the Santee River. Data was constrained to female American shad and covered ages 3 through 7. Mann-Kendall Trend analysis failed to detect any change in mean length-at-age over time in the Santee River (Table 248).

3.19.8.4 Delay-Difference Model

Two abundance indices for American shad were developed for this system that were identified as suitable for use in the delay-difference model, the Santee River Commercial CPUE index and the Cooper River Recreational Creel Survey. The delay-difference model was run using semelparous life history parameters and each of the indices individually.

Total commercial fishery catch was available for years between 1996 and 2017, while abundance indices developed from commercial CPUE surveys in the Santee River were available for 2001 through 2017. Since the delay-difference model requires identical time series length for catch and index, the total catch was truncated to 2001 through 2017. Estimated biomass decreased over the time series from a median high of 894,445 lbs in 2001 to a time series low of 403,348 lbs in 2016, then increasing to 434,117 lbs in 2017 (Figure 330). The ratio of estimated biomass to initial biomass demonstrates an exaggerated view of the difference in biomass over time, with decreasing trend over the time series. The index decreased sharply after 2014, ending the time series below average. Effort showed opposing trends to the index, with effort exhibiting an anomalously high year in 2011. Observed and estimated catch from the model simulations show that total catches varied widely throughout the time series, with periods of increased harvest followed by periods of decreased harvest. Median TAC over 100 simulations was estimated to be 122,903.6 lbs. Overfishing is likely to occur at catch levels equal to the mean of the final 3 years of the time series; however, confidence bounds indicate that overfishing might not occur.

Total commercial fishery catch was available for years between 1996 and 2017, while abundance indices developed from the Cooper River Recreational Creel Survey were available for 2000 through 2017. Since the delay difference model requires identical time series length for catch and index, the total catch was truncated to 2000 through 2017. Estimated biomass decreased over the time series from a median high of 1,002,830 lbs in 2000 to a time series low of 378,192 lbs in 2012, then increasing to 564,903 lbs in 2017 (Figure 331.A). The ratio of estimated biomass to initial biomass demonstrates an exaggerated view of the difference in biomass over time, with decreasing trend over the time series (Figure 331.B). The index increased over time, with a sharp drop at the end of the time series. Effort showed opposing trends to the index (Figure 331.C). Observed and estimated catch from the model simulations (Figure 331.D, black line and gray ribbon, respectively) show that total catches varied widely throughout the time series, with periods of increased harvest followed by periods of decreased harvest. Median TAC over 100 simulations was estimated to be 195,421.4 lbs (Figure 331.E), with overfishing unlikely to occur within the confidence intervals at catch levels equal to the mean of the final 3 years of the time series.

3.19.8.5 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Santee-Cooper system, habitat estimates were based on information from the Santee, Cooper and Ashely Rivers. Current unobstructed habitat area for the Santee-Cooper System represents 20.95% of the historical habitat extent (37.19 of 177.50 square kilometers).

3.19.9 Stock Status and Conclusions

Mortality[2]

Juvenile mortality status is unknown due to lack of data to make this determination. Adult mortality status is also unknown due to conflicting results of the delay-difference models. The delay-difference model using Santee River Commercial CPUE indicated unsustainable mortality levels as the three-year average catch in 2017 was greater than the median TAC estimate, while the delay-difference model using the Cooper River Recreational Creel Survey index indicated sustainable mortality levels with the three-year average catch in 2017 being less than the median TAC estimate.

There were inconsistent trends detected in female length from four data sets of varying time series (1979-2017, 2000-2014, 2000-2017, 2006-2017). There were no YOY recruitment data to compare to mean length trend analyses.

Abundance

Abundance status is unknown. There were no YOY abundance data available. There have been conflicting trends in adult abundance since 2005, with an increasing trend detected from the Cooper River Recreational Creel Survey and no trend detected from the Santee River Adult Gill Net Survey or Santee River Commercial CPUE, further confounding assessment of abundance conditions in recent years.

3.19.10 Research Recommendations

Refer to Section 3.18.10 for general South Carolina research recommendations.

3.20 ACE Basin

3.20.1 Habitat Description

The lower portions of these systems comprise the ACE (Ashepoo-Combahee-Edisto) Basin National Estuarine Research Reserve (Figure 309). The Edisto River system drainage, which has no dams, is approximately 4,800 km^2 within the South Carolina Coastal Plain and is

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[2] This status determination changed following the Peer Review Workshop. See the addendum (Section 9) for final status determination.

approximately 320 km long. At approximately rkm 180, the North and South Forks merge forming the Edisto River proper. Returning American shad reach at least rkm 161 in the North Edisto and at least rkm 193 in the South Edisto on their spawning migration (Walburg and Nichols 1967). The system is tidally influenced 75 km upstream and the lower 50 km drains substantial areas of fresh, brackish and salt marsh. The watershed is similar to that of its smaller sister rivers, the Combahee and Ashepoo, as all three of these rivers are connected in their lower 20 km before entering the Atlantic Ocean through St. Helena Sound. The Combahee River is a black-water river about 72 km long and is formed at the confluence of the Salkehatchie and Little Salkehatchie before draining into St. Helena Sound. There are no impediments on the Combahee River and spawning shad reach rkm 137 near Walker, South Carolina (Walburg and Nichols 1967). The Ashepoo River is the smallest of the ACE Basin Rivers and has no obstructions to shad migration. Shad reach rkm 80 on their annual spawning migration (Walburg and Nichols 1967).

An environmental factor that might have affected the American shad population in the ACE Basin was the increase in timber harvest in the 1980s possibly resulting in increased siltation from the flood plains to potential spawning habitat (Chris Thomason, SCDNR, personal communication).

3.20.2 Fishery and Management History

South Carolina manages its shad fisheries using a combination of seasons, gear restrictions, and catch limits implemented for the Edisto River and all tributaries and distributaries.

The first river-specific commercial regulations for American shad in South Carolina were enacted in 1993 for the Edisto River in response to SCDNR's studies that identified overfishing as a major contributor to a perceived trend of population decline [Act # 343 of the 1992 South Carolina General Assembly]. Beginning with the 1998 commercial shad-netting season, all licensed fishermen are required to report their daily catch and effort to SCDNR. In 2000, Act #245 of the 2000 South Carolina General Assembly was passed in response to the perceived population status of shad populations in each of the state's river systems supporting an American shad fishery. This Act led to the closure of the commercial gill-net fishery on the Coosawhatchie River and a substantial reduction in potential gill-net fishery effort for other systems supporting small American shad stocks in South Carolina, including the Combahee, Ashepoo, and Ashley rivers (www.dnr.sc.gov).

Significant changes in shad and herring regulations became effective with the 2001 with the passage of the Marine Resources Act of 2000, which gave giving SCDNR authority to implement a permit program for the State's shad and herring fisheries. All commercial shad and herring fishery license holders were issued permits that could be used to "restrict the number of nets for taking shad…in any body of water where the number of nets or fishermen must be limited…to prevent congestion of nets or watercraft, or for conservation purposes." The number and conditions of permits can be controlled "to designate areas, size, and take limits, hours, type and amount of equipment, and catch reporting requirements," and enabled SCDNR to phase out the ocean-intercept fishery by 2005. In addition, a recreational aggregate creel limit of 10 American and hickory shad per person was implemented in all state waters, except for the Santee River in which a 20 fish creel limit was set.

Additionally, with requirements initiated by Amendment 3 to the ASMFC Shad and River Herring FMP, South Carolina was required to develop a shad Sustainability Fishery Management Plan (SFMP) to demonstrate sustainability in all rivers where shad fisheries occurred. A sustainable fishery was defined as “those that demonstrate their stock could support a commercial and/or recreational fishery that will not diminish the future stock reproduction and recruitment.” Acceptable measures to develop sustainability benchmarks included mark-recapture studies, enumeration at fish passage facilities, catch-per-unit-effort (CPUE) by appropriate sample gear, or other indices of abundance. If sustainability could not be demonstrated, those fisheries were to be closed. In 2012 and again in 2017, South Carolina’s SFMP was approved by the ASMFC Shad and river herring Technical Committee and Shad and river herring Management Board. Measures in the SFMP required a 50 %percent statewide reduction for available commercial gill nets and a 80-90 %percent reduction in rivers where declining trends were observed (Edisto and Combahee Rivers), juvenile shad fishery independent surveys, and closure of several river systems where sustainability could not be demonstrated.

3.20.2.1 Edisto River

The Edisto River is approximately 356 km long and is open to the shad gill net fishery (both set and drift nets) for its entirety and continues to support a gill net fishery to approximately rkm 161. The Edisto River has supported commercial shad fishery for over 100 years and a recreational fishery since the late 1960s (Walburg and Nichols 1967; Wade 1972). Historically commercial fishery effort was concentrated between rkm 30 and 50, with gill netting, bow netting, and hook and line fishing occurring to rkm 170. Sporadic recreational netting extended into the North and South Forks for at least an additional 50 km. Current fisheries occur in the same areas, but at reduced levels of effort. Both set or anchored and drifting gill nets have been used in the commercial fishery for many years. Both historically and in recent years, there has been virtually no effort below rkm 32.

Set nets fished between rkm 40 and rkm 48 are typically fished only during flood and slack tide periods when currents are weakest. From rkm 48 to about rkm 161, relatively short set nets are typically fished in eddies or slow-moving waters below creek entrances, below the mouths of oxbows lakes, or in deep holes along undercut banks on the outside of river bends.

A noteworthy shad fishery existed on the Edisto River in the vicinity of Willtown Landing that began after WWII and lasted through the early 1980s. There were at least 30 “Willtown netters” and they used both drift and set gill nets (William J. McCord, SCDNR, pers. comm.).

In 2013, as part of South Carolina’s SFMP, the number of lawful gill nets allowed was reduced by 80%, resulting in a dramatic decline of licensees for this river in recent years.

3.20.2.2 Combahee River

The Combahee River is approximately 72 km long and both drift and set gill nets are legal. Nearly all activity in the fishery occurs between about rkm 40 and rkm 80. Drift nets are rarely, if ever, used on the Combahee River due to its winding channels, rapid currents, varying water depths, and many bottom obstructions.

In 2013, as part of South Carolina's SFMP, the number of lawful gill nets allowed was reduced by 90%, resulting in a dramatic decline of licensees for this river in recent years.

3.20.3 System-Specific Life History

American shad returning to South Carolina rivers are generally believed to be semelparous. In annual compliance reports to ASMFC, SCDNR reports that no repeat spawning marks have been observed in their sampling since 2001. Approximately 200 fish were sampled each year from both river and coastal ocean locations. SCDNR compliance reports note a low degree of repeat spawning in 1985 (3% for males and 2% for females) and Walburg (1956) did not record presence of spawning marks. There are no recent studies on the growth and fecundity of South Carolina shad.

3.20.3.1 Age

In the Edisto River, age data were available for 1955 (Walburg 1956), 1979 to 1985, 1996-1997, and 2006-2007 and the maximum observed ages for males (age 5) and females (age 6) did not change between the two periods. Age distributions for male and female shad between the two periods also appear similar (Figure 332 and Figure 333). The percentage of female shad at each age was virtually the same, while the males were similar. No length data from Walburg (1956) were available to compare the two periods.

3.20.4 Anthropogenic Sources of Mortality and Productivity

Potential sources for anthropogenic mortality are available in the SCDNR American Shad Habitat Plan (http://www.asmfc.org/files/ShadHabitatPlans/AmShadHabitatPlan_SC.pdf).

Additionally, as part a trial stock enhancement restoration effort (2010-2017), SCDNR partners with USFWS to capture adult American shad during spring spawning runs using with electrofishing methods. Fish are used as brood fish to produce fry to be stocked in the Edisto River. Through 2017, a total of 155,695 (0 - 88,458) fry were released.

3.20.5 Fishery-Dependent Data Sources

South Carolina has monitored commercial fisheries for American shad within state waters since 1979, although historical records for South Carolina date back much farther (Figure 310). The NOAA Fisheries landings data before 1979 were collected from major wholesale outlets located near the coast; therefore, it is likely that inland landings were not completely accounted for in these years, since many shad fishermen claim not to sell their catch and keep it for personal consumption. This results in discrepancies between SCDNR and NOAA Fisheries American shad landings in South Carolina through the time series. No landings were attributed to the South Carolina ocean-intercept fishery before 1979. SCDNR has records of landings by system since 1979 for the Atlantic Ocean (i.e., the ocean-intercept fishery), Edisto River and Combahee Rivers (Table 249; Figure 336). Data collected since 1979 generally include inland landings and should be considered as a separate time series.

3.20.5.1 Edisto River

3.20.5.1.1 Landings

The magnitude of the Edisto River commercial fishery has consistently declined over the last century. In 1896, landings were 58,732 kg, but they dropped to 15,145 kg in 1960. From 1979 to 2005, Edisto River commercial shad landings averaged 2,934 kg a year. Landings in the Edisto River have been below the time series average (2,934 kg) for 13 of the last 15 years (ASMFC 2007b). The lowest landings in the time series occurred from 1994 to 1997 when annual landings ranged between 354 kg and 1,132 kg. Since 1999, landings have averaged 1,380 kg a year with 898 kg landed in 2017.

3.20.5.1.2 Catch and Effort

No effort data were collected for American shad fisheries before 1979; thus, it was not possible to attribute stock fluctuations to changes in fishing effort, changes in spawning stock size, or other factors. License data are available but are not useful as many shad fishermen participated on a part-time basis and the amount of gear deployed was not specified in records. In addition, approximately 80 percent of the licensed fishermen fished infrequently, precluding estimation of total effort and, therefore, CPUE (Ulrich et al. 1978).

Commercial American shad catches were sampled to collect biological data (e.g., length, weight, and age) by SCDNR from American shad fishermen at boat ramps from 1979 to 1985 for rivers with an active American shad fishery. During this time, SCDNR identified a group of “reliable” fishermen from which to collect catch and effort data. Voluntary catch records (data sheets) from these fishermen were used to develop fishery-dependent catch-per-unit-effort (CPUE) from 1979 to 2000. Starting in 1998, SCDNR instituted mandatory reporting for all commercial shad fishermen. In order to maintain consistency with previous years, mandatory reporting records from the “reliable” fishermen have been used to calculate CPUE for specific rivers since 2001. Every attempt was made to use data from the same fishermen over time, but some difficulties were encountered (e.g., one or two fishermen did not fish for the season, fishermen changed their fishing gear, or fishermen may have left the fishery). Such events might have affected the CPUE estimates, but these problems were minimal and these data constitute the only available long-term CPUE series for South Carolina American shad fisheries. Records were separated by river and in some cases by specific regions of a river and by gear: Edisto River (Jacksonboro set nets, lower 24-hour set nets, and tide set nets) and Combahee River (set nets. Not all systems were monitored each year due to personnel limitations. Data collected from open-ocean waters, such as Charleston Harbor, were excluded, because river origin cannot be determined for shad collected from these areas. For this assessment, data collected through mandatory reporting means (1999-2017) were used. Since this includes reports from all fishers and not just those fishers selected in previous data (1979-2001), data prior to 1999 is considered a separate time series and is not included in this analysis. Catch rate estimates is determined by annual landings (kg) per trips. To maintain confidentiality, landings for the ACE Basin (Edisto and Combahee Rivers) have been combined, but standardized indices are available. Many variables, such as water temperature, water levels, and flow rates, affect observed CPUE values and these parameters are highly variable between seasons and might have substantial impacts on catchability, and even effort, particularly in certain rivers. Linear regressions of CPUE against year were conducted to determine the significance of any trends in these data time series.

Data are available from 1999 through 2017 for the Edisto River gill net fisheries (Table 250). The annual CPUE does not show a significant trend ($p = 0.7652$, slope = -0.02, and $R^2 = 0.005$; 0).

3.20.5.2 Combahee

3.20.5.2.1 Landings

In 1896, 6,419 kg of shad were harvested on the Combahee River; landings dropped to 878 kg in 1960 (Walberg and Nichols 1967). The Combahee has supported a small fishery that has landed an average of 715 kg shad per year since 1979 (ASMFC 2007b). Landings varied from 702 kg up to 2,081 kg a year from 1979 to 1985, before declining sharply in 1986 and 1987. A slight upturn in landings in 1987 (1,216 kg) preceded another decline in the early 1990s. No landings were reported from 1994 through 1997. Since 1999, landings have been below the time series average, but have been stable. There have been an average of 35 trips per year since 1999 and five commercial shad trips were made on the Combahee in 2017.

3.20.5.2.2 Catch and Effort

CPUE data for the Combahee River do not show a significant trend ($p = 0.975$, slope = 0.0042, $R^2 = <0.001$; Figure 334).

3.20.6 Fishery-Independent Data Sources

3.20.6.1 Adult Fishery-Independent Data Sources

3.20.6.1.1 Edisto River and Combahee River Adult Gill Net Surveys

South Carolina DNR has conducted tag-return studies on the Edisto (1989 to 1990, 1994 to 1999, 2006 to 2007 to estimate the in-river relative exploitation rate (RE) for pre-spawning female American shad. In this report, data for male American shad are also presented. In 1993 and 1999, SCDNR tagged fish on the Combahee River. Only 12 fish (5 males, 7 females) were tagged and no tags were returned in 1993 and 9 female shad were tagged with three returns in 1999. The poor capture success and low sample size for the Edisto and Combahee Rivers prevented development of RE estimates.

For the Edisto River, fishery-independent CPUE data were collected using 12.7 mm stretch mesh drift gill nets for the years 1994 to 1998 and 2006 to 2007 in the South Edisto River employing similar methods as the Waccamaw River. These data are not discussed in terms of stock status, since less than 10 years of consecutive data exist.

3.20.7 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance. Delay-difference models were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Details for these methods are provided in Section 2.

3.20.8 Results

3.20.8.1 Abundance Trends

3.20.8.1.1 Power Analysis

The only abundance index for American shad in this region containing estimates of PSE was the Edisto River Commercial CPUE index. This survey had high a median PSE (1.628), and thus it exhibited very little power to detect a 50% change in abundance over 10 years (Table 25). Currently, this survey is used in the SFMP for sustainability targets and monitoring.

3.20.8.1.2 Mann-Kendall Analysis

American shad abundance indices developed from commercial CPUE in the Edisto River were available for years between 2001 and 2017. Plots of the data showed very little changeover the entire time series (Figure 334). Mann-Kendall analysis failed to detect a trend for either time period examine.

3.20.8.2 Delay-Difference Model

The delay-difference model for the ACE Basin was run using the semelparous life history parameters and the Edisto River Commercial CPUE as the abundance index. Total commercial fishery catch was available for 1978 through 2015, while the abundance index was available for 2001 through 2017. Since the delay-difference model requires identical time series length for catch and index, the total catch was truncated to 2001 through 2015. Estimated biomass declined over the time series from a median estimate of 7,127 lbs in 2001 down to a low of 4,838 lbs in 2006 before rising to a final estimate of 5,651 lbs in 2015 (Figure 335). The ratio of estimated biomass to initial biomass indicated a decrease between 2001 and 2006, followed a flat trend through 2017. The index and effort showed opposing trends throughout the time series alternating widely between 2001 and 2015, with both ending the time series with a decreasing trend. Observed and estimated catch from the model simulations show that total catches varied widely from 2001 through 2005, with little variability from 2005 through the 2015. Due to confidentiality concerns TAC estimates are not provided; however, overfishing is not likely to occur at catch levels equal to the mean of the final 3 years of the time series, with confidence bounds indicating that overfishing could occur.

3.20.8.3 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the ACE Basin system, habitat estimates were based on information from the Ashepoo, Combahee, and Edisto Rivers. Current unobstructed habitat area for the ACE Basin system represents 82.28% of the historical habitat extent (31.14 of 37.84 square kilometers).

3.20.9 Stock Status and Conclusions

Mortality[2]

Juvenile mortality status is unknown due to lack of data to make this determination. Adult mortality status is sustainable as the three-year average catch in 2017 was less than the delay-difference model median TAC estimate.

There were no mean length data available for trend analyses.

Abundance

Abundance status is unknown. There were no YOY abundance data available and no trend detected in adult abundance since 2005.

3.20.10 Research Recommendations

Refer to Section 3.18.10 for general South Carolina research recommendations.

3.21 Savannah

3.21.1 Habitat Description

The Savannah River forms the border between South Carolina and Georgia, and thus management of the river is shared between the two states. It drains a watershed of approximately 17,022 km^2. The first barrier to upstream migration on the Savannah River is the New Savannah Bluff Lock and Dam (NSBLD), located at river km 301, just south of Augusta, GA. American shad once passed through the dam, but in recent years the U.S. Army Corps of Engineers has declared the facility unsafe to operate, and thus it is now a true migration barrier and the uppermost reach of American shad migration on the Savannah River.

The Savannah River, which is approximately 560 km long and was open to a shad gill netting up to about rkm 322 until 2013 when law changes resulting from South Carolina’s SFMP allowed gill netting only to rkm 192. This change was largely in response to a mandate by NOAA Fisheries to account for and reduce by-catch of sturgeon in shad fisheries. The first barrier to

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[2] This status determination changed following the Peer Review Workshop. See the addendum (Section 9) for final status determination.

upstream migration is the New Savannah Bluff Lock and Dam (NSBLD) located at Augusta, Georgia (approximately rkm 301) (Figure 309). The lock at NSBLD is designed for navigation and does not provide effective fish passage and in more recent years has not been used for any passage due to concerns with structural integrity of the facility. During high flow periods, the river can rise above the NSBLD, which allows for some anadromous fish passage. There are 43 km between NSBLD and the next dam, J. Strom Thurmond Dam. Water quality may be a problem in the Savannah as the dissolved oxygen in the lower Savannah can fall below 1.0 ppm (Billy McCord, SCDNR, personal communication). Walburg and Nichols (1967) reported that dealers noted oil pollutants causing an "oily flavor" of Savannah River shad.

New Savannah Bluff Lock and Dam are located at rkm 301 of the Savannah River. The dam was constructed in the 1930s as a commercial navigation lock. Currently, fish passage is possible only by fish passing freely at river flows greater than 453 cms when water levels above and below the dam are roughly equal.

3.21.2 Fishery and Management History

South Carolina manages its shad fisheries using a combination of seasons, gear restrictions, and catch limits implemented for the Savannah River Basin.

Beginning with the 1998 commercial shad-netting season, all licensed fishermen are required to report their daily catch and effort to SCDNR. In 2000, Act #245 of the 2000 South Carolina General Assembly was passed in response to the perceived population status of shad populations in each of the state's river systems supporting an American shad fishery.

Significant changes in shad and herring regulations became effective with the 2001 with the passage of the Marine Resources Act of 2000, which gave giving SCDNR authority to implement a permit program for the State's shad and herring fisheries. All commercial shad and herring fishery license holders were issued permits that could be used to "restrict the number of nets for taking shad…in any body of water where the number of nets or fishermen must be limited…to prevent congestion of nets or watercraft, or for conservation purposes." The number and conditions of permits can be controlled "to designate areas, size, and take limits, hours, type and amount of equipment, and catch reporting requirements," and enabled SCDNR to phase out the ocean-intercept fishery by 2005. In addition, a recreational aggregate creel limit of 10 American and hickory shad per person was implemented in all state waters, except for the Santee River in which a 20 fish creel limit was set.

Additionally, with requirements initiated by Amendment 3 to the ASMFC shad and river herring Fishery Management Plan (FMP), South Carolina was required to develop a shad Sustainability Fishery Management Plan (SFMP) to demonstrate sustainability in all rivers where shad fisheries occurred. A sustainable fishery was defined as "those that demonstrate their stock could support a commercial and/or recreational fishery that will not diminish the future stock reproduction and recruitment." Acceptable measures to develop sustainability benchmarks included mark-recapture studies, enumeration at fish passage facilities, catch-per-unit-effort (CPUE) by appropriate sample gear, or other indices of abundance. If sustainability could not be demonstrated, those fisheries were to be closed. In 2012 and again in 2017, South Carolina's SFMP was approved by the ASMFC Shad and river herring Technical Committee and Shad and river herring Management Board. Measures in the SFMP required a 50 %percent statewide reduction for available commercial gill nets, juvenile shad fishery independent surveys, and cooperative fishery independent surveys with GADNR on the Savannah River, due to the shared border, and closure of several river systems where sustainability could not be demonstrated.

In South Carolina, the Savannah River is open to commercial fishing with set and drift gill nets up to about rkm 192. Until 2015 there was a substantial recreational hook and line fishery below New Savannah Bluff Lock and Dam at Augusta, Georgia. Fishers are no longer allowed to fish on the wing wall of the dam due to the ongoing structural issues at the lock. Drift nets are generally most prevalent in tidal portions of the river. Set nets are the principal gear used throughout the river. In the lower 40 km, which is strongly influenced by tides, set nets are fished only during flood and slack tide periods when currents are weakest. In areas above significant tidal influence (up to about rkm 192), set nets are fished in eddies or slow-moving waters below creek entrances, below the mouths of oxbow lakes, or in deep holes along undercut banks on the outside of river bends.

For the Savannah River system in Georgia, the current American shad SFMP provides for commercial fishing to occur from the U.S. Hwy 301 Bridge downstream to the Atlantic Ocean, though most effort in recent years occurs in the lower reach of the river. The Savannah River is open Tuesday through Friday east and Wednesday through Saturday west of the I-95 bridge. Approved commercial fishing gear is drift or set gill nets having a minimum 4.5" stretch mesh, with additional length and placement restrictions. Recreationally, bow nets or hook/line gear may be used, with a daily creel limit of 8 shad (American and/or hickory). However, the closure of the NSBLD in 2014 to recreational anglers essentially eliminated most of the known portion of the recreational fishery on the river. The management benchmark and trigger used in the Altamaha River system is the Commercial Gill Net CPUE Index. Using this index, management triggers occur after 3 consecutive years below the benchmark value of 9.03 shad/trip. In the event of a trigger, GADNR will evaluate and identify the causes of such decline and initiate appropriate actions, potentially including reducing the number of fishing days, modifying season dates, or altering legal fishing gears. In the event such actions do not reverse negative trends, GADNR would then consider fishery closures.

3.21.3 System-Specific Life History

American shad returning to South Carolina rivers are generally believed to be semelparous. In annual compliance reports to ASMFC, SCDNR reports that no repeat spawning marks have been observed in their sampling since 2001. Approximately 200 fish were sampled each year from both river and coastal ocean locations. SCDNR compliance reports note a low degree of repeat spawning in 1985 (3% for males and 2% for females) and Walburg (1956) did not record presence of spawning marks. There are no recent studies on the growth and fecundity of South Carolina shad.

3.21.4 Anthropogenic Sources of Mortality and Productivity

Potential sources for anthropogenic mortality are available in the SCDNR American Shad Habitat Plan (http://www.asmfc.org/files/ShadHabitatPlans/AmShadHabitatPlan_SC.pdf).

3.21.5 Fishery-Dependent Data Sources

No effort data were collected for American shad fisheries before 1979; thus, it was not possible to attribute stock fluctuations to changes in fishing effort, changes in spawning stock size, or other factors. License data are available but are not useful as many shad fishermen participated on a part-time basis and the amount of gear deployed was not specified in records. In addition, approximately 80 percent of the licensed fishermen fished infrequently, precluding estimation of total effort and, therefore, CPUE (Ulrich et al. 1978).

Commercial American shad catches were sampled to collect biological data (e.g., length, weight, and age) by SCDNR from American shad fishermen at boat ramps from 1979 to 1985 for rivers with an active American shad fishery. During this time, SCDNR identified a group of "reliable" fishermen from which to collect catch and effort data. Voluntary catch records (data sheets) from these fishermen were used to develop fishery-dependent catch-per-unit-effort (CPUE) from 1979 to 2000. Starting in 1998, SCDNR instituted mandatory reporting for all commercial shad fishermen. In order to maintain consistency with previous years, mandatory reporting records from the "reliable" fishermen have been used to calculate CPUE for specific rivers since 2001. Every attempt was made to use data from the same fishermen over time, but some difficulties were encountered (e.g., one or two fishermen did not fish for the season, fishermen changed their fishing gear, or fishermen may have left the fishery). Such events might have affected the CPUE estimates, but these problems were minimal and these data constitute the only available long-term CPUE series for South Carolina American shad fisheries. Records were separated by river and in some cases by specific regions of a river and by gear: Savannah River (lower set nets). Not all systems were monitored each year due to personnel limitations.

For this assessment, data collected through mandatory reporting means (1999-2017) were used. Since this includes reports from all fishers and not just those fishers selected in previous data (1979-2001), data prior to 1999 is considered a separate time series and is not included in this analysis. Catch rate estimates is determined by annual landings (kg) per trips. Many variables, such as water temperature, water levels, and flow rates, affect observed CPUE values and these parameters are highly variable between seasons and might have substantial impacts on catchability, and even effort, particularly in certain rivers. Linear regressions of CPUE against year were conducted to determine the significance of any trends in these data time series.

3.21.5.1 Landings

Landings have decreased by an order of magnitude from 1896 (94,074 kg) and 1960 (74,671 kg) to 2005 (9,773 kg) in the Savannah River (Walberg and Nichols 1967; ASMFC 2007b). The Savannah River has supported the third largest commercial river-specific shad fishery in South Carolina since 1979 (ASMFC 2007b). Fishermen from both Georgia and South Carolina catch shad in the Savannah River; therefore, each state has shad landings data for this river. SCDNR data goes back to 1979, while GA DNR landings go back to 1964, but data are not available for shad from 1983 to 1988. Georgia landings data from 1967 are unusually low compared to other years of data from the 1960s. From 1964 to 1979, annual landings in Georgia average approximately 30,000 kg. South Carolina shad landings were stable from 1979 to 1987 averaging 16,689 kg per year but have decreased since then with landings not exceeding 10,000 kg since 1997 and have reached a time series low of 1,208 kg in 2006. Savannah River shad landings for South Carolina in 2005 were 3,400 kg. For the years where landings data are available from both states (1979 to 2005, except 1983 to 1988), Georgia landings have accounted for 71 percent of the total (449,699 kg) amount of Savannah River shad landings. Georgia's Savannah River annual landings since 2000 averaged 3,957 kg, with a low of 1,732 kg in 2002 and a high of 6,380 kg in 2005.

3.21.5.2 Catch Rates

3.21.5.2.1 South Carolina DNR

The CPUE time series for the Savannah River gill net fisheries showed a positive, but not significant trend (p = 0.7698, slope = 0.2757, R^2 = 0.005; Table 252; Figure 336).

3.21.5.2.2 Georgia DNR

Trip level commercial catch data from the Savannah River in Georgia from 2001-2017 were used to develop an index of adult abundance. Records of hickory shad or unknown/unclassified shad were removed from the data set and only American shad catch records were used in developing the index. Catches of roe and buck shad were combined for each trip to calculate total pounds landed. All trips from January through April were used. Only records with effort information (hours gear was fished) were included. This removed 175 records from the data set (15% of the data set) and resulted in at least 25 trip reports per year (mean: 57 trips, range: 25-104 trips). Gear type for most trips were drift nets followed by set nets; less than one percent of records were from unknown gear and these were removed from the data set. Data from multiple USGS gage stations were analyzed for possible use in this analysis, however, most gages near the fishing grounds did not start collecting data until around 2007. The closest gage at Clyo (approximately 48 km upstream) had discharge data back to 1985 but was missing data for 2006 and 2007. The next closest gage with as long of a time series of discharge data was at Augusta but was deemed to be too far upstream to be useful for this analysis. The data were standardized using a negative binomial GLM that included year, gear type, day of year, and an effort offset (hours fished). However, diagnostics indicated a poor fitting model and the likelihood ratio test showed that the model was not better than an intercept only model (p=0.99). Therefore, the geometric mean index is recommended for the assessment.

The index varied without trend from 2001-2006 and decreased slightly starting in 2007 (Table 251, Figure 337). From 2007-2011, it continued to vary without trend at this lower level. While the index peaked in 2013, it has decreased since then with the lowest point in the time series occurring in 2016. The 2017 index is slightly above 2016 but still below all other years observed.

3.21.5.3 Creel Survey

The creel survey by Boltin (1999) provides a snapshot of estimated recreational catch for 1999 and cites earlier catch estimates from creel surveys conducted by GADNR (1997) and SCDNR (1998). The estimated catch decreased in each year, but (1) methods were not available for each year and (2) in both 1998 and 1999, extreme conditions were cited as reducing recreational effort substantially on the Savannah River. The total number of shad caught in the 1999 survey was 3,645 shad compared to the reports of 6,664 and 34,895 shad caught in 1997 and 1998. Effort data are available only for the 1999 survey.

3.21.6 Fishery-Independent Data Sources

As part of requirements of ASMFC Amendment 3 to the Shad and river herring FMP, spawning adult surveys were initiated by GADNR at the NSBL&D in Augusta, GA. Catch rates of 132.4, 480.6, 506.4, 319.0, and 1146.8 shad/hour were observed in 2014, 2015, 2016, 2017, and 2018 respectively. However, because the data time series is less than 10 years, data is not used in this assessment.

3.21.7 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance. Delay-difference models were used to evaluate adult mortality. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Details for these methods are provided in Section 2.

3.21.8 Results

3.21.8.1 Abundance Trends

3.21.8.1.1 Power Analysis

For the Savannah River system, both GADNR and SCDNR developed respective fishery-dependent commercial CPUE indices based on observed commercial harvest and effort data available in their state, both of which are used in the SFMP for sustainability targets and monitoring. Of these, the GADNR commercial index exhibited sufficient power to detect a 50% increase in abundance over 10 years (Table 25). In contract, higher variability in the commercial CPUE from SCDNR (median PSE = 0.600) results in this survey possessing in-sufficient power to detect a 50% change in abundance within 10 years.

3.21.8.1.2 Mann-Kendall Analysis

Both South Carolina and Georgia provided data from the commercial fishery for American shad in the Savannah River from 2001-2017. A plot of the indices versus time appeared to show a general increase since 2009 in South Carolina, but Georgia data showed an apparent decline from 2003 through 2017 (Figure 336 and Figure 337). Mann-Kendall analysis failed to detect any trends for the time series or period after 2005 for either index.

3.21.8.2 Delay-Difference Model

The delay-difference model for the Savannah River was run using the semelparous life history parameters and the GADNR Savannah River Commercial CPUE index as the abundance index. Total commercial fishery catch was available for 1978 through 2017, while the abundance index was available for 2001 through 2017. Since the delay-difference model requires identical time series length for catch and index, the total catch was truncated to 2001 through 2017. Estimated biomass declined over the time series from a median estimate of 37,642 lbs in 2001 down to a low of 14,502 lbs in 2011 before rising slightly to a final estimate of 14,636 lbs in 2017 (Figure 338). The ratio of estimated biomass to initial biomass indicated a decline throughout the time series. The index and effort showed opposing trends throughout the time series alternating widely, with effort ending the time series with an increasing trend and the index exhibiting a decreasing trend. Observed and estimated catch from the model simulations show that total catches have decreased substantially over the time series. Median TAC over 100 simulations was estimated to be 3,289.1 lbs. Overfishing is likely to occur at catch levels equal to the mean of the final 3 years of the time series; however, confidence bounds indicate that overfishing might not occur.

3.21.8.3 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Savannah system, current unobstructed habitat area represents 59.19% of the historical habitat extent (58.65 of 99.09 square kilometers).

3.21.9 Stock Status and Conclusions

Mortality[2]

Juvenile mortality status is unknown due to lack of data to make this determination. Adult mortality status is unsustainable as the three-year average catch in 2017 was greater than the delay-difference model median TAC estimate.

There were no mean length data available for trend analyses.

Abundance

Abundance status is unknown. There were no YOY abundance data sets with appropriate time series available and no trend detected in adult abundance (two data sets) since 2005.

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[2] This status determination changed following the Peer Review Workshop. See the addendum (Section 9) for final status determination.

3.21.10 Research Recommendations

Refer to Section 3.18.10 for general South Carolina research recommendations.

3.22 Altamaha

The Georgia Department of Natural Resources (GADNR) manages American shad by river system. Historically, the Altamaha (formed by the confluence of the Oconee and Ocmulgee rivers), Ogeechee, Satilla, Savannah, and St. Mary's rivers all support commercial American shad fisheries. Of these, the Altamaha, Savannah, and Ogeechee generally yielded most of the shad landed in Georgia in recent decades, with no commercial landings having been reported from the Satilla and St. Mary's rivers since the 1980s. Currently, only the Altamaha and Savannah rivers are open to commercial shad fishing.

3.22.1 Habitat Description

The Altamaha River is Georgia's largest watershed, draining 37,192 square kilometers. The Altamaha is formed by the confluence of the Oconee and Ocmulgee rivers and flows for 240 km to the Atlantic Ocean. The Altamaha River is free of dams for the entire length of the river; however, dams are located on both of its major tributaries. Walburg and Nichols (1967) reported that shad ascended the Altamaha River to the vicinity of Hawkinsville, Georgia on the Ocmulgee River (482 km from the mouth of the Altamaha River) and reached Dublin, Georgia (402 km from mouth of Altamaha) on the Oconee River. In recent years, American shad have been documented immediately below the farthest downstream dams on both the Ocmulgee River (~rkm 547) and Oconee River (~rkm 451). Neither dam currently has dedicated fish passage. The only major point source of pollution on the Altamaha is a pulp mill located at Doctortown, Georgia approximately 80 km upstream from the river mouth. Walburg and Nichols (1967) noted that shad were abundant in the Altamaha River in the late 1800s, but the transportation infrastructure was lacking to supply more than local markets. Shad are reported to spawn at least 90 to 95 km upstream and in each of the major tributaries when water temperature is between 12.3 and 22°C (Walburg and Nichols 1967; Godwin 1968; Godwin and Adams 1969).

The main stem of the Altamaha River has a large commercial fishery for American shad throughout the entire river but has no known directed recreational fishery. Historically, commercial set nets were observed in the Ocmulgee River (just below Abbeville, Georgia), though it is believed most shad captured were retained for personal consumption and not sold through a fish dealer. Anecdotally, a small recreational fishery was reported to occur below Juliette Dam near Macon, Georgia on the Ocmulgee River. There has been very little recreational activity observed or reported from the Oconee River. Currently, commercial fishing is not allowed in any portion of the Altamaha River above US Hwy 1, which includes all of the Oconee and Ocmulgee rivers.

In an effort to address depressed shad populations, the GADNR implemented a plan for stocking American shad within the Altamaha River Basin with specific goals and strategies for the restoration and management that are congruent with the goals of the ASMFC Interstate

Fisheries Management Plan for Shad and River Herring. The restoration plan is based on the assumption that the Altamaha River American shad population pre-exploitation and pre-dam construction was much larger than today's population. Specific goals include restoration of historical American shad distribution in the basin where feasible, enhancement of the spawning population of American shad in the basin, and management for sustainable recreational and commercial fisheries. The plan entails stocking American shad to "jump-start the recovery effort as a complement to ongoing efforts to obtain fish passage and increase the availability of spawning habitat above dams" (Harrison, 2013). The long-term goal of the plan is to "re-establish self-sustaining spawning migrations that more closely approximate the historic range in the Altamaha Basin" through stocking efforts above existing dams in the Ocmulgee and Ogeechee rivers (Harrison, 2013). Since 2014, brood fish have been collected each year for fish production and 300,000 – 900,000+ fry have been stocked annually at multiple (≤3) locations above dams in both the Ocmulgee and Oconee rivers. All fry have been marked with OTC in accordance with ASMFC requirements.

3.22.2 Fishery and Management History

The harvest of shad in Georgia dates back to at least the late 1800s (ASMFC 1985). At one time or another, the Altamaha, Ogeechee, Satilla, Savannah, and St. Mary's rivers all supported commercial shad fisheries. Of these, the Altamaha River has served as the largest component of the shad fishery in Georgia for the past several decades, a distinction that remains even today. Commercial fisheries in the Satilla and St. Mary's rivers remained viable until the early 1980s, and shad in the Ogeechee River were harvested until the late 2000s, albeit in a declining effort by 2010. Commercial fisheries in the Ogeechee, Satilla, and Saint Mary's rivers have all be closed, currently leaving only the Altamaha and Savannah rivers open for commercial shad fishing.

Commercial fishing for shad currently occurs in 2 rivers: Altamaha River and Savannah River. In these rivers, set and drift gill nets (≥11.4 cm mesh) are the only legal commercial gear for American shad in Georgia. By law, gill nets must be set in flowing water (within the banks of river channels) and not in areas such as sloughs and oxbow lakes. Set nets must be less than 30.5 m long and set at least 183 m apart with one end secure to the stream bank and the other buoyed and clearly visible to boaters. Drift nets must be fished at least 91 m apart and no longer than 305 m long. Both gears must allow half the width of the river or stream to be open to the passage of fish and have a permanent tag labeled with fisherman's name, address, and commercial fishing license number. All sturgeon, catfish, and non-shad gamefish must be immediately released.

Closed seasons and days during the commercial season allow additional escapement of spawning fish. In 1960, the commercial season extended from January 1 to April 1, except for the St. Mary's River (where the season was December 15 to April 15) (Walburg and Nichols 1967). At that time, no commercial fishing was permitted on weekends from sundown Friday to sunrise Monday. Recreational fishing was allowed seven days a week and the creel limit was eight fish (Walburg and Nichols 1967). Prior to 1980, a shad license was required to fish commercially for American shad and hickory shad (*A. mediocris*) in Georgia. From 1980 through

2018, commercial shad fishing was covered under a general commercial fishing license. A decrease in shad landings from the commercial and recreational fishery on the Ogeechee River led to reduction in commercial fishing days from 4 to 2 days per week and a reduction in the recreational bag limit from 8 fish to 2 fish per day in 1987 (GADNR 1995). The creel limit was revoked in 1993 and, beginning in 1995, the weekly openings for commercial fishing had to be on consecutive days (GADNR 1995). Set gill nets were banned in the lower Savannah River beginning in 1990 to protect striped bass, which had the effect of affording American shad protection from reduced netting effort in the lower Savannah.

Currently, the commercial shad season for both American and hickory shad is open from January 1 to March 31. During the season, the Savannah River is open to commercial fishing from Tuesday through Friday below the Interstate-95 bridge and Wednesday through Saturday above the bridge. The Altamaha River is open Monday through Friday below the saltwater demarcation line (Seaboard) and Tuesday through Saturday above Seaboard. Though shad season typically runs January 1 – March 31, it has been extended during certain years. In 2003 – 2009, the commercial shad season above the Interstate-95 bridge on the portion of the Savannah River was extended to April 15 to match the South Carolina commercial shad season for this section of river.

In Georgia, dealers are required to report commercial harvest of shad. The CRD receives dealer reports and tabulates the total commercial landings for Georgia. Landings are reported by sex, river, and gear for American shad. NOAA Fisheries port agents collected commercial shad landings until 1978, when GADNR assumed this responsibility (Michaels 1993). GADNR recognized that NOAA Fisheries port agent coverage focused on dealers operating in coastal and lower river locations, and that it did not account for the landings of fishermen operating in upriver locations, resulting in significant underreporting. GADNR conducted several studies to characterize the state’s commercial shad fishery, as well as to determine the extent of underreporting (Hardisky and Smith 1980; Essig 1983; Michaels 1984, 1990, and 1993). Additionally, these studies identified that drift gill nets were the predominant means of shad harvest in the coastal and downriver locations, while set gill nets were most commonly employed in inland and upriver locations. Essig (1983) noted that market saturation, which was attributed to shad entering the markets from points north, occurred during the latter portions of the Georgia shad run resulting in depressed prices, possibly providing some conservation benefit to late spawning shad. Historically, Georgia has had no ocean-intercept fishery.

Currently, dealers are required to report commercial harvest of shad to the CRD. Commercial fishing effort for shad has been collected by the CRD via a trip ticket system beginning in 2000 that collects data from fishermen each time they sell their catch. These individual trip forms are then submitted to CRD and tabulated. Effort estimates include the number of fishing trips from both drift and set gill nets by river. Before the trip tickets were implemented, catch and effort data were required, but were not always able to be collected due to difficulties in enforcement. In some cases trip level data can be linked to the harvester, but in many cases only daily or weekly summaries were available.

Before 1979, commercial shad fisherman were required to hold a shad license, which was applicable for both American shad and hickory shad, but no other effort data were collected. GADNR trip level records begin in 1989; however, these data do not necessarily correspond to a single trip as "trips" could be partial trips, full trips, or combined trips before 2000 and GADNR does not consider trip level data before 2000 as an accurate measure of a trip. In order to meet coastwide commercial catch and effort data reporting standards set by the Atlantic Coastal Cooperative Statistics Program, trip ticket reporting was implemented in 2000 that included information on gear quantity, soak time, and number of sets. Reporting of these factors has improved since implementation, which should permit more specific estimates of effort and CPUE in future years. Additionally, Georgia began requiring shad fishermen to purchase a "shad endorsement stamp" in 2018. Similar in concept to the shad license required before 1980, this new license will aid in better identifying all fishermen targeting shad commercially in Georgia. Furthermore, it will provide fishery managers with the ability to better know who to contact with regards to landings and fishing effort data. Upriver effort and landings sampling estimates remain troublesome to quantify and have not been examined since 1992 (Michaels 1993).

3.22.2.1 Altamaha River SFMP

For the Altamaha River system, the current American shad SFMP for Georgia provides for commercial fishing to occur from the U.S. Hwy 1 Bridge downstream to the Atlantic Ocean. The Altamaha River is open Monday through Friday below and Tuesday through Saturday above the Seaboard Railroad bridge crossing. Approved commercial fishing gear is drift or set gill nets having a minimum 4.5" stretch mesh, with additional length and placement restrictions. Recreationally, bow nets or hook/line gear may be used, with a daily creel limit of 8 shad (American and/or hickory). The management benchmark and trigger used in the Altamaha River system is the Gill Net CPUE Index. Using this index, management triggers occur after 3 consecutive years below the benchmark value of 1.11 shad/ft-hr. In the event of a trigger, GADNR will evaluate and identify the causes of such decline and initiate appropriate actions, potentially including reducing the number of fishing days, modifying season dates, or altering legal fishing gears. In the event such actions do not reverse negative trends, GADNR would then consider fishery closures.

3.22.3 Fishery-Dependent Data Sources

Like other states, Georgia collects commercial landings data on all species commercially harvested, including American shad. According to commercial landings reported to the Coastal Resources Division (CRD) of GADNR, of the 2 rivers open to commercial shad fishing, the Altamaha River currently has the largest commercial shad harvest in Georgia. Shad landed in the Savannah River (the shared border with South Carolina) are reported to either the GADNR CRD or South Carolina Department of Natural Resources.

Theoretically, recreational fisheries exist in the Altamaha (including the Oconee and Ocmulgee rivers), Ogeechee, Satilla, Savannah, and St. Mary's rivers. However, the only known current recreational fishing effort according to anecdotal evidence occurs in the Ogeechee and Savannah rivers. Most recreational shad fishing in the Ogeechee occurs in the lower portion of the river, while the primary location of the Savannah River recreational fishery is immediately below the New Savannah Bluff Lock and Dam (NSBLD). While the Ogeechee River fishery has continued, shad fishing effort on the Savannah River has dramatically waned in recent years. This significant reduction is the result of the US Army Corps of Engineers (USACE) closing access to much of the NSBLD in 2014 due to safety concerns associated with the NSBLD structure.

Fishing effort and landings data from both targeted (e.g. shad fishermen) and non-targeted (e.g. other commercial fisheries) are provided to GADNR. Currently, the only fishery-dependent data collection involving shad fishermen that GADNR performs uses fishery observers to monitor bycatch associated with commercial shad trips on the Altamaha and Savannah rivers. Per requirements established by the National Marine Fisheries Service, GADNR personnel must observe a minimum of 10% of the trips conducted by commercial shad fishermen. These observations are required primarily due to concerns over sturgeon (Atlantic and shortnose) interactions with commercial shad gear. To accomplish these observations, GADNR staff will observe fishermen multiple days each week during the shad season, watching fishermen as they fish their nets and recording any bycatch observed during these efforts.

With regards to data from non-targeted sources (e.g. shad captured as bycatch in other fisheries), commercial shrimp trawling is the only commercial fishery in Georgia to which shad are vulnerable. Since commercial shrimp fishermen are required to use bycatch reduction devices in their nets, shad are rarely caught in commercial shrimp trawling off the Georgia coast (Ottley et al. 1998; Gaddis et al. 2001; Page et al. 2004). GADNR has employed fishery observers to monitor bycatch on commercial shrimp boats, but currently does not do so.

3.22.3.1 Landings

Landings data for the Altamaha River are available from 1962 to 2018. From 1962 to 1973, unadjusted reported landings from the Altamaha River averaged 188,624 lbs. The Altamaha River (unadjusted landings) accounted for 64 percent of all reported in-river shad landings since 1962 and has produced the highest river-specific landings in all but six years in that period.

Reported unadjusted landings peaked in 1968 at 213,963 lbs and then declined steadily to the early 1980s. From 1983 to 1988 landings average 122,150 lbs, before declining to an average of 44,675 lbs from 1989 to 1994. Results from the roving commercial survey conducted from 1982 to 1991 indicated that annual shad drift-net landings from the Altamaha River were greatly underreported. Landings increased briefly from 1995 to 1998, averaging 106,646 lbs annually, and then declined to a mean of 30,535 lbs a year from 1999 to 2005. In the period of 2006 – 2017, landings ranged from 24,000 – 55,000 lbs, averaging over 37,000 lbs during that time.

3.22.3.2 Catch Rates

Trip level commercial catch data from the Altamaha River in Georgia from 2001-2017 were used to develop an index of adult abundance. Records of hickory shad or unknown/unclassified shad were removed from the data set and only American shad catch records were used in developing the index. Catches of roe and buck shad were combined for each trip to calculate total pounds landed. The majority of trips reported were between January and March; eight trips reported in April and December were removed from the data set. Effort information (total hours gear was fished) was missing for a number of records, especially trips from 2001-2003. Trips without effort data were removed which resulted in the final index beginning in 2002 rather than 2001. Gear type for most trips used drift nets, followed by set nets, and unknown nets. USGS gage data from Doctortown and Everett City were explored in order to potentially include environmental data in the GLM standardization. Data from Everett City were not available until 2008 and while discharge information was available from Doctortown, gage height was not available until 2007 and water temperature was not available until 2016. A full model predicting catch as a linear function of year, gear type, day of year, discharge, and an effort offset was explored. Using a negative binomial GLM, all variables except for discharge were determined to be significant. However, the model residuals showed heterogeneity and did not appear to have a great fit to the data, indicating that important explanatory variables are likely missing from the model. Therefore, the geometric mean index is recommended.

The commercial shad index in the Altamaha River generally increased from 2002 through 2006 (0, Figure 340). While a slight dip in CPUE was observed from 2007-2012, CPUE again increased, peaking in 2014. Since 2014, CPUE has declined.

3.22.4 Fishery-Independent Data Sources

3.22.4.1 Adult Fishery-Independent Data Sources

3.22.4.1.1 Altamaha River Gill Net Survey

Each year, staff with the GADNR utilize drift gill nets to capture American shad and examine CPUE rates for the species. This effort is done in conjunction with ongoing tagging efforts to examine fishing mortality associated with the commercial fishery and in an effort to generate a population estimate of the shad run each year. To accomplish this, a drift gill net is deployed and fishing time, along with net total length (in feet), are recorded. Upon retrieval, all shad are removed and the total number of shad for the drift is recorded. Because nets used during the survey may be of various lengths, a standard CPUE identified as “number of shad per net foot per hour” (shad/net ft-hr) is calculated (Table 254, Figure 339). GADNR staff use the current CPUE benchmark (75% of the mean for 3 consecutive years) value of 1.11 shad/ft-hr (as accepted in October 2017) as the sustainability measure for both the commercial and recreational fisheries in the Altamaha River. If gill netting CPUEs drop below 1.11 shad/ft-hr for 3 consecutive years, GADNR will evaluate commercial fishing regulations and harvest data and consider modifications to the Altamaha fishery to ensure the fishery remains sustainable.

3.22.4.1.2 Tagging Studies

Relative minimum exploitation rates and population estimates have been estimated using tag-return methodology on an annual basis since 1982. GADNR collects American shad for its tag-return program from the Altamaha River by using drift gill nets with a mesh sizes from 11.4 to 13.3 cm (mostly between 11.4 and 12.7 cm). A goal of tagging 500 American shad is pursued annually. Six to eight tagging locations downstream and upstream of Seaboard bridge have been used since the early 1990s, when use of tagging sites in Altamaha Sound ended. American shad are sampled at least once a week during the entire shad season (January 1 to March 31). Captured fish are sexed, measured, and tagged with a standard T-bar floy tag. Tide, river flow, and capture success dictate allocation of the sampling effort. Tagging is conducted on the weekends (when the Altamaha River commercial fishery is closed) to avoid interference with commercial fishermen and to ensure that tagged fish have at least 12 hours to disperse before the fishery reopens. The gear used during GADNR sampling efforts is essentially the same gear used by commercial fishermen. A reward system is used to encourage commercial fishermen to return the tags. The rewards are $4, $10, $50, or $100 per tag, with the values randomly assigned.

Relative minimum exploitation rates for the Altamaha River population were estimated as the ratio of the number of recaptured tags to the number of tags released. GADNR estimates population size by dividing the adjusted Altamaha River American shad landings in numbers, by the exploitation rate estimates. Exploitation rates have varied annually, ranging from 53% (1989) to 7% (2014), and averaging 44% (1982-1991), 28% (1992-2001), and 18% (2002-2011). From 2012 – 2017, exploitation rates averaged 13% annually. Landings in numbers are estimated by converting the adjusted Altamaha River American shad landings from weight to numbers by dividing by an annual average weight.

3.22.5 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance. Delay-difference models were used to evaluate adult mortality. There were diagnostic problems with the delay-difference models, so the results are not provide. Habitat assessment was applied to assess current habitat availability relative to historical habitat. A population model was also used to evaluate abundance and exploitation. Details for all methods except the population model are provided in Section 2. Details for the population model are provided below.

3.22.5.1 Population Model

Relative minimum exploitation rates and population estimates have been estimated using tag-return methodology on an annual basis since 1982. GADNR collects American shad for its tag-return program from the Altamaha River by utilizing drift gill nets with a mesh sizes from 11.4 to 13.3 cm (mostly between 11.4 and 12.7 cm). A goal of tagging 500 American shad is pursued annually. Six to eight tagging locations downstream and upstream of Seaboard bridge have been used since the early 1990s, when use of tagging sites in Altamaha Sound ended. American shad are sampled at least once a week during the entire shad season (January 1 to March 31). Captured fish are sexed, measured, and tagged with a standard T-bar floy tag. Tide, river flow, and capture success dictate allocation of the sampling effort. Tagging is conducted on the weekends (when the Altamaha River commercial fishery is closed) to avoid interference with commercial fishermen and to ensure that tagged fish have at least 12 hours to disperse before the fishery reopens. The gear utilized during GADNR sampling efforts is essentially the same gear used by commercial fishermen. A reward system is utilized to encourage commercial fishermen to return the tags. The rewards are $4, $10, $50, or $100 per tag, with the values randomly assigned.

Relative minimum exploitation rates for the Altamaha River population were estimated as the ratio of the number of recaptured tags to the number of tags released. GADNR estimates population size by dividing the adjusted Altamaha River American shad landings in numbers, by the exploitation rate estimates.

3.22.6 Results

3.22.6.1 Abundance Trends

3.22.6.1.1 Power Analysis

The only abundance index for American shad in this region containing estimates of PSE was the Altamaha River fishery-dependent commercial CPUE index. This survey had the lowest median PSE (0.058) of all the surveys used in this assessment, and thus it exhibited the highest power to detect a 50% increase in abundance over 10 years (Table 25). For both linear and exponential trends, the power was 1.00. Currently, this survey is not used in the SFMP for sustainability targets and monitoring.

3.22.6.1.2 Mann-Kendall Analysis

Altamaha River (FI CPUE)

A fishery-independent gill net survey for American shad in the Altamaha River provided length information from 1982-2017. A plot of the index versus time shows low levels from 1982-1993, an increase through 1998, followed by a decrease through 2005, and finally an increase through the end of the time series (Figure 339). Mann-Kendall analysis found an increasing trend over the full time series and for the period after 2005.

Altamaha River (FD CPUE)

Georgia DNR provided data from the commercial fishery for American shad in the Altamaha River from 2002-2017. A plot of the index versus time shows an increase from 2002-2006 and then again from 2012-2014, before declining in 2015-2017 (Figure 340). Mann-Kendall analysis found an increasing trend over the full time series but failed to detect a trend for the period after 2005.

3.22.6.2 Tag-Recapture Population Model

Exploitation rates have varied annually, ranging from 53% (1989) to 7% (2014), and averaging 44% (1982-1991), 28% (1992-2001), and 18% (2002-2011). From 2012 – 2017, exploitation rates averaged 13% annually. Landings in numbers are estimated by converting the adjusted Altamaha River American shad landings from weight to numbers by dividing by an annual average weight.

The previous SAS that conducted the 2007 benchmark stock assessment recommended against using the estimates from this model for assessment conclusions. The previous SAS cited concerns with unvalidated assumptions including: (1) no post-tagging loss of tags; (2) no tag mortality; (3) all recovered tags are reported; (4) age and size distribution of tagged fish mimics that of the populations; (5) tagged fish randomly mix with untagged fish; and (6) all tagged fish continue upriver and do not stop their migrations after tagging. These concerns were reiterated by the current SAS, but the SAS felt assumptions were not violated in a manner that would have biased the trends in estimates. Based on discussion with the GA TC representative, fall back (i.e., violation of assumption 5 and 6) was the primary concern noted, but the SAS believes the reporting rate and tag retention are likely high. Additionally, the trend in population estimates agrees with trends from abundance data sets. Ultimately, the SAS believes the implications of the most likely assumption violations are exploitation estimates biased low and population estimates biased high (i.e., denominator of population estimates, total annual tag returns, biased low), but there is no apparent support for temporal effects of assumption violations that would bias trends in estimates. The SAS believes the previous SAS' recommendations were focused on using absolute population estimates from this model and maintain this recommendation, but agree with the conclusions of model results that exploitation has declined over time.

3.22.6.3 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the Altamaha system, current unobstructed habitat area represents 82.24% of the historical habitat extent (121.73 of 148.01 square kilometers).

3.22.7 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. The adult mortality status is also unknown, as the delay-difference model experienced diagnostics problems and could not be used for status determination.

There were no mean length data available for trend analyses, but there has been a decline (based on visual inspection) in exploitation since the late 1980s estimated from the tag-recapture population model.

Abundance

Abundance status is unknown. There were no YOY abundance data available. There have been conflicting trends in adult abundance since 2005, with an increasing trend detected from the Gill Net Survey and no trend detected from Commercial CPUE, further confounding assessment of abundance conditions in recent years.

3.22.8 Research Recommendation

Population Model Recommendations

- Continue high and low reward tagging, but print the reward amount on all tags in the future to better estimate reporting rate. Reward amounts are currently not printed on tags so there is no way to compare return rates of low reward tags to return rates of high reward tags (i.e., assumed≈100%).
- Double tag fish to estimate tag retention rates.
- Investigate fall back rates of tagged fish with PIT tags and/or acoustic tags.

3.23 St. Johns

3.23.1 Habitat Description

The St. Johns River, Florida hosts the southernmost run of spawning American shad. The St. Johns River is the only river within the state with a notable spawning population of American shad. The St. Johns River emerges from the headwater marshes in Indian River and Brevard Counties and flows approximately 450 km north to the mouth in Jacksonville. Several broad shallow lakes lie within the run of the river. Stream gradient is small with the river bottom dropping 4 meters between river kilometer (rkm) 450 and rkm 314. The river bottom is at or below sea level downstream of rkm 314 although the head of the tide is generally Lake George at rkm 182. Weak tides can reach as far as the Lake Monroe outlet at river kilometer 266 during low flow. Wind events can cause the flow to stop or reverse for a period of days at low flows (Kroening 2004). The marshes of the upper basin were ditched, levied, and drained for agriculture, livestock grazing, and flood control from 1900 through 1970. As much as 62 percent of the floodplain in the Upper St. Johns River Basin was drained and water was diverted to the Indian River Lagoon. Passage of the National Environmental Policy Act in 1970 focused management of the upper basin on flood control and water storage to accommodate marsh restoration and enhancement, restoration of natural hydrology and floodplain connectivity, and improved water quality. In the last 45 years, the 166,500-acre Upper St. Johns River Basin Flood Control Project has grown to include four water management areas, four marsh conservation areas and two marsh restoration areas managed by the St. Johns River Water Management District and the US Army Corps of Engineers (SJRWMD 2007).

Spawning occurs from late December to early May in most years, with peak activity from mid-January to mid-March. (Walburg 1960, Williams and Bruger 1972, McBride and Holder 2008) which corresponds to the declining flows of the Florida Peninsula dry season (Kelly and Gore 2008). The spawning grounds have been documented from rkm 230 to rkm 433 near the headwaters (Williams and Bruger 1972, Williams et al. 1975). Of that distance 160km can be classified as river and 43 km as lake. Primary spawning grounds were in river habitats between rkm 275 and rkm 360 (Williams and Bruger 1972). Contemporary egg collection (Miller et al. 2012b) and telemetry (Dutterer et al. 2011) confirm that spawning grounds still exist between rkm 230 and a weir at rkm 415. The primary spawning areas are still between rkm 275 and 360. The only physical barrier to spawning migration is a low weir with a crest height of 3.8 m NAVD88 built at the outlet of Lake Washington in 1976. Fish can pass over the weir in very high water, but it is generally the upstream terminus of migration. It blocks access to approximately 14 km of potential spawning habitat in the uppermost river. Approximately 146 kilometers of potential habitat remains available for spawning depending on water level.

There are extensive non-tidal lentic and tidal freshwater habitats available to juveniles as well as several lakes. There are 95 kilometers of flowing river between Lake Harney and Lake George, 260 km2 of lake surface within the run of the river. The tidal freshwater downstream from Lake George extends for about 105 km at widths of 200 to 2,000 meters wide.

There are two main habitat issues that could negatively impact American shad in the St. Johns River, Florida; water quantity and water quality. The human population is growing rapidly in Florida which is putting increasing pressure on freshwater resources.

There is a proposal to allow withdrawal of up to a total of 262 million gallons per day (mgd) of surface water from the basin with a total of 155 mdg from several sites along the middle and upper St. Johns River. The District completed the St. Johns River Water Supply Impact Study (WSIS) in 2012 (Lowe et al. 2012). The intent of the WSIS "was to provide a comprehensive and scientifically rigorous analysis of the potential environmental effects to the St. Johns River associated with annual average surface water withdrawals as high as 262 mgd" (155 mgd from the St. Johns River and 107mgd from a tributary). Chapter 12 focused on fishery impacts of the proposed withdrawals with special consideration given to anadromous herrings in appendix 12-C (Miller et al. 2012a and 2012b). WSIS found that impingement/entrainment of anadromous herring eggs and larvae could occur at all proposed intake sites and could be potentially significant at two locations under consideration. The WSIS recommended reducing the impingement/entrainment risk to alosines by considering: intake designs that are safer for ichthyoplankton, alternative intake locations to avoid core spawning locations of American shad, and curtailing withdrawals on the spawning grounds during the spawning season at sites with high egg/larval abundance. WSIS found that optimal spawning habitat for American shad as delineated by depth and velocity shrinks under low flow conditions. Since the St. Johns River has low gradient and American shad spawning season corresponds with what is usually the dry season, adequate river discharge is probably important for St. Johns River shads (Harris and McBride 2004). The WSIS finds that access to spawning grounds and acreage of spawning grounds will not be adversely affected by withdrawals due to offsetting effects of base flow augmentation by the Upper Basin Restoration Project. The frequency and duration of low flow events are expected to decline slightly under modeled expected scenarios. It will be important to define relationships between environmental parameters and successful spawning. The surface water intakes proposed are no yet operating.

Water quality could impact juvenile American shad during their nursery period. Nutrient loads are high in the St. Johns River Basin which results in cyanobacteria dominated algae blooms and occasional hypoxia both in freshwater reaches and in the brackish estuary near the river mouth (Appendix 1 Hyle et al. 2012, Hendrickson et al. 2003). Algae blooms may occur in the lower river from summer through early fall which can negatively alter zooplankton communities (Paerl et al. 2002). Reduction in DO may impact larval and juvenile American shad nursery habitat and/or juvenile emigration corridors. Florida Department of Environmental Protection (FDEP) has established Total Maximum Daily Loads (TMDL) for nitrogen, phosphorus, and/or DO in the upper, middle, and lower St. Johns River. (Gao 2006, 2009, Magley and Joyner 2008).

Some tributaries to the St. Johns River that are thought to include American shad spawning habitat are the Econlockhatchee River which enters the St. Johns at rkm 317 in the heart of the spawning grounds, the Wekiva River which enters the St. Johns between Lake Monroe and Lake George at rkm 255, the Ocklawaha River which enters the St. Johns in tidal freshwater at rkm 168 near Welaka, and Black Creek at rkm 74.

The Econlockhatchee River is the second largest tributary to the St. Johns River encompassing a watershed area of 700 km2 with a stream length of 57 km. It discharges into the St. Johns River at rkm 317. American shad spawning has been documented in the lower Econlockhatchee River (Williams and Bruger 1972). It is not known if the Econlockhatchee River supports its own run of American shad or if it attracts strays from the adjacent St. Johns River spawning grounds. However, recent electrofishing and telemetry surveys have located adult shad from rkm 4 to rkm 14 during the spawning season (McBride and Holder 2008, Holder et al. 2012, Dutterer et al. 2011, Hyle 2019) in all years that sampling has occurred. Portions of the Econlockhatchee River watershed are densely developed which affects stormwater flow patterns and pollution. Management of associated run off is covered by the Middle St. Johns River Basin SWIM plan (SJRWMD 2002). Stormwater diversion and reclamation could reduce pollutant loads to the Econlockhatchee River but could also reduce base flow during the winter dry season in which American shad spawn. There is evidence that the Econlockhatchee River provides some amount of alternative habitat for American shad in the upper St. Johns River during periods of extreme low flow in the St. Johns River (Hyle 2019).

The Wekiva River is a spring fed tributary to the St. Johns River and shares extensive floodplain forest with the St. Johns River in its lower reaches. Preliminary investigations for the previous stock assessment found a few spawning capable American shad in the lower reaches of the Wekiva River. Blueback Herring and Hickory Shad were more common (Mcbride et al. 2008, McBride 2007). As a small tributary the main threat to habitat would be the impact of water withdrawals on minimum flows. The St. Johns River Water Management District is reviewing minimum flows and levels (MFLs) for the Wekiva River to appraise whether the existing MFL are appropriate for environmental and hydrologic goals; this included appraising whether habitat is suitable for anadromous herrings. A preliminary field study found suitable substrate and velocity for American shad in only 7.6 km of river (Miller and Mace 2019).

The Ocklawaha River is the largest tributary of the St. Johns River but it does not have a documented historical spawning run of American shad. It flows 119 kilometers from Lake Griffin to the St. Johns River with a total drainage area of 7,250 km2. There is a dam located at rkm 19 that was constructed in 1968 (Senator George Kirkpatrick Dam). Habitat upstream of the impoundment and below the dam appears suitable, similar substrate types and water velocities as the St. Johns River spawning grounds, for American shad to spawn. However, records of a spawning run of or fishery for American shad from the Ocklawaha River have not been found.

One specimen was noted in a dissertation entitled “Fishes of the St. Johns River System” (McLane 1955). There are anecdotes from veteran commercial fishermen of American shad present in the Ocklawaha River prior to dam construction (Jordan 1994) but no confirmation. There are modern anecdotes of shad present below the dam but recent efforts to locate spawning American shad in the Ocklawaha River below the dam have yielded none (Holder et al. 2012, McBride 2007).

Black Creek is a small tributary of about 200 km2 that drains from the ridge that separates the Suwannee River watershed from the St. Johns River. An Ichthyoplankton survey in 1972 and 1973 collected a very small number of American shad eggs and larvae from Black Creek and a fish camp along the river reported that some anglers caught shad there (Williams et al. 1975). Most recently, one ripe female American shad was captured in the north fork of Black Creek in exploratory electrofishing that occurred during the 2004 and 2005 spawning seasons (McBride 2007).

Monitoring and research of the St. Johns River, Florida American shad population was historically focused on the primary run in the main stem of the river where the bulk of the run and almost all the fishing occurred. This is true of modern sampling efforts.

3.23.2 Fishery and Management History

3.23.2.1 Commercial Fisheries

Netting began in the 1800s. Peak commercial landings exceeded 1.4 million kg at the beginning of the 20th century (Walburg 1960). Shad were harvested by drift gill nets, haul seines, and anchored or staked gill nets in the late 19th and early 20th century (Walburg and Nichols 1967) with netting being heavy in the lower river near Jacksonville. In the late 19th century there were concerns that netting in the lower river was so intense as to completely block the run. Regulations at the time were that there was no fishing allowed on Sunday and the season was December 1 to March 31, mesh size was regulated on gill nets (min 5” stretch) and seines (max 3” stretch), and no seining was allowed in the lakes above the tide. Haul seines between Palataka and Welaka were the dominant form of commercial harvest in the 1950s (Walburg 1960). In 1960 the commercial season ran from November 15 to March 15 and no commercial nets were permitted south of Lake George (Walburg and Nichols 1967). Fishing mortality of St. Johns Shad in the 1950s was estimated from tagging studies downstream of the fisheries to be between 15 and 37 percent with estimated population sizes from 0.41 to 1.68 million kg (Talbot and Sykes 1958, Walburg 1960, Nichols 1964, 1965, 1966a). Haul seining was phased out by the early 1970s and commercial fishing shifted to gill netting closer to the river mouth (Williams et al. 1975, Williams and Bruger 1972). Regulations in the 1990s phased out the commercial fishery for American shad. The minimum mesh size for a gill net in the river was increased to six inches in 1992 and the ocean shad fishery in state waters was regulated by a phase-in of net-tending and soak time regulations by 1994 (Williams 1996). In addition to those rules, a ballot referendum to amend Florida’s constitution passed in 1995 in which banned the use of entanglement nets in state waters (Constitution of Florida, article X, section 16). Effective January 1997, hook and line fishing is the only allowable gear to fish for any alosa species

(Chapter 46-52.001 [2], Florida Administrative Code [FAC]). Commercial netting no longer occurs for shad in Florida.

Commercial fishing harvest estimations are based on data reported to Florida's Marine Fisheries Information System (MFIS). Since 1986, Florida law requires wholesale transactions of marine organisms landed within the state to be reported to the MFIS. Annual landings were grouped as a fishing year (July June) because alosa species spawn in Florida between November and May. There has been essentially no commercial fishery for alosa species in Florida since 1996 when the net limitation amendment was enacted (Table 255).

3.23.2.2 Recreational Fisheries

Recreational hook and line sport fishing for American shad was popular on the St. Johns River by the 1950s and 1960s (Nichols 1959, 1966a; Walburg and Nichols 1967). In 1958 there were an estimated 6,000 boat trips by anglers targeting American shad in the St. Johns River that harvested 63,693 American shad. The average effort was about 5,000 angler hours from 1993 to 2005 with total catch ranging from 1,860 fish to 12,106 shad and harvest from 328 to 1,509 fish (McBride and Holder 2008).

An in-river recreational fishery for American shad continues in the St. Johns River. Effective January 1997, hook and line fishing is the only allowable gear to fish for any alosa species (Chapter 46-52.001 [2], Florida Administrative Code [FAC]) and the possession of more than an aggregate of 10 American, hickory, or Alabama shad is unlawful (Chapter 46-52.001 [3], FAC). A saltwater fishing license is also required of most anglers to fish for alosa species in Florida

3.23.2.3 SFMP summary and metrics

There is a sustainable fishing plan in place for the St. Johns River, Florida. The state of Florida has a statewide possession limit of all alosa species of 10 fish per person per day in aggregate. Additionally, hook and line gear is the only allowable gear permitted for the taking of shads. The sustainable fishing plan maintains the open status of the hook and line fishery with fishery-independent and dependent monitoring occurring in the St. Johns River. Current sustainability metrics are based on the fishery-independent spawning stock and juvenile abundance indexes.

The St. Johns River is the only river in the state with a known fishery for American shad. This is a recreational fishery limited to the spawning grounds with most fishing occurring between river kilometers 279 and 298, river kilometers 314 and 321, and a small amount in the Econlockhatchee River which is a tributary that enters the St. Johns River at river kilometer 317. There have been no reported commercial landings of American shad since the year 2000 (Table 255).

An access point creel survey estimates effort, catch, catch rate, and harvest in the recreational fishery from boat ramps at river kilometer 285, 290, and 316. The access point creel survey began in 2011 and covers the "Mullet Lake Creel Area" roving creel that occurred from 1993 to 2005 and was reported in the 2007 stock assessment plus an upstream location. Fishing effort has steadily declined in the "Mullet Lake Creel Area" with an apparent shift of effort into the upstream location (Figure 341). Harvest is a small fraction of total catch (Figure 342). The method of fishing has also changed from majority trolling to majority fly fishing and spin casting. The estimated CPUE has been relatively stable despite changes in the fishery (Figure 343).

The 2007 stock assessment recommended a restoration target CPUE of one fish per angler hour in the recreational survey because that was the longest relative abundance time series at the time. However, this target may not be useful because the location and method of recreational fishing have changed. The recreational fishery will be monitored for detection of increases in effort, CPUE, catch, and harvest. It may be possible in the future to generate a “relative exploitation index” from a relationship between the fishery-independent CPUE and the estimated angler harvest.

Fishery-independent data are collected for relative abundance and biological data of the spawning stock and relative abundance of YOY American shad. The spawning stock index is the seasonal geometric mean CPUE from samples occurring between river kilometer 314 and 358 (Figure 344). The JAI is the peak nightly geometric mean CPUE from samples occurring in the lower SJR between river kilometer 125 and 165 (Figure 344). The collection methods for the spawning stock survey have been standardized since 2003. The collection methods for the YOY survey have been standardized since 2007. The current sustainability metrics are both derived from these fishery-independent relative abundance data. A management review should occur if either index falls below the 25th percentile of the time series (Table 256, Figure 345 and Figure 346). The spawning stock index may need to be standardized to account for interannual differences in catchability caused by river conditions at the time of sampling (Figure 346, see years 2015 and 2016).

3.23.3 System-Specific Life History

American shad in the St. Johns River were reported to be ages two to seven based on scale ages in various studies from the 1950s to early 1970s (Walburg 1960, Leggett 1969, Williams et al. 1975). Females were generally one year older than males. Williams et al. (1975) found peak abundance at age five in 1972 and age 4 in 1973.

Modern age data derived from otoliths show ages two through eight observed and a modal peak of age four or five being most common and occasionally ages six or seven in instances of relatively strong year classes. For example, a strong 2010 year class produced high relative abundance of males at ages three through seven from 2013 through 2017 and high relative abundance of females at ages four through seven in 2014 through 2017 respectively (Table 257).

The caveat for modern age data is that the samples were aged by a single reader using the Massachusetts manual as a guide to technique and photos of known-age specimens from the Delaware River for training. Double-rings/false annuli seem to be causing over-ageing of some smaller and presumably younger fish which may be why the otolith ages are occasionally as high as age eight. Another challenge is identifying the first annulus. There are dry and warm falls when American shad remain in the lower St. Johns River for their most of their entire 1st year of life before emigrating to the ocean whereas there are years when a major tropical system causes extreme high freshwater discharge and emigration occurs in the early fall. In the case of 2008 there were abundant juvenile American shad in the tidal freshwater of the St. Johns River until Tropical Storm Fay produced 70-80 cm of rain which flushed the entire river to the mouth with very fresh low-dissolved oxygen water. That year class was well represented in the adult runs of 2012-2014 so the juveniles presumably survived the early departure from the nursery.

Despite the current lack of error analysis or specific validation of otolith-based ageing for St. Johns River American shad, the apparent ability to track a year class through monitoring catches gives some confidence that otolith bases ages are useful. Scale ages for shad were called into question (McBride et al. 2005) but it may be the case this semelparous population with relatively young ages may be amenable to using scale ages since the historic scale ages are somewhat mirrored by the current otolith estimates. It is noted that the modern otolith-based ages are slightly older than prior reported scale ages. This can result from the current otolith-based ages being over-estimates or due to the scale age estimates being too young.

3.23.3.1 Growth

McBride and Holder (2008) reported smaller average sizes of American shad from the St. Johns River as compared to samples collected from haul seines in 1958. For example, the mean female size in 1958 was 427 mm FL whereas it was 385 – 402 mm FL in the 2002 through 2005 runs. It is notable that the size of shad in the spawning run increased from 2003 through 2017 so that the mean female size was 416 – 418 mm FL from 2014 – 2017 (Figure 347). However, the mean size of females and males in all the runs through 2017 were smaller than the mean sizes reported from prior studies. Walburg (1960) reported a larger size at age at all ages greater than three than have been estimated from current otolith-based ages (Figure 348).

3.23.3.2 Maturity and Fecundity

3.23.3.2.1 Maturity

American shad in the St. Johns River are semelparous. No scales that have been examined to look for spawning marks have had spawning marks (LaPointe 1957, Walburg 1960, Leggett 1969). No mature shad tagged within the river has been recaptured outside the river (Talbot and Sykes 1958, Walburg 1960). Some male shad mature as early as age 2. Greater than 90 percent of males were age three to five (Walburg 1960, Williams et al. 1975). Female shad begin to mature at age 3 with greater than 90 percent maturing at ages four to six. For all years with available age data, the most abundant age within year varies from year to year (Figure 348).

A better maturity schedule for this stock could be refined if age data collection continues and issues with accuracy and precision of age estimates can be resolved. The 2008, 2009, and 2010 cohorts were fully recruited to the spawning stock by 2017. Since age samples as part of monitoring began in 2011 the proportion of each cohort maturing at age can be estimated for ages three through seven (Table 257).

3.23.3.2.2 Fecundity

Older estimates of fecundity were based on counting oocytes of fish entering the St. Johns River representing a potential annual fecundity (Davis 1957, Walburg 1960, Leggett 1969, Leggett and Carscadden 1978). But American shad are batch spawners with asynchronous oocyte development and potentially have indeterminate fecundity (Olney et al. 2001, Hyle et al. 2014). Olney and McBride (2003) estimated a batch sizes of 6,000 to 98,000 eggs and an oocytes per gram of ovary-free body weight similar to the Mattaponi River. The residence time of female American shad on the spawning grounds of the St. Johns River can exceed 50 days (Dutterer et al. 2011). The histology and batch fecundities from ovaries collected between 2003 and 2005 indicate that St. Johns River shad have batch fecundities and spawning frequencies comparable to the Mattaponi River, Virginia (McBride, Hyle and Holder, unpublished data).

3.23.4 Anthropogenic Sources of Mortality and Productivity

There are currently no stocking programs, water withdrawals that pose an impingement or entrainment risk, or structural features that could injure or kill migrating juvenile or adult American shad in the St. Johns River, Florida. There are proposed surface water withdrawal sites at the spawning grounds that could pose a risk of impingement/entrainment of eggs and larvae. The permitting agency for water use is aware of the high abundance of American shad eggs and larvae in the vicinity of proposed withdrawal sites (Miller et al. 2012b).

3.23.5 Fishery-Dependent Data Sources

3.23.5.1 Commercial

There have been no reported landings of American shad from any commercial fishery in Florida state waters since 2000. So, no fishery-dependent data are available from commercial sources.

3.23.5.2 Recreational

There is a small recreational fishery in the St. Johns River that has averaged about 4,000 angler hours targeting shad since 2011. The harvest rates is generally less than 80% so there are not enough shad retained by anglers to provide biological data from this fishery. Two creel surveys provide general effort and catch/harvest information from the recreational fishery for American shad in the St. Johns River.

A roving creel survey of recreational anglers was conducted between the mouth of Lake Jesup (rkm 285) and just south of Iron Bend (rkm 298) in 11 out of 13 years from 1992 to 2005 (McBride and Holder 2008). This creel documented declining effort and relatively stable catch rates (Figure 341 and Figure 342). An access point creel was introduced in 2011 and will continue annually as funds allow. The access point creel covers the old creel area (Mullet Lake Creel Area) via two boat ramps and an upstream area (Puzzle Lake Creel Area) via one boat ramp. The upstream stratum was introduced because the fishing effort has shifted into this area (Figure 342) and fly fishing/ spin casting has eclipsed trolling as the primary method of angling for shad.

In the modern creel survey recreational fishing effort, catch rate, total catch, and harvest of American shad were estimated using a stratified access point creel survey. The survey begins on January 1st of each year and consists of three periods of 28 days with 14 samples per period and two area strata. Seven random samples were obtained per 28-day period in each stratum; four from 20 possible week days and three from eight possible weekend days. Days were divided into two work periods of 0900-1330 and 1330-1800 with probabilities of 0.35 and 0.65, respectively. Location probabilities were 0.5 for the two ramps in the Mullet Lake Cree Area stratum. A total of 42 samples were taken during the 12-week creel. FWC analyzes creel data using the FWC Creel Analysis 3.1 program (Connor 2007) which calculates CPUE for completed trips using a ratio of means (Pollock et al. 1997).

Catch rate data are not considered representative of interannual abundance changes and were not used in the assessment for abundance trend anlyses (Table 13).

This is a short seasonal fishery and effort can be influenced by weather, water level, and social media. Poor weather or high water during the season can reduce effort. Most anglers are local so word of mouth indicating a good or bad run will influence their decision to target American shad or not.

3.23.6 Fishery-Independent Data Sources

3.23.6.1 Adult Fishery-Independent Data Sources

3.23.6.1.1 St. Johns River Spawning Ground Electrofishing Survey

Electrofishing samples on the spawning grounds provide catch per unit effort, length, and sex of American shad beginning in 2003. Sub-samples of the electrofishing catch are taken for otolith-based ageing beginning in 2011.

Electrofishing for American shad began in December 2001. The 2001/2002 season was exploratory in nature and does not provide useful relative abundance information. Areas sampled were described in McBride 2007 and McBride and Holder 2008.

Useful relative abundance data begin in January 2003. Sample months also spanned from November/December until the end of April or early May until 2005. Sampling occurred bi-weekly between rkm 279 and 298 for the duration of the season in 2003/2004 and 2004/2005. Sampling in three other areas occurred on a six-week rotation (McBride and Holder 2008). The methods and locations for index sampling were standardized beginning in 2006. Appraisal of trends in relative abundance that use catches from 2003 to 2005 should only use electrofishing trips that overlap the current standardized survey in location and seasonal timing. Locations for relative abundance have been designated as “CA” (rkm 279-298), “PZ” (rkm 314-320), and “SR50” (rkm 346-357) (Figure 344). Samples in December, April, and May are outside the body of the spawning run and add zero-data that do not reflect the abundance of the spawning run.

Additionally, there were nocturnal samples in 2004 that should not be included in relative abundance calculation because all standard monitoring samples occur during daylight hours.

Sampling was bi-weekly from January to April in the CA, PZ, and SR50 strata from 2006 through 2009. After 2009, sampling was bi-weekly in the upstream PZ and SR50 strata and two peak-season trips in the CA stratum. Trips aimed at assessing relative abundance consisted of collections from 10 randomly selected river kilometers in the CA stratum, four samples in the PZ stratum, and six samples in the SR50 stratum. To date, annual compliance reports and the SFMP for the St. Johns River combine catches from the PZ and SR50 stratum for calculation of an annual abundance index (Table 258).

Standard relative abundance samples consisted of electrofishing for 10 minutes of “on” time while meandering downstream between the one-meter depth contours at a speed of 1.5 - 2 mph faster than the ambient current. Electrofishing power was applied to the water on a 25 second on and 5 second off cycle. Electrofishing was accomplished with a boat mounted Smith-Root 9.0 electrofishing unit using a pair of 4-dropper Wisconsin rings as anodes and the hull of the aluminum boat as the cathode. Power to the water was applied according to conductivity and temperature to optimize shocking effect. All samples used two dip-netters.

There are potential environmental effects on catchability and distribution of American shad on the spawning ground. The water level is typically low and stable or declining during the spawning run because the run occurs during the Florida peninsular dry season. There is little expectation that catchability between the two areas varies in most years. However, in very low flow conditions shad may concentrate in small areas further upstream where channel constrictions and higher gradient produces suitable current. This has the effect of increasing the patchiness of fish distribution. Fish that are concentrated in shallow water are also more vulnerable to the electrofishing gear. Also, in rare winter high flows, the PZ and SR50 upstream strata flood out and take on a lacustrine character with no discernable channel. Near-record high flows in 2015 and 2016 flooded the rkm 314 – 358 reach resulting in an inverse relationship between the two indexes (Figure 346).

Catch Rates

Each electrofishing collection was treated as an independent observation. One standard unit of effort was defined as 10 minutes of accumulated electrofishing effort by the vessel traveling downstream at 2.5 kilometers per hour faster than the ambient current and applying electricity to the water in a cycle of 25 seconds on and 5 seconds off. There were 15 years of data with averages of 73 positive observations per year and 63.0% positive observations per year. Variables available for potential inclusion in the standardization model included sampling year (discrete), day of year (continuous), average daily discharge at USGS Station 02232500 (St. Johns River Near Christmas, FL; https://waterdata.usgs.gov/fl/nwis/inventory/?site_no=02232500; continuous), and sampling stratum (discrete). Model types considered included negative binomial generalized linear models (NB GLM), negative binomial generalized additive models (NB GAM), zero-inflated negative binomial generalized linear models (ZINB GLM), and zero-inflated negative binomial generalized additive models (ZINB GAM). All GAM models were fit assuming cubic regression splines for continuous variables and with a gamma penalty of 1.4 for all models (NB GAM) and sub-models (ZINB GAM). AIC was used to select the final model type (NB GLM, ZINB GLM, NB GAM, or ZINB GAM), covariates, and basis dimensions for smoothing functions. Prior to model fit, the data was constrained to only represent collections made within the first 120 days of the year; collections at later times in the year rarely encountered American Shad.

A ZINB GAM was used to estimate a standardized index of abundance accounting for variability in annual catchability effects due to available covariates. The final model included count of landed American Shad as the response variable and the variables sampling year (count model only), day of year by survey stratum, average daily discharge by survey stratum, and stratum.

The final model suggests the catchability of adult American Shad is affected by sampling stratum, day of year, and average daily discharge of the St. Johns River. Catches of adult American Shad increase from January 1 through approximately mid-February (DOY = 45), after which catches decrease steadily through day 120 (approximately May 1). There is a strong indication that average daily discharge of the St. Johns River, as measured near Christmas, FL, strongly influences the catchability of adult American Shad in the survey, with catches showing an inverse relationship with daily discharge. Catches also vary by survey stratum, with notably fewer adult American Shad encountered in the “CA” stratum.

The standardized index follows the same trend as the arithmetic mean catch rates for most years, with the notable exception of 2003; during 2003 the standardized index suggests much higher relative abundances of adult American Shad in the St. Johns River than suggested by the arithmetic mean catch. The standardized index suggests a decrease to record low, but stable abundances through 2008, followed by a gradual increase in relative abundance through the mid-2010s. The most recent two-years of data suggest the abundance of American Shad has begun decreasing again. Annual CVs averaged 0.16 over the time series (Table 260).

Biological Data

For all samples the collected fish were held live, processed between transects, and then released. Sex, determined by external inspection, and total length (TL) in mm were recorded for all alosa spp. collected. A subsample of 5 to 10 American shad of each sex per centimeter group was sacrificed for otolith removal for ageing in each year beginning in 2011. Dissolved oxygen (mg/l), conductivity (µS/cm), temperature (C), and Secchi depth (m) were recorded at each sample site. Total length was converted to fork length [FL = 0.8888*TL-.4.158 (R^2 = 0.9896)] when needed to compare size of fish in recent collection with older samples that were reported in fork length.

3.23.6.2 Young-of-Year Fishery-Independent Data Sources

3.23.6.2.1 St. Johns River Juvenile Pushnet Survey

The sample gear consisted of a 5.3 m aluminum boat used to push a modified four panel Cobb trawl mounted on a rigid frame. The net opening was 1.2 m high X 1.5 m wide. The body was 3 m deep and constructed of 19 mm stretched mesh knotless nylon. The cod end was 2 m deep and constructed of 12.7 mm stretched mesh knotless nylon. Distance pushed through the water was measured using a General Oceanics 2030R mechanical flowmeter mounted between the inner and outer vertical bars of the frame. Tow speed was standardized to an engine RPM of 2,000. This produces a speed of 2.6 statute miles per hour in still water. The vessel, motor, and net configuration were the same for all years 2007 through 2017. Catch per standard net haul can be standardized by flowmeter count to ensure that similar volume of water is filtered.

Juvenile American shad have been collected from the St Johns River, Florida by nocturnal pushnet samples since 2007. Samples were collected monthly from March to October in four 40 km reaches between rkm 125 and 305 from 2007 to 2009. During that time 12 samples were collected each night from randomly selected river kilometers within each 40 km reach. In 2010 the program switched to biweekly sampling in a 40 km reach, rkm 210 – 249, above the head of the tide but below the primary spawning grounds where the constricted nature of the river made it appear suitable to capture juveniles moving downstream. It turned out that high flows early in the year could make fish move through this stretch quite quickly and not be adequately represented in bi-weekly samples. In 2011 a 40 km reach in tidal freshwater, rkm 125 – 164, was added back into the monitoring schedule. Samples in this lower reach were monthly in 2011 and bi-weekly from 2012 to 2017. The number of samples in this reach and months are summarized in Table 259. A sample night has always been 12 standard tows in randomly selected river kilometers within the 40 km reach. Data from the tidal freshwater stretch are currently considered the best index of juvenile abundance because the residence time of emigrating juveniles in this stretch appears to be less sensitive to interannual differences in river discharge.

Biological and Environmental Sampling

YOY American shad are sorted and counted. Surface temperature, conductivity, and dissolved oxygen are collected at each station. Additional environmental variables are available from a USGS station.

Evaluation of Survey Data

An index of juvenile American shad abundance was developed from this survey. American shad were caught with 61% positive tows. A full model that predicted catch as a linear function of year, surface water temperature, conductivity, and dissolved oxygen was compared with nested submodels using AIC. Based on several diagnostics (AIC, dispersion, percent deviance explained, and resulting CVs), the model chosen was a negative binomial that included only year.

Abundance Index Trends

The survey of relative abundance of juvenile American shad in the St. Johns River in Florida showed low abundance in 2007 through 2009, followed by the highest value in 2010 (Table 261, Figure 349). The index was variable, but demonstrated three peeks over the time series: 2010, 2012-2013, and 2015-2016. Abundance decreased in the terminal year of 2017.

3.23.7 Methods

Power analysis and Mann-Kendall analysis were used to evaluate trends in abundance and mean length. Habitat assessment was applied to assess current habitat availability relative to historical habitat. Details for these methods are provided in Section 2.

3.23.8 Results

3.23.8.1 Abundance Trends

3.23.8.1.1 Power Analysis

Two abundance indices for American shad were developed for this system that contained estimates of PSE, the St. Johns River Juvenile Pushnet Survey index (median PSE = 0.167) and the St. Johns River Spawning Ground Electrofishing Survey (median PSE = 0.174). Each of these surveys are currently used in the SFMP for sustainability targets and monitoring. Both of these surveys exhibited sufficient power to detect a 50% decrease in American shad abundance in 10 years, though both fell short of the desired 0.80 power for detecting a 50% increase in American shad abundance (Table 25).

3.23.8.1.2 Mann-Kendall Analysis

St. Johns River (JAI)

Data from the St. Johns River Juvenile Pushnet Survey was provided for the period between 2007 and 2017. Values consistently fluctuated every few years, but a plot showed a slight increase over time for the short time series (Figure 349). However, Mann-Kendall analysis failed to detect a trend for either time period examined.

St. Johns River (FI CPUE)

Data from the St. Johns River Spawning Ground Electrofishing Survey was provided for the period between 2003 and 2017. A plot of the data showed an initial decrease in the index and an increase from 2008-2015, followed by a sharp decrease (Figure 350). Mann-Kendall analysis failed to detect a trend over the full time series, but did find an increasing trend for the period from 2005 forward.

3.23.8.2 Mean Length Trends

The St. Johns River has only a 9.1 m elevation change over its entire 499 km length with one dam on the main stem at Lake Washington. The FLFWC submitted American shad lengths from the St. Johns River Spawning Ground Electrofishing Survey. A plot of mean total lengths collected from 2003-2017 showed an increase for both males and females during that time with both sexes in steady increase since 2012 (Figure 351). Mann-Kendall trend analysis supports this showing a significant positive trend in lengths for both male and female American shad.

3.23.8.3 Habitat Assessment Results

Current American shad habitat was estimated as a proportion of total historical habitat extent. Current unobstructed habitat is defined as habitat area below the first impoundment, while historical habitat extent includes all American shad habitat historically accessible in the absence of impoundments.

For the St. Johns system, current unobstructed habitat area represents 90.04% of the historical habitat extent (44.38 of 49.28 square kilometers).

3.23.9 Stock Status and Conclusions

Mortality
Juvenile and adult mortality status is unknown due to lack of data to make this determination.

There was in increasing trend in female mean length detected since 2003 and no trend in YOY abundance detected since 2007.

Abundance
Abundance status is unknown. There was no trend in YOY abundance detected since 2005. There was an increasing trend in adult abundance detected since 2005.

3.23.10 Research Recommendations

- Continue adult monitoring in sensitive habitats such as the Wekiva river and the Econlockhatchee River: Sampling has occurred in the Econlockhatchee River in most years (Hyle et al. 2019) since 2007. The Econlockhatchee provides several kilometers of spawning habitat. The Wekiva River has not been monitored. American shad detections there were sporadic in 2003 – 2005 and it appears to be more suitable habitat for Hickory Shad and Blueback Herring. American shad habitat in the Wekiva River appears very limited (Miller and Mace 2019).

- Continue, and expand where possible, sampling into more upstream areas of the spawning grounds. Use these data to understand spawning site selection and spawning success: The standardization of sampling for CPUE monitoring increased the intensity of sampling in key spawning habitats. Key spawning habitats were identified by egg/larval surveys (Miller et al. 2012) and by Telemetry (Dutterer et al. 2011).

- Learn more about the juvenile downstream migration: The pushnet survey has provided data that should be able to describe interannual differences in downstream migration timing. Additionally, an incomplete attempt is in the works to look at stock-recruit relationships, environment-recruit relationship with respect to spawning season river discharge, and whether the lower river JAI predicts future CPUE at age in the spawning stock.

- Initiate a Cating-like study of shad scales and otoliths: No progress. The otolith-based ages from 2011 to 2017 are older than historic scale-based ages and modern fish are smaller than historic. The scale and otolith-based ages for the St. Johns River need to be reconciled so that it can be determined whether growth is indeed slower in the last decade than in the mid-20th century.

- Catch-and-release mortality: No progress. Low priority. Fishermen are only fishing in a small amount of available spawning habitat and shad are generally release back to the water very quickly after capture.

- Develop and mark-recapture approach to learn more about population size, mortality, habitat selection, and movements: There have been no population estimates. Telemetry has given some insight into habitat selection, life-span of this semelparous fish on the spawning grounds, and movement of fish on the spawning grounds (Dutterer et al. 2011).

- Create more data regarding habitat selection. Apply such data toward management needs, particularly minimum flow level determinations as mandated by the St. Johns River Water Management District: See (Miller et al. 2012c, Dutter et al. 2011).

4 COASTWIDE METAPOPULATION AND MIXED-STOCK ANALYSES

4.1 Fishery-Dependent Data Sources

4.1.1 U.S. Coastwide Commercial Landings

Dealer reported commercial landings from all jurisdictions along the U.S. Atlantic Coast were provided through the Atlantic Coastal Cooperative Statistics Program (ACCSP) Data Warehouse. Landings are available from 1950 through 2017. ACCSP does not maintain landings data prior to 1950. These total coastwide landings include reported landings from in-river fisheries, estuarine fisheries, and ocean fisheries, but cannot be comprehensively partitioned into these fisheries due to varying temporal and spatial resolution recorded by jurisdictions. Landings can be partitioned for some fisheries (i.e., the Delaware Bay mixed-stock fishery) and, where they are believed to impact multiple stocks in mixed-stock fisheries, are provided in addition as stand-alone time series below for further information on potential impacts of fishing on multiple stocks. Jurisdiction-specific details on commercial landings are provided under the “Fishery-Dependent Data Sources” headings in Section 3.

Total commercial landings fluctuate around eight million pounds through the 1950s, decline to just over two million pounds in 1976, increase through the mid-1980s, and then decline through the remainder of the time series (Table 262, Figure 352). Landings have been below one million pounds since the closure of the ocean intercept fishery in 2005 and fell below half a million pounds in all of the most recent three years (2015-2017).

4.1.1.1 Catch Rates

4.1.1.1.1 New Jersey Ocean Commercial Logbook Index

Data from ocean commercial logbooks were available for 1999-2013. Effort was calculated as the square feet of net fished multiplied by the average net soak time in hours. While American shad were reported as being caught in the ocean from November-June, the majority of trips occur in the spring. Therefore, the data set was subset to only March through May. The net type category was collapsed into three different net types: anchor, drift, or stake nets. As only 5 trips in the data set were categorized as stake net trips, this net type was dropped from the analysis. Only trips with complete information on square feet of net fished, soak time, mesh size, day of year, and net type were used. Effort data was not available for 1999 so the final index is from 2000-2013. Because multiple mesh sizes were sometimes reported, an average mesh size per trip was used and mesh size was therefore considered a continuous variable. While the majority of catch was reported in 3.25-6 inch meshes, two trips reported shad caught in 12 inch mesh. This outlier mesh panel data was removed from the data set for analysis. The day of year and mesh size appeared to have non-linear relationships with the catch and a negative binomial GAM was used for standardization. While a GAM model with year, net type, a smoother for mesh, and an effort offset was developed, it was found to have poor model diagnostics including a dispersion estimate greater than 2. For these reasons, the geometric mean index is recommended for the assessment.

Data is not available for 2011 as the only ocean harvest was reported in January and December that year, not the months of March-May. Additionally, no harvest was reported in 2013 despite trips being reported. One ocean trip was reported for 2016 but no date information was included in the logbook and the harvest were from stake nets which were removed from the analysis due to low sample size.

The geometric mean index had an increasing trend from 2000 to 2002 before falling slightly in 2003 and 2004 (Table 263, Figure 376). After peaking in 2005, the index fell sharply in 2006-2007. A small increase in CPUE was observed through the late 2000s before falling again in 2010. Since 2012, the CPUE has been at the lowest levels observed in the time series with a value of 0 observed in 2013. No March-May logbook trips reported shad catch since 2013.

4.1.1.1.2 Atlantic Ocean Commercial CPUE (NC DMF)

In North Carolina, commercial landings of American shad have been reported sporadically since 1880 and consistently since 1950. From 1950 to 1978, North Carolina landings data were collected by NOAA Fisheries. From 1978 to 1993, commercial landings in North Carolina were acquired via an NCDMF and National Marine Fisheries Service cooperative statistics program on a monthly basis from licensed seafood dealers; however, reporting was not mandatory at that time. In 1994, NCDMF implemented a mandatory commercial harvest data collection system known as the Trip Ticket Program. The Trip Ticket Program is a dealer-based reporting program that obtains a trip-level census of commercial landings in North Carolina and continues to the present day (NCDMF 2018).

Estimates of fishery-dependent CPUE from the Atlantic Ocean are only available after the inception of the North Carolina Trip Ticket Program in 1994 through 2004 (Table 264 and Figure 377). The ocean intercept fishery for American Shad was closed to all harvest January 1, 2005 (ASMFC 2002). CPUE is calculated as total catch, in pounds, divided by the total number of directed shad trips. Directed trips are those trips landing at least 100 pounds of shad. This method assumes that effort was relatively uniform among trips with respect to net yardage and soak time. Exact estimates of yardage used are not available from the Trip Ticket Program.

Estimates based on maximum yardage allowed are unrealistic and would over-inflate the amount of effort actually expended.

4.1.2 Delaware Bay Mixed-Stock Fishery

4.1.2.1 Landings

Commercial exploitation of the Delaware River American shad stock is permitted by the states of New Jersey and Delaware within the Delaware River Basin. Harvest occurs generally during the spring spawning migration from late February into May principally using anchored or drift gill nets. In the 2012 Delaware River Basin Fish and Wildlife Management Cooperative (Co-op) SFMP, the Co-op acknowledged that the commercial fishery in the Delaware Bay exploited American shad from mixed-stocks, along with the Delaware River stock. A demarcation line from Leipsic River, DE to Gandys Beach, NJ was established, where landings in the upper estuary are considered to be 100% Delaware River American shad stock and landings in the bay were of mixed-stock, with an estimated 40% of Delaware River origin. Upon further examination of reporting regions in the state of Delaware, it was determined that the four reporting regions (River, Upper Bay, Mid Bay, and Lower Bay) do not allow for landings to be divided at the Leipsic River. A new delineation point was selected for the state of Delaware (Bowers Beach), which now assigns landings to Delaware River stock harvest for the upper three reporting regions in that state. Available tagging and genetic studies, suggest continuance of assignment of the proportion of the Delaware River stock at a similar rate as the 2012 SFMP. Harvest on the mixed-stock occurs in both Delaware and New Jersey in the Delaware Bay. Mixed-stock landings were highest in the early 1990s and have been generally declining since that time (Figure 130). Landings on the mixed-stock have been below the time-series mean (1985-2018) since 2006.

The Co-op currently uses five indices with benchmarks for sustainability in their SFMP, including one pertaining to the mixed-stock landings. The SFMP benchmark was developed to limit expansion of the fishery in this mixed-stock area. This mixed-stock index is calculated as the annual landings from the mixed-stock fishery. It is calculated as 60% of total shad landings below the demarcation line (Bowers Beach, DE to Gandys Beach, NJ). The benchmark is based on data from 1985 – 2015 and failure is defined as the occurrence of 2 consecutive years above a value of 47,650 (i.e., the 75th percentile of historical data, where 25% of values are higher) (Figure 130). The benchmarks have been set to respond to any potential decline in stock. Thus, all benchmarks are viewed as conservative measures. Failure to meet any of the defined benchmarks will independently cause immediate management action. The severity of the action will be situational and proportional to the number of benchmarks exceeded. All benchmarks are reviewed annually after completion of annual ASMFC Shad and River Herring compliance reports.

4.1.2.2 Catch Rates

4.1.2.2.1 New Jersey Delaware Bay Commercial Logbook Index

Data from commercial logbooks was available for 1999-2017. Effort was calculated as the square feet of net fished multiplied by the average net soak time in hours. While American shad are caught as bycatch in some other fisheries in Delaware Bay throughout the year, the majority of trips occur in the spring. Therefore, the data set was subset to just February through May trips. The net type category was collapsed into three different net types: anchor, drift, or stake nets. Only trips with complete information on square feet of net fished, soak time, mesh size, day of year, and net type were used. Effort data was not available for 1999 so the final index is from 2000-2017. Because multiple mesh sizes were sometimes reported, an average mesh size per trip was used and mesh size was therefore considered a continuous variable. Both day of year and mesh size where found to have non-linear relationships with the catch and a negative binomial GAM was used for standardization. The final negative binomial model used year and net type as covariates, a smoother for mesh size and day of year, and an effort offset to estimate the pounds of shad caught. However, the dispersion was estimated to be over 2 and the model diagnostics were poor. Therefore, the geometric mean index is recommended for the assessment.

While the index has been variable year to year, there is a general decline in CPUE since the beginning of the time series and the peak CPUE observed in 2001 (Table 265, Figure 378). The lowest CPUEs were observed in 2015 and 2016 with a small increase in CPUE observed in 2017.

4.1.2.2.2 Delaware State Delaware Bay Catch Rates

Data from commercial landings was available from 1985 – 2017. Commercial landings were determined from mandatory reports submitted by Delaware commercial fishermen. Almost all shad landed were in conjunction with the spring Striped Bass commercial season since American shad are caught as bycatch in this fishery. All landings were by gill net, both anchored (fixed) and drifted. Anchor nets were used primarily in Delaware Bay; drift nets were used exclusively in the Delaware River by regulation. CPUE was calculated as the pounds of shad harvested per amount of net fished (yards).

Overall, the CPUE for Delaware state landings from the Delaware Bay has been declining since the beginning of the time series (Table 266, Figure 379). The highest CPUE observed in recent years occurred in 2014 while the lowest CPUE in recent years was recorded during 2012.

4.1.3 Canadian Commercial Landings

Commercial landings were also provided for the Maritime region of the Canadian Atlantic Coast by Canada Department of Fisheries and Ocean. Due to confidentiality constraints, area and month information could not be provided. These landings likely include fish from Canadian and U.S. stocks and are included to provide some insight on potential Canadian fishery impacts on U.S. stocks.

Canadian landings fluctuate around approximately 90,000 pounds through the early 2000s and then decline and fluctuate around approximately 50,000 pounds through the remainder of the time series (Figure 353, Table 267).

4.1.4 Incidental Ocean Catch

4.1.4.1 Methods

The total incidental catch of American shad in U.S. oceanic state and federal waters was estimated following the methods described in the most recent river herring assessment (ASMFC 2017a), which were developed during Amendment 14 to the Atlantic Mackerel, Squid and Butterfish (MSB) Fishery Management Plan.

The total (retained + discarded) incidental catch of American shad from 1989-2017 was quantified by fleet. Fleets included in the analyses were those sampled by the NEFOP and were stratified by region fished (Mid-Atlantic versus New England), time (year and quarter), gear group, and mesh size. Region fished was defined using statistical areas for reporting commercial fishery data; the Mid-Atlantic region included statistical areas greater than 600, and New England included statistical areas 464 through 599. Gear groups included in the analyses were: bottom trawls, paired midwater trawls, single midwater trawls, gill nets, dredges, handlines, haul seines, longlines, pots/traps, purse seines, scallop trawl/dredge, seines and shrimp trawls. Bottom trawls and gill nets were further stratified into three mesh-size categories (Table 268).

Mesh information was not available for some trips; in these instances, mesh was assumed based on gear or species caught. Mesh category for bottom trawl fleets was determined for trips with missing mesh information based on the primary species caught. For gill nets, trips with missing mesh information were assumed to come from the large mesh category.

The combined ratio method (Wigley et al. 2007) is the standard discard estimation method implemented in NEFSC stock assessments. This method was used to quantify and estimate the precision (CV) of American shad total incidental catch for 1989 – 2017 across all fleets. Incidental catch estimates for the midwater trawl (MWT) fleets are only provided for 2005-2017 because marked improvements to NEFOP sampling methodologies occurred in the high-volume MWT fisheries beginning in 2005, limiting the interpretability of estimates from these fleets in prior years.

For each trip, NEFOP and At Sea Monitoring (ASM) data were used to calculate a total catch to kept (t/k) ratio, where t represents the total (retained + discarded) catch of American shad and k is the kept weight of all species. Annual estimates of total incidental catch were derived by quarter. Imputations were used for quarters with one or zero observed trips.

The t/k ratios were expanded using a raising factor to quantify total incidental catch. With the exception of the midwater trawl fleets, total landed weight of all species (from the dealer database) was used as the raising factor. Total landings from the dealer database are considered to be more accurate than those of the VTR database because VTR landings represent a captain’s hail estimate. However, for the MWT fleets, the dealer data could not be used to estimate the kept weight of all species when stratifying by fishing area. When the area allocation (AA) tables were developed, MWT was not included in effort calculations because of difficulties determining effort for paired MWTs. Only those gears with effort information could be assigned to a statistical area. Consequently, VTR data were used as the expansion factor for the MWT fleets. A comparison of the number of observed trips to the total number of trips from either the VTR or dealer databases is detailed in Table 269 and Table 270.

To estimate American shad discards by fishing fleet, the above analysis was repeated using discarded catch instead of total catch. Discard estimates were then compared to total catch estimates to calculate the proportion of American shad catch that is discarded.

Length information from observed NEFOP and ASM trips were also used to evaluate the size distribution of American shad caught. Length data were available for bottom trawl, gill net and midwater trawl fleets.

4.1.4.2 Results

From 1989-2017, the total annual incidental catch of American shad ranged from a minimum of 42 metric tons in 2016 to a maximum of 262 metric tons in 2000, averaging 64 metric tons since 2010 (Table 271, Figure 355). The corresponding estimates of precision varied substantially among years but since 2010 have averaged 0.19 (Table 271, Figure 354 and Figure 355).

The distribution of incidental catches was summarized by quarter, gear and fishing region for 2005-2017 (Table 272). Across gear types, catches of American shad were greater in New England (65%) than in the mid-Atlantic (35%), though the contribution of each fishing region varied among years (Figure 356). American shad catches occurred primarily in large-mesh gill nets (38%), small-mesh bottom trawls (34%) and paired midwater trawls (13%); however, primary gear and mesh category also varied across years (Table 272-Table 273, Figure 357-Figure 358). The percentages of small-mesh bottom trawl catches were similar between the mid-Atlantic (16%) and New England (18%). However, large-mesh gill net catches were over two times higher in New England (27%) than the mid-Atlantic (11%).

For small-mesh bottom trawls and large-mesh gill nets, the majority of catches are discarded (89% and 92%, respectively, since 2010); however, most catches from midwater trawl vessels are retained (95%) (Table 274).

The size distribution of observed American shad varied by gear (Figure 359). Bottom trawls encountered individuals ranging from 10-77 cm with a mode at 26 cm. Approximately the same size range (14-76 cm) was caught in gill nets; however, the mode (47 cm) was substantially higher than that for bottom trawls. This is consistent with trends in catches by mesh category where bottom trawl catches were primarily from small-mesh trawls where gill net catches were mainly from large-mesh nets (Table 272, Figure 357-Figure 358). The size distribution of American shad caught in midwater trawls was smaller and more limited (13-51 cm) than those from the other dominant gears; however, the mode (25 cm) was similar to that of bottom trawls (Figure 359).

4.1.4.3 Interpretation and limitations

The estimates present here represent the total (retained + discarded) catch of American shad in U.S. oceanic state and federal waters. Catch estimates can be attributed to a specific fishing fleet defined by a combination of gear, mesh, quarter and region fished, but cannot be attributed to a specific fishery because species managed through multiple fishery management plans are often caught on one fishing event. Furthermore, due to a lack of genetic information and the likely extent of stock mixing on the shelf, it is not possible to attribute catch estimates to particular stocks of American shad. Finally, because coastwide estimates of absolute abundance are not available, it is not possible to determine the level of mortality that these catch estimates represent.

4.1.5 Marine Recreational Information Program

American shad is a rare event species intercepted by MRIP sampling, primarily due to limited spatial overlap of sampling and American shad recreational fisheries. These data are not useful for assessment purposes.

4.2 Fishery-Independent Data Sources

4.2.1 Sub-Adult and Adult Fishery-Independent Data Sources

4.2.1.1 Maine – New Hampshire Trawl Survey

4.2.1.1.1 Survey Design and Methods

The Maine-New Hampshire Inshore Groundfish Trawl Survey is a fisheries independent assessment of fisheries resources inside the coastal waters of Maine and New Hampshire. Its purpose is to fill a significant information gap that effects efficient management of Maine’s fisheries resources. The survey is designed to provide biological, environmental and timing data on a number of commercial and non-commercial fish species found in the coastal waters during the spring and fall of each year. When the survey originally began in the fall of 2000 the focus was to assess groundfish abundance. Over the course of the survey the focus changed to include all commercial and noncommercial species.

Survey staff sample 120 stations stratified among five sections along the Maine coast each spring and fall. The survey counts and weighs all shad caught at each of the 120 sample stations. The coast is divided into 5 areas based on geologic, oceanographic, geographic and biologic factors. Each area is divided into four depth strata; 5-20, 21-35, 36-55, and 55+ fathoms. Stations are located randomly to reflect representative conditions within each of the strata.

Gear consists of a modified shrimp net with 2-inch mesh in the wings and a 1/4 inch mesh liner in the cod end. Foot rope and head ropes are 57' and 70' respectively, with 6-inch rubber cookies. The gear was designed to be very light on the bottom to minimize habitat disruption. The survey subsamples the shad catch and measures individual fork length to the nearest centimeter.

The highest catch rates of older juvenile American shad in coastal ocean waters generally occurred in Regions 1 and 2 along the westernmost coast of Maine. These regions bracket the mouths of the Saco and Kennebec rivers. The highest arithmetic mean catches per trawl tended to occur most often during the fall rather than the spring, most likely due to the numbers of juveniles leaving the river systems. For six of the last seven years the spring survey captured higher mean numbers per trawl and were generally more consistent than the mean catches during the fall trawl survey. The percent occurrence of American shad captured for all tows conducted during the spring and fall survey time series indicate that an increasing number of tows capture American shad. Captured American shad were 7 to 48 cm FL. Mean lengths tended to be 15 to 20 cm. Age-length curves developed for American shad of the Hudson River suggest that these fish were one and two years old (Stira 1976). The trawl survey data indicate a general increase and length and weight of American shad captured since the beginning of the survey. Numbers captured during the spring survey were generally higher during the fall survey, but the stratified means were below 20 fish for both surveys.

4.2.1.1.2 Biological and Environmental Sampling

Finfish are sorted by species, counted, weighed, and lengths are taken. Water temperature, surface temperature, and salinity are collected at each station.

4.2.1.1.3 Evaluation of Survey Data

A spring index of American shad abundance was developed from this survey. American shad were caught in the spring with 51% positive tows. A full model that predicted catch as a linear function of year, stratum, depth, water temperature, surface temperature, and salinity was compared with nested submodels using AIC. Based on several diagnostics (AIC, dispersion, percent deviance explained, and resulting CVs), the model chosen was a negative binomial that included year, stratum, depth, and water temperature.

A fall index of American shad abundance was developed from this survey. American shad were caught in the fall with 28% positive tows. A full model that predicted catch as a linear function of year, stratum, depth, water temperature, surface temperature, and salinity was compared with nested submodels using AIC. Based on several diagnostics (AIC, dispersion, percent deviance explained, and resulting CVs), the model chosen was a quasi-Poisson that included year, stratum, depth, surface temperature, and salinity.

4.2.1.1.4 Abundance Index Trends

The survey of relative abundance of American shad in Maine and New Hampshire coastal waters in spring showed peak abundances in 2002, 2006, 2011-2012, and a smaller peak beginning in 2015 (Table 275, Figure 380). Abundance reached the highest value in 2006, followed by sharp declines through the late 2000s. Abundance increased again in 2015 is remaining stable in the terminal year of 2017.

The survey of relative abundance of American shad in Maine and New Hampshire coastal waters showed low abundance in the early 2000s with some peaks in abundance in the mid-

2000s followed by low abundance in 2010 – 2014 and a final peak in 2015 (Table 276, Figure 381). The index was variable through the 2000s followed by very low values from 2010-2014. Abundance increased in 2015 and decreased through the terminal year of 2017.

4.2.1.2 Rhode Island Coastal Trawl Survey (Monthly Segment)

4.2.1.2.1 Survey Design and Methods

The Rhode Island Coastal Trawl Survey began operating in 1990. The monthly segment of the survey is conducted year-round and samples 13 fixed stations - 12 inside Narragansett Bay and 1 in Rhode Island Sound. At each station, an otter trawl is towed for twenty minutes.

4.2.1.2.2 Biological and Environmental Sampling

Finfish are sorted by species, counted, weighed, and lengths are taken. If a large catch of a single species is collected, a sub-sample is taken for length measurements. Temperature, salinity, dissolved oxygen, cloud cover, and wind direction and speed are collected at each station.

4.2.1.2.3 Evaluation of Survey Data

An index of American shad abundance was developed from this survey. American shad were caught with 17% positive tows. A full model that predicted catch as a linear function of year, stratum, depth, and water temperature was compared with nested submodels using AIC. Based on several diagnostics (AIC, dispersion, percent deviance explained, and resulting CVs), the model chosen was a negative binomial that included year, stratum, depth, and water temperature.

4.2.1.2.4 Abundance Index Trends

The survey of relative abundance of American shad in Rhode Island coastal waters showed low abundance in the early 1990s with some peaks in abundance in the late 1990s (Table 277, Figure 382). The index was variable through the 2000s followed by several peaks in 2008, 2012, and 2016-2017. Abundance decreased to a low value in the terminal year of 2018.

4.2.1.3 Rhode Island Coastal Trawl Survey (Spring Segment)

4.2.1.3.1 Survey Design and Methods

The Rhode Island Coastal Trawl Survey began operating in 1979. The seasonal segment of the survey is conducted in April & September with a time series spanning 1979-2017. An otter trawl is towed for approximately 20 minutes at 2.5 knots at each of the 44 stations. At each station, an otter trawl is towed for twenty minutes.

4.2.1.3.2 Biological and Environmental Sampling

Finfish are sorted by species, counted, weighed, and lengths are taken. If a large catch of a single species is collected, a sub-sample is taken for length measurements. Temperature, salinity, dissolved oxygen, cloud cover, and wind direction and speed are collected at each station.

4.2.1.3.3 Evaluation of Survey Data

A spring (April) index of American shad abundance was developed from this survey. American shad were caught in April with 19% positive tows whereas September had 3% positive tows. A full model that predicted catch as a linear function of year, stratum, depth, and water temperature was compared with nested submodels using AIC. Based on several diagnostics (AIC, dispersion, percent deviance explained, and resulting CVs), the model chosen was a quasi-Poisson that included year, stratum, and depth.

4.2.1.3.4 Abundance Index Trends

The survey of relative abundance of American shad in Rhode Island coastal waters is restricted to begin in the mid-1990s due to a lack of positive tows from 1979 through 1994. The survey showed low abundance through the mid-2000s followed by three strong peaks in 2008, 2012-2013, and 2017 (Table 278, Figure 383). Abundance in the terminal year of 2018 (incomplete data set).

4.2.1.4 Connecticut Long Island Sound Trawl Survey

4.2.1.4.1 Survey Design and Methods

The Connecticut Long Island Sound Trawl Survey began operating in 1984. The survey is conducted in the Connecticut and New York waters of Long Island Sound from 5 to 46 m in depth in spring (April, May, June) and fall (Sept., Oct.). It is a stratified-random design. Sampling area is divided into 1x2 nautical mile sites with each site assigned to one of 12 strata defined by depth interval (0-9.0 m, 9.1-18.2 m, 18.3- 27.3 m, or 27.4+ m) and bottom type (mud, sand, or transitional). There are 40 samples per month for a total of 200 sites annually.

4.2.1.4.2 Biological and Environmental Sampling

Finfish are sorted by species, counted, weighed, and lengths are taken. Surface temperature, bottom temperature, and salinity are collected at each station.

4.2.1.4.3 Evaluation of Survey Data

A spring (April-June) index of American shad abundance was developed from this survey. American shad were caught in the spring with 28% positive tows. A geometric mean was calculated from the data.

A fall (September-October) index of American shad abundance was developed from this survey. American shad were caught in the fall with 31% positive tows. In 2010, vessel malfunction resulted in the loss of all sampling opportunities. A geometric mean was calculated from the data.

4.2.1.4.4 Abundance Index Trends

The survey of relative abundance of American shad in Long Island Sound in spring was highest in 1985, and highly variable through the early 2000s with values alternating substantially interannually. A large peak in abundance occurred in the late 1990s, followed by a sharp drop in the early 2000s (Table 279, Figure 384). Abundance increased after 2006 has remained relatively stable until the terminal year, which indicates a sharp drop.

The survey of relative abundance of American shad in Long Island Sound in fall was variable from 1984 through the mid-2000a, with peaks in abundance occurring in the late 1980s, mid-1990s, late 1990s, and a smaller peak in the early 2000s before remaining very low from 2006 through 2014 (Table 280, Figure 385). Abundance increased after 2015.

4.2.1.5 New Jersey Ocean Trawl Survey

4.2.1.5.1 Survey Design and Methods

The New Jersey Ocean Trawl Survey is a multispecies survey that started in August 1988 and samples the near shore waters from the entrance of New York Harbor south, to the entrance of the Delaware Bay five times a year (January, April, June, August and October). There are 15 strata with five strata assigned to three different depth regimes; inshore (3 to 5 fathoms), mid-shore (5 to 10 fathoms), and off-shore (10 to 15 fathoms). Station allocation and location is random and stratified by strata size.

4.2.1.5.2 Biological and Environmental Sampling

The survey net is a two-seam trawl with forward netting of 4.7 inch stretch mesh and rear netting of 3.1 inches stretch mesh. The codend is 3.0 inches stretch mesh and is lined with a 0.25 inch bar mesh liner. Each trawl is 20 minutes long and at the end of each tow, the total weight of each species is measured in kg and the length of all individuals, or a representative sample by weight for large catches, is measured to the nearest cm. A series of water quality parameters, such as surface and bottom salinity, temperature and dissolved oxygen, are also recorded at the start of each tow.

4.2.1.5.3 Evaluation of Survey Data

An index of American shad abundance was developed from this survey. American shad were caught with 34% positive tows. A full model that predicted catch as a linear function of year, station, water temperature, salinity, and dissolved oxygen was compared with nested submodels using AIC. Based on several diagnostics (AIC, dispersion, percent deviance explained, and resulting CVs), the model chosen was a quasi-Poisson that included year, station, and temperature.

4.2.1.5.4 Abundance Index Trends

The survey of relative abundance of American shad in New Jersey coastal waters showed variable abundance throughout the time series with three large peaks in 2002, 2012, and 2016 (Table 282, Figure 386). Abundance decreased in the terminal year of 2017.

4.2.1.6 Delaware Bay 30’ and 16’ Trawl Surveys

4.2.1.6.1 Survey Design and Methods

Delaware began operating the Delaware Bay 30’ Trawl Survey in 1966 and has conducted a juvenile fish trawl survey since 1978. The juvenile fish trawl survey was originally designed to monitor blue crab abundance in the Delaware Bay but was expanded to include juvenile fish beginning in 1980. In 1989, six stations were added in the lower Delaware River upstream of the Chesapeake and Delaware Canal to better monitor juvenile Striped Bass and other anadromous fish year class strength. Stations in the river and upper bay were sampled monthly from April through October using a 16’ otter trawl towed for 10 minutes or a 30’ trawl towed for 20 minutes from March through December. The 30’ trawl samples nine fixed stations in Delaware Bay. Fish densities were calculated by dividing the number of individuals for a species by the distance towed (number/nautical mile) at each station sampled for the two trawls. The low catches of Age 1 shad most likely represent gear avoidance of the bottom trawl by older and presumably stronger swimming shad schooling in mid-water depths.

4.2.1.6.2 Biological and Environmental Sampling

Finfish are sorted by species, counted, weighed, and lengths are taken. If a large catch of a single species is collected, a sub-sample is taken for length measurements. Temperature, salinity, and dissolved oxygen are collected at each station.

4.2.1.6.3 Evaluation of Survey Data

An index of American shad abundance was developed from the 30’ Trawl Survey. American shad were caught with 11% positive tows. American shad were not encountered frequently enough by the 16’ Trawl Survey to develop in index of abundance (Table 18). A full model that predicted catch as a linear function of year, station, depth, salinity, and water temperature was compared with nested submodels using AIC. Based on several diagnostics (AIC, dispersion, percent deviance explained, and resulting CVs), the model chosen was a negative binomial that included year, station, and water temperature.

4.2.1.6.4 Abundance Index Trends

The survey of relative abundance of American shad in the Delaware Bay showed low abundance in the early 1980s with an increase in abundance in the mid-1990s (Table 281, Figure 387). The index was variable through the early 2000s followed by several peaks in 2004, 2006, 2009, and 2011. Abundance decreased to 1980s levels by the terminal year of 2017.

4.2.1.7 Northeast Area Monitoring and Assessment Program (NEAMAP) Trawl Survey

4.2.1.7.1 Survey Design and Methods

The Northeast Area Monitoring and Assessment Program Trawl Survey began operating in 2007. The random stratified trawl survey has two cruises per year (Spring and Fall), with 150 stations per cruise. It covers 15 regions, ranging from Cape Hatteras, NC north to Cape Cod, MA. It samples near shore water to a depth of 60 feet and the sounds to 120 feet. At each station the net is trawled along the bottom for 20 minutes, at a speed of 2.9-3.3 knots. Work is completed during daylight hours and each cruise takes approximately 28-30 days to complete.

4.2.1.7.2 Biological and Environmental Sampling

For each size group, for 5 specimens length, individual weight (whole), sex, maturity, diet (stomach full/not), and for the remainder of the specimens (all beyond those chosen for the above processing), aggregate weight and individual length measurements recorded. Atmospheric and water quality data are also recorded, these include wind speed & direction, air temperature, relative humidity, barometric pressure, sea state, water temperature, water depth, salinity, and dissolved oxygen.

4.2.1.7.3 Evaluation of Survey Data

An index of American shad abundance was developed from this survey using Spring data only due to very low occurrence in Fall tows. No tows were conducted in April or May of 2007 or 2017, so these years were dropped from the data set. American shad were caught with 25% positive tows. A full model that predicted catch as a linear function of year, region, depth, water temperature, salinity, and dissolved oxygen was compared with nested submodels using AIC. Based on several diagnostics (AIC, dispersion, percent deviance explained, and resulting CVs), the model chosen was a quasi-Poisson that included year, region, temperature, salinity, and dissolved oxygen.

4.2.1.7.4 Abundance Index Trends

The survey of relative abundance of American shad in coastal waters showed low abundance in the late 2000s followed by small peaks in 2011 and 2013 and the highest value in 2015 (Table 283, Figure 388). Abundance decreased in the terminal year of 2016.

Catch rates compared spatially in five year intervals don’t indicate any large scale changes in distribution over the time series (Figure 360-Figure 361).

4.2.1.8 Northeast Fisheries Science Center (NEFSC) Bottom Trawl Survey

4.2.1.8.1 Survey Design and Methods

The NEFSC bottom trawl surveys are conducted in both the spring and fall and sample from the Gulf of Maine through Cape Hatteras, North Carolina (Azarovitz et al 1997). Data collected during the NEFSC bottom trawl surveys were used to derive seasonal relative abundance and biomass indices for American shad.

The NEFSC bottom trawl surveys follow a stratified random sampling design with strata defined primarily by depth and stations allocated approximately in proportion to stratum area (Azarovitz 1981). Inshore strata (depths less than 27m) south of Massachusetts were sampled beginning in fall 1972/spring 1973 and inshore Gulf of Maine strata were added beginning in spring 1979 (Sosebee and Cadrin 2006). Accordingly, American shad relative abundance indices were derived from these trawl surveys for 1979-2017.

Through 2008, standard bottom trawl tows were conducted for 30 minutes at 6.5 km/hour (3.5 knots) with the Albatross IV as the primary survey research vessel (Despres-Patanjo et al. 1988). During these years, gear changes included the use of multiple vessels (RVs Albatross IV and Delaware II), use of a #41 Yankee trawl from 1973-1981 instead of a #36 Yankee trawl, and a switch in the trawl doors in 1985; however, conversion factors to adjust survey catches for these changes are not available for American shad (Byrne and Forrester 1991). In 2009, the survey changed primary research vessels from the Albatross IV to the Henry B. Bigelow. Due to the deeper draft of the Bigelow, the two shallowest series of inshore strata (8-18m depths) are no longer sampled. Concurrent with the change in fishing vessel, substantial changes to the characteristics of the sampling protocol and trawl gear were made, including tow speed, net type and tow duration (NEFSC 2007). Calibration experiments, comprising paired standardized tows of the two fishing vessels, were conducted to measure the relative catchability between the two vessel-gear combinations and develop calibration factors to convert Bigelow survey catches to Albatross equivalents (Miller et al. 2010). However, for American shad there were not a sufficient number of paired tows where both vessels exhibited positive catches to reliably estimate calibration coefficients. Therefore, relative abundance indices were derived as two separate time series: 1979-2008 (Albatross years) and 2009-2017 (Bigelow years).

Bottom trawl catches of alosid species tend to be higher during the daytime due to diel migration patterns (Loesch et al. 1982; Stone and Jessop 1992). Accordingly, only daytime tows were used to compute relative abundance and biomass indices. Daytime tows, defined as those tows between sunrise and sunset, were determined for each survey station based on sampling date, location, and solar zenith angle using the method of Jacobson et al. (2011). Although there is a clear general relationship between solar zenith and time of day, tows carried out at the same time but at different geographic locations may have substantially different irradiance levels that could influence survey catchability (NEFSC 2011). Preliminary analyses (Lisa Hendrickson, NOAA Fisheries – unpublished data) confirmed that alosid catches were generally greater during daylight hours compared to nighttime hours.

Season-specific relative abundance (stratified mean number-per-tow) and biomass (stratified mean kilogram-per-tow) indices were derived for American shad for 1979-2008 and 2009-2017. In the spring of 2014, stations south of Maryland were not sampled due to delays in the survey. Accordingly, the spring survey index in this year is not based on all of the strata incorporated into other years. Furthermore, indices from the 2017 fall bottom trawl survey are treated as missing because the full survey was not completed due to vessel mechanical issues.

4.2.1.8.2 Abundance Index Trends

The proportion of tows that encountered American shad was greater during the spring than the fall. For the Albatross years of 1979-2008, the proportion of positive spring survey tows appeared to vary without trend and averaged 14% over the time series, where the proportion of positive tows in the fall survey showed a slight increasing trend but averaged only 7% over the time series (Figure 362-Figure 363). For both the spring and fall surveys, relative abundance indices showed substantial interannual variability during 1979-2008 and generally varied without trend.

For the Bigelow years of 2009-2017, the proportion of positive tows in the spring survey averaged 24% where the proportion of tows with positive catches in the fall survey averaged only 13% (Figure 364-Figure 365). Spring survey relative abundance indices did not exhibit a consistent temporal trend. In 2017, relative abundance was just below the time series median and relative biomass was approximately at the median (Figure 364). Fall survey indices showed a slight increasing trend. In 2017, both relative abundance and biomass were above the time-series medians for 2009-2017 (Figure 365).

During 1979-2008, American shad lengths ranged from 10-60 cm in the spring survey and 11-62 cm in the fall survey (Figure 366-Figure 367). In contrast, during the Bigelow years of 2009-2017, the observed size range of American shad decreased with the changes in the sampling protocol, and ranged from 10-45 cm in the spring survey and 12-43 cm in the fall survey (Figure 368-Figure 369). Similarly, during the Albatross years, the modes of the length distributions generally ranged from 15-33 cm and 20-25 cm during the spring and fall, respectively; however, during the Bigelow years, the modes only ranged from 16-25 cm in the spring and 19-25 cm in the fall. Length compositions varied over time, with some years exhibiting bimodal distributions and other years exhibiting unimodal distributions. Temporal patterns in length distributions were not apparent.

During the spring bottom trawl survey, notable changes in the distribution of American shad on the Northeast U.S. shelf were apparent (Figure 370). Catches primarily occurred in southern New England and the mid-Atlantic during the beginning of the time series and increased catches on Georges Bank, Cape Cod Bay and the Gulf of Maine (GOM) occurred during the latter part of the time series. The fall survey showed a more northerly distribution of American shad with catches primarily in southern New England, Georges Bank and especially during the most recent 10-15 years, the inshore GOM (Figure 371).

4.2.1.9 Mixed-Stock Hierarchical Indices of Abundance

Various indices of abundance with small spatial scales were explored for possible estimation of underlying metapopulation trends of abundance with Bayesian analysis following the methods of Conn (2010). The objectives were to (1) compare and contrasts abundance patterns among indices and, if appropriate, (2) combine indices into a single, more accurate index of abundance that could be used in subsequent assessment approaches at the regional or coastwide level.

Conn (2010) showed through simulation analysis that his Bayesian model combining multiple available indices results in an index that performs similar to or outperforms the arithmetic mean across the available indices and often outperformed selecting one index from the multiple available indices to infer the true population trend. Specifically, the hierarchical index performed similar to the arithmetic mean across indices and better than selecting one index from multiple available indices when process and sampling error varied among surveys and when spatial dynamics (i.e., varying proportions of the population covered by the various indices) were included in the simulated data and performed better than both when multiple noisy indices were available. The hierarchical index was also robust to indices covering different time periods and varying selectivity patterns.

The analysis assumes all indices are measuring the same quantity with different catchabilities and varying levels of measurement error, which are input as CVs, and process error, which are estimated. Process error is due to interannual variation in catchability, which is often assumed to not occur (i.e., time-invariant catchability) when interpreting indices of abundance. Process error is assumed to be time-invariant, but variable among indices. Bayesian analysis is applied via MCMC to approximate the posterior distribution of parameters including survey-specific process error, survey-specific catchability (interpreted here as the scaling between the survey-specific indices and the resultant hierarchical index), and annual means of the hierarchical index. Analysis was performed in R (R Core Team 2019) and OpenBUGS via the R2OpenBUGS package (Sturtz et al. 2005).

Data sets were grouped based on the coastwide or regional metapopulation structure defined in section VII.D.2 and life stage encounter by the surveys. The groups included coastwide YOY surveys, southern iteroparous spawning adult surveys (sex aggregate), southern iteroparous female spawning adult surveys, and semelparous spawning adult surveys (sex aggregate). There was no group explored for the northern iteroparous region because most abundance data are from fish counts without estimates of measurement error. Data time series were subset to the first year at least 50% of indices were available.

Model specifications used by Conn (2010) were applied for this analysis. Prior distributions for survey-specific catchability on the log scale, annual means of the hierarchical index on the log scale, and survey-specific process error were specified as normal distributions with a mean of log(0.01) and standard deviation of 0.5, normal distributions with a mean of log(100) and standard deviation of 1, and uniform distributions with bounds of 0 and 5, respectively. Four independent MCMC chains with 60,000 iterations each were run to sample the posterior distributions. The burn-in period was the first 10,000 iterations of each chain and these samples were discarded. A thinning rate of 10 was applied so that 5,000 iterations were retained from each chain to estimate the posterior distribution.

Upper confidence intervals of Gelman and Rubin's convergence diagnostic values were one for all parameters and all models indicating convergence on a posterior distribution across chains (Gelman and Rubin 1992).

The model of coastwide YOY surveys estimated process errors that ranged from 0.7 to 2.9 and credible intervals that did not overlap for several combinations of surveys (Figure 372). Notably, process error for Chesapeake Bay surveys indicated different patterns in abundance were being tracked than in other southern iteroparous surveys (Hudson River YOY 3/8" Seine Survey, Tidal Delaware River Striped Bass Seine Survey, Non-Tidal Delaware River Juvenile Seine Survey). Surveys south of the Chesapeake Bay (Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey, St. Johns River Juvenile Pushnet Survey) also had process error estimates indicative of different abundance patterns and were more similar in magnitude to the Chesapeake Bay surveys.

The model for the southern iteroparous spawning adult surveys (sex aggregate) estimated process errors ranging from 0.4 to 1.5 and credible intervals did not overlap for several combinations of surveys (Figure 373). A notable process error estimate was for the Potomac River Striped Bass Spawning Stock Survey which was the greatest in magnitude and had credible intervals that overlapped with few other surveys. This survey index has generally increased throughout the time series

The model for the southern iteroparous female spawning adult surveys estimated process errors that ranged from 0.6 to 0.9 (Figure 374). Not to be unexpected since all three of the included surveys are relatively close to each other in Virginia, these process errors are more similar than for the other southern iteroparous model including sex aggregate indices. However, even on this smaller spatial scale there is divergence between the Rappahannock and York River surveys and the James River survey due to different trends in abundance among these rivers.

The model for the semelparous spawning adult surveys (sex aggregate) estimated process errors that ranged from 0.3 to 1.3 (Figure 375). These process error estimates were generally more similar than in the southern iteroparous model including sex aggregate indices, with one exception for the Waccamaw River Commercial CPUE. Credible intervals for this process error estimate did not overlap with several other surveys further to the south and did nor overlap with process error means of other South Carolina surveys in close proximity, including other set net surveys. Interestingly, the process error for the Cape Fear River Adult Spawning Area Electrofishing Survey, the system farthest to the north and which represents the border between the southern iteroparous and semelparous regions, is the second largest in magnitude.

Based on the results of these models suggesting different patterns in abundance within regions, a regional index was not developed. A regional hierarchical index may trend upwards even in cases where system-specific indices are trending down due to large and divergent process error estimates, potentially masking troubling declines in some systems. This also appears to violate the underlying assumption of the analysis that all included indices are tracking the same quantity.

4.3 Methods

Power analysis, Mann-Kendall analysis, and ARIMA were used to evaluate trends in abundance. Habitat assessment was applied to assess current habitat availability relative to historical habitat and spawner potential. Details for these methods are provided in Section 2.

4.4 Results

4.4.1 Abundance Trends

4.4.1.1 Power Analysis

There are 19 indices available from monitoring programs that encounter mixed populations of American shad. These surveys generally occur in estuarine or oceanic waters where the catch of American shad would be expected to represent catch from multiple populations. Being representative of mixed-stocks, none of these surveys are currently used in the SFMP.

From these surveys, only the New Jersey Delaware Bay commercial CPUE index exhibits sufficient power to detect a 50% increase in American shad abundance in 10 years, though several would be able to detect a 50% decrease in the same period (Table 25).

4.4.1.2 Mann-Kendall Analysis

FD CPUE

Both New Jersey and North Carolina provided index values from commercial CPUE surveys of mixed-stocks from the Atlantic Ocean. Plots of New Jersey Ocean Commercial Fishery CPUE data showed a slight increase from 2000-2005, followed by a steep decrease (Figure 376). Mann-Kendall analysis confirmed the declines with a negative trend for both the full time series and for the period after 2005 (Table 21). When plotted, index data from North Carolina for 1994-2004 fluctuated with peaks in 1995, 1998, 2000, and 2003 but there were no apparent trends (Figure 377). Similarly, Mann-Kendall trend analysis did not detect any trends for the full time series or the period after 2005 (Table 21).

Two fishery-dependent surveys were provided for the Delaware Bay commercial fishery. The NJ Delaware Bay Commercial Fishery showed a steady decline in CPUE over the full time series and therefore the period after 2005 (Figure 378). Similarly, the second Delaware Bay index showed a general decline since 1990, and survey values have remained low since with the exception of large peak in 2014 (Figure 379). Mann-Kendall trend analysis found a negative trend for the time series in both indices and for the period from 2005 forward for the NJ Delaware Bay Commercial Fishery index, however no trend was detected for the later period in the second survey (Table 21).

FI CPUE

Data from several trawl surveys were provided with various sampled years beginning as early as 1979 and some stratified by seasonal (spring and fall) sampling dates (Figure 380-Figure 396). Mann-Kendall trend analysis failed to detect any trend for the full time series or the period after 2005 in most of the indices. A few surveys (RI MCTS-Figure 382, RI SCTS-Figure 383, and

NEAMAP-Figure 388) had increasing trends in either the full time series or period after 2005, but no trawl survey index examined had a decreasing trend (Table 21).

4.4.1.3 ARIMA

It is important to note that due to unknown stock composition of American shad captured in trawl surveys, it is difficult to infer population status relative to any one specific stock. Therefore, results should only be interpreted as trends in relative abundance and American shad metapopulation status relative to the 2005 index value in each survey, respectively.

ARIMA descriptive statistics from all trawl surveys below are provided in Table 288. Fitted indices for all surveys are provide in Figure 397. ARIMA models provided adequate fits for 11 of the 13 trawl surveys. Residuals from the CT LIS Spring, DE River and Bay Adult Finfish and NEFSC Bottom Trawl-Albatross Fall surveys were not normally distributed and the resulting bootstrapped probabilities of being above the respective 2005 index values should be considered with caution.

4.4.1.3.1 Maine-New Hampshire Trawl Survey – Fall 2000-2017

The fitted index increased from 2000 through the mid-2000s, declined slightly from mid-2000s until 2010 and has slightly increased through 2017 (Figure 397). The terminal year is credibly above the 2005 index value [P(>2005) = 0.77; Table 288)].

4.4.1.3.2 Maine-New Hampshire Trawl Survey – Spring 2001-2017

The fitted index increased from 2001 to 2007 and remained stable through 2017 (Figure 397). The terminal year is credibly above the 2005 index value [P(>2005) = 0.78; Table 288)].

4.4.1.3.3 Northeast Fisheries Science Center Bottom Trawl Survey-Fall 1979-2008

The fitted index increased from 1979 to the mid-1980s and remained relatively stable through 2008 (Figure 397). The index is credibly above the 2005 index value [P(>2005) = 0.51; Table 288)].

4.4.1.3.4 Northeast Fisheries Science Center Bottom Trawl Survey-Spring 1979-2008

The fitted index decreased from 1979 to the early 1980s and steadily increased from the mid-1980s through 2008 (Figure 397). The index is credibly above the 2005 index value [P(>2005) = 0.51; Table 288)].

4.4.1.3.5 Northeast Fisheries Science Center Bottom Trawl Survey-Fall 2009-2016

The fitted index increased sharply from 2009 through 2016 (Figure 397). The index is credibly above the 25th percentile of the bootstrapped time series mean [P(terminal year<$ts_{Q0.25}$) = 0.99] and the 2009 index value [P(<2009) = 0.99; Table 288)].

4.4.1.3.6 Northeast Fisheries Science Center Bottom Trawl Survey-Spring 2009-2017

The fitted index varied greatly over the time series (Figure 397). The index is credibly above the 2009 index value [P(<2009) = 0.78; Table 288)].

4.4.1.3.7 Rhode Island Coastal Trawl Survey- Monthly Segment 1990-2017

The fitted index increased sharply from 1990 to late 1990s, remained stable until mid-2000s, and steadily increased from mid-2000s through 2017 (Figure 397). The terminal year is credibly above the 2005 index value [P(>2005) = 0.86; Table 288)].

4.4.1.3.8 Rhode Island Coastal Trawl Survey- Spring Segment 1981-2017

The fitted index increased from 1981 to late 1980s, declined until mid-1990s, and steadily increased from the mid-1990s through 2017 (Figure 397). The terminal year is credibly above the 2005 index value [P(>2005) = 0.86; Table 288)].

4.4.1.3.9 Connecticut Long Island Sound Trawl Survey-Spring 1984-2016

The fitted index increased sharply from 1984 to the mid-1980s, remained stable until the early 2000s and slightly declined from early 2000s through 2017 (Figure 397). The terminal year is credibly below the 2005 index value [P(>2005) = 0.49; Table 288)].

4.4.1.3.10 Connecticut Long Island Sound Trawl Survey-Fall 1984-2009

The fitted index decreased sharply from 1984 to mid-1980s, increased slightly until the early 1990s, and steadily decreased from the early 1990s through 2009 (Figure 397). The terminal year is credibly below the 2005 index value [P(>2005) = 0.45; Table 288)].

4.4.1.3.11 Delaware River and Bay Adult Finfish Trawl Survey 1990-2017

The fitted index increased from 1990 to the mid-1990s and steadily decreased from the mid-1990s through 2017 (Figure 397). The index is credibly below the 2005 index value [P(>2005) = 0.27; Table 288)].

4.4.1.3.12 New Jersey Ocean Trawl Survey 1989-2017

The fitted index decreased sharply from 1989 to 1990, increased slightly until the mid-1990s, and decreased from the mid-1990s to the early 2000s and has remained relatively stable through 2017 (Figure 397). The index is credibly below the 2005 index value [P(>2005) = 0.40; Table 288)].

4.4.1.3.13 Virginia Northeast Area Monitoring Program Trawl Survey 2008-2016

The fitted index has decreased from 2008 through 2016 (Figure 397). The index is credibly above the 2008 index value [P(>2008) = 0.50; Table 288)].

4.4.1.4 Sensitivity Results

All surveys were insensitive to the starting year of the survey except for the NEFSC Fall survey 1979-2008 (Figure 398 and Figure 399). All surveys were insensitive to terminal year when using the mean of the final three years of index values as the terminal year index value of a given survey save two, the New Jersey Ocean Trawl Survey and NEFSC Fall survey 1979-2008 (Figure 400).

4.4.1.5 Discussion

When considering the entire time series, trends in trawl surveys varied with some surveys increasing, some decreasing and some with no discernable trend, however; surveys within similar geographic regions largely followed similar trends. Surveys in the northern region (ME-CT) generally showed increasing trends while surveys in the southern region (NY-NC) showed decreasing trends in American shad abundance indices. NEFSC coastwide (ME-NC) trawl surveys show stable to slightly increasing trends in American shad abundance indices.

The probability of the terminal year of a survey being above the 2005 index value had mixed results across regions, however; surveys within regions generally had similar results (Table 288, Figure 397). Terminal year index values for surveys in the northern region were credibly above their respective 2005 index values except for the fall CT LIS trawl survey 1984-2009. Terminal year index values for surveys in the southern region were credibly below their respective 2005 index values. The coastwide NEFSC trawl surveys were credibly above their respective 2005 index values.

Nine out of 13 trawl surveys were credibly above their respective 2005 index values, however; these results do not necessarily indicate an increase in relative abundance following the management action implemented in 2005. Following the 2005 closure of the ocean intercept fishery, there were no discernable change in trends in any survey. For instance, if a trend in a given survey was increasing, decreasing or stable in the time period prior to 2005, it exhibited a similar trend after 2005 (see results of Mann-Kendall trend analysis in Section 2.3.3). Therefore, from a coastwide metapopulation perspective, these results suggest American shad relative abundance in trawl surveys had no response to the closure of the ocean intercept fishery in 2005.

4.4.2 Habitat Assessment and Simulation Modeling

Coastwide, the theoretical capacity to support runs of adult American shad into rivers based on identified historic habitat is twice that of rivers for which dams fully occlude access (Figure 401). While the values of spawner estimates are realistic in magnitude, it is likely these estimates are conservatively low based on the model construction and parameter values applied. The value of this exercise is to assess the relative influence of dams. Of note here is the result that the application of optimistic upstream and downstream passage rates at dams affords a remarkably small increase in the theoretical production potential relative to rivers that are wholly inaccessible upstream of the first dam.

Overall, the historic habitat available to American shad is divided about evenly between the three life-history regions, with 42, 30 and 28% of the habitat being found in the northern iteroparous, southern iteroparous and semelparous regions, respectively (Figure 402).

Dams partly or completely blocked nearly 40% of the total habitat once used by this species (Figure 403). The loss of historical habitat due to migration barriers is greatest in the US portion of the northern iteroparous region (65% loss) but is high for all regions (31, 44, and 38% loss for northern iteroparous [Canada only], southern iteroparous and semelparous regions). Interestingly, the proportional distribution of accessible habitat has remained relatively constant between the three life-history regions when governmental borders are not considered. This indicates that while impacts are regionally variable, dam construction has influenced habitat access by American shad similarly throughout their range.

For clarity, these data are also presented for US rivers only in Figure 404. Of note are the significant contribution several rivers make to available historic habitat (i.e., the Delaware, James, Santee-Cooper and Ogeechee) that are significantly impacted by dams. The Susquehanna is 94% impacted by impoundments, yet this intact river would have accounted for almost a tenth of coastwide production (9.5%).

While the historic spawner production potential is higher in the north and lower to the south, it is notable that each of the regions generally lost comparably high proportions of production habitat. These losses in potential are significant in each state and region (Figure 405 and Figure 406). The US section of the northern iteroparous region has suffered a 65% (58% with current passage) decline in its production potential, the southern iteroparous region has lost 47% and the semelparous region 38% (45 and 34% respectively with current passage).

Changes in available habitat have similarly influenced the theoretical spawning potential of American shad coastwide. Based on this modeling exercise, coastwide production potential is more than 72.8 million spawners per year compared with the no passage scenario of just under 42.8 million spawners, a reduction of 41%. It is estimated that fishway passage coastwide may alleviate the spawner potential by less than 3 million fish annually. This is evidence that even with extensive fish passage efforts, dams represent a fixed constraint of about 37% on the fishery potential of American shad. It is notable that this significant imposition on theoretical spawning potential results from a model that incorporates optimistic estimates of contemporary passage values. True impacts of dams in systems with poor fish passage may be greater than estimated here. In addition, other factors (habitat degradation and fisheries mortalities) may impose further loss of spawning potential on a river and region specific level.

4.5 Conclusions

4.5.1 Mortality

Juvenile mortality status could not be determined for the coastwide metapopulation or any system-specific stocks due to data limitations. The lack of these determinations remains a significant uncertainty in assessment advice for management of American shad.

Adult mortality for the coastwide metapopulation is also unknown, but was determined to be unsustainable for some system-specific stocks indicating the continued need for action to reduce adult mortality. Though adult mortality was determined to be sustainable for some system-specific stocks, it is important to note that maintaining sustainable adult mortality will not result in favorable abundance status if the previously mentioned unknown juvenile mortality is occurring at unsustainable levels.

4.5.2 Abundance

Abundance trend analyses indicate a continued lack of consistent response in coastwide abundance to the 2005 management change (ocean intercept fishery closure). There may still not have been enough time for coastwide abundance to respond to the 2005 management change, given various factors impeding consistent positive responses among systems. Trends from mixed-stocks are conflicting, confounding interpretation of what these trends represent and further support assessment of American shad stocks at the system level.

There was no definitive link between ocean incidental catch and the lack of response in population trends identified and, though incidental catch impacts on this response can’t be ruled out given the data limitations faced, other impacts such as habitat loss can’t be ruled out either. In fact, the dam impact analysis suggests that habitat loss due to barriers is likely restricting positive responses in the coastwide metapopulation abundance.

Based on the decline in coastwide landings since the 1950s by more than an order of magnitude and the lack of response in abundance trends, the metapopulation abundance is depleted.

5 FUTURE STOCK ASSESSMENTS AND RESEARCH RECOMMENDATIONS

5.1 Timing of Future Stock Assessments

The TC recommends the next American shad stock assessment be conducted in ten years (2030) as a benchmark stock assessment. The basis for this time frame is current data limitations and uncertainty (e.g., lack of power in many data sets to detect changes in abundance over a ten year time frame, see Section 2.3.4). Given the large number of individual systems assessed, the TC recommends conducting the assessment in a staggered approach assessing systems within each region (northern iteroparous, southern iteroparous, semelparous; not necessarily in this order) subsequently during the stock assessment.

5.2 2020 Stock Assessment Recommendations

System-specific research recommendations are provided for some systems under *Research Recommendations* subheadings in Section 3. The following research recommendations are broadly applicable to most or all systems and/or mixed-stock aggregations.

5.2.1 Data Collection Recommendations

- Transition historical biological sampling data and store all future biological sampling data into digital, query-able databases with standardized fields and format. Unique identifiers should be assigned to individual fish to link all associated data collected. (short-term, moderate priority)

- Develop a centralized repository for agencies to submit and store genetic sampling data for future analysis. The Atlantic sturgeon repository at the USGS Leetown Science Center should serve as an example. (long-term, high priority)

- Collect genetic samples from YOY and returning mature adults during spawning runs for future analysis of baseline genetic population structure and site fidelity/straying rates. These data will help define stock structure, identify stock composition from genetic sampling of American shad catch in mixed-stock fisheries, and provide information on recolonization capabilities in defunct American shad systems. (long-term, high priority)

- Conduct annual stock composition sampling through existing and new observer programs from all mixed-stock fisheries (bycatch and directed). Potential methods include tagging (conventional external tags or acoustic tags) of discarded catch and genetic sampling of retained and discarded catch. Mortality rates of juvenile fish in all systems remain unknown and improvement in advice from future stock assessments is not possible without this monitoring. Known fisheries include the Delaware Bay mixed-stock fishery and all fisheries operating in the Atlantic Ocean (U.S. and Canada) that encounter American shad (see Section 4.1.4). (long-term, high priority)

- Otoliths should be collected as the preferred age structure. If collection of otoliths presents perceived impact to conservation of the stock, an annual subsample of paired otolith and scales (at least 100 samples if possible) should be collected to quantify error between structures. (short-term, high priority)

- Repeated estimates of spawn mark counts should be incorporated into data collection protocols to improve understanding of error in these data. (short-term, moderate priority)

- Conduct tagging studies to increase sample size of fish with known spawn mark histories. Focus tagging efforts on fish most likely to be virgin spawners. (long-term, moderate priority)

- Add age at first spawn, identification of skip spawning, and the age at which skip spawning occurred as standard data fields from spawn mark counts. (short-term, low priority)

- Error between structures, if scales are the primary age structure collected, and for spawn mark count estimates (either between multiple readers or within reader) should be quantified on an annual basis. A mean CV of 5% and detection of no systematic bias should serve as targets for comparisons. (short-term, high priority)

- Two readers should determine consensus ages and spawn mark counts based on improvements in ageing error in the Delaware system when consensus-based estimates were part of the ageing protocol. (short-term, high priority)

- Conduct a coastwide age/spawn mark workshop to develop a standardized ageing/spawn mark count protocol for American shad. The example protocol included in this assessment (section 1.1.4.1) can be used as a foundation for a final protocol. (short-term, moderate priority)

- Collect standardized maturity status data to provide greater resolution on data for length-weigh relationships. Maturity status codes should be: Immature, mature resting, gravid/not yet ripe, flowing, or spent. (short-term, moderate priority)

- Conduct acoustic tagging studies to determine skip spawning behavior and iteroparity rates. This information will also improve understanding of selectivity by in-river fisheries and monitoring programs. (short-term, moderate priority)

- Implement fishery-independent YOY and spawning run surveys in all systems with open fisheries. Surveys should collect catch rates, length, individual weight, sex (spawning runs), and age (spawning runs) data at a minimum to allow for assessment of stocks with legal harvest. Require these surveys be in operation in systems with requested fisheries before opening fisheries. (long-term, high priority)

- Task survey leads with providing as much insight as possible on suspected catchability effects (e.g. environmental covariates) with catch rate data during future stock assessments to improve standardization of abundance trends. Collect necessary data to support standardization model estimation of catchability effects. (short-term, moderate priority)

- Mark hatchery-reared fish and sample nursery habitat after stocking to obtain data that could be used to estimate absolute YOY abundance. (long-term, moderate priority)

- Conduct complete in-river catch monitoring in all systems with open fisheries. Monitoring programs should collect total catch, effort, size, individual weight, and age data at a minimum. Require these surveys be in operation in systems with requested fisheries before opening fisheries. (long-term, high priority)

- Require total catch and biological sampling of fish removed for broodstock purposes as these are useful data that can be obtained with little additional costs. (long-term, moderate priority)

- As catch of other bait species (i.e., Atlantic herring) is reduced, characterize changes in use of American shad as bait to supplement these primary bait species. (long-term, low priority)

5.2.2 Assessment Methodology Recommendations

- Determine appropriate uses of age composition data collected from semelparous stocks. (short-term, moderate priority)
- Investigate how anthropogenic sources of production (i.e., YOY stocking) affect population dynamics and assessment of stocks against traditional biological reference points. (long-term, low priority)
- Develop density-based reference points (number of fish per acre of habitat) from GIS mapping analysis that can be compared to passage counts at fishways. See ME DMR river herring SFMP as an example. (long-term, moderate priority)
- Conduct more frequent analyses connecting YOY abundance trends with mature adult abundance trends to provide warning of unfavorable stock conditions due to changes in mortality during the data gap between these life stages. (short term, moderate priority)
- Develop targets for power of abundance indices. (short-term, low priority)

5.2.3 Future Research Recommendations

- Explore implications (predator-prey relationships, recruitment success, interactions with various fisheries) of climate change on environmental spawning cues. (long-term, moderate priority)
- Quantify precision of OTC mark identification. (long-term, moderate priority)
- Conduct maturity studies designed to accommodate the unique challenges American shad reproductive behavior (i.e., segregating by maturity status during spawning runs) poses on traditional monitoring programs. This information will also improve understanding of selectivity by in-river fisheries and monitoring programs. (long-term high priority)
- Investigate hooking and handling induced mortality in recreational fisheries. This pertains to all system because catch-and-release fisheries are still allowed for systems under moratoria. (long-term, moderate priority)
- Conduct fish passage research at barriers with adults for both upstream and downstream migration and movements and with juveniles for downstream as discussed in Section 1.1.9.5 Fish Passage. (long-term, high priority)

5.2.4 Management-related Recommendations

- As additional stock structure information becomes available, continue working on standard definitions of stock systems for use in future assessment and management of unique stocks. These should be described in text and associated maps included in SFMPs to capture all inland waterbodies with shad habitat considered part of the stock system. (long-term, low priority)

- Request managers provide future guidance on management goals in terms of productivity potential. Are goals to rebuild populations to historic levels of productivity or manage stocks relative to recent productivity potential? Clear guidance would help provide assessment advice on stock status. (short-term, low priority)

5.3 Responses to 2007 American Shad Stock Assessment Recommendations (*responses in italics*)

5.3.1 Assessment/Modeling Recommendations

The SASC pointed out that American shad is a species well known for its life history variations with latitude (e.g., Leggett and Carscadden 1978, Limburg et al. 2003), but did not emphasize this in its report. The Review Panel felt that such information would have been useful to summarize, and to compare current parameters to historic data.

> *The SAS used regional life history parameters in this assessment based on the best available information to define regional metapopulations where intra-region life history parameters are expected to be more similar than inter-region life history parameters (see Section 1.1.2). This included regional growth from hierarchical models, regional maturity, regional length-weight relationships, and regional natural mortality estimates. Iteroparous stocks were combined to estimate natural mortality because of a perceived data limitation for the northern iteroparous region where a longer history of manmade barriers is believed to have reduced the age structure data available for this region to a degree that it was considered more appropriate to borrow southern iteroparous age structure data to determine maximum age. The differences in life history parameters were intuitive given knowledge of regional effects (e.g., higher natural mortality in semelparous stocks).*

It was noted that linkages between life stages and between indices could be improved in the future.

> *One SFMP (Delaware River Co-op: Delaware River) and one system Section in this assessment report (NYSDEC: Hudson River) provided evaluation of using early life stage indices as surrogate adult indices with simple linear regression. In the Delaware River, no significant correlations were found between life stages; therefore, the spawning stock relative abundance cannot predict the current years YOY abundance. It was concluded that the lack of correlation was most likely related to sampling variability and environmental influences, especially on early life stages.*
>
> *Conversely, in the Hudson River, NYSDEC reported significant correlations between an egg index and the two adult spawning indices between 1985 and 2001. Unfortunately, the NYSDEC adult abundance survey used in the analysis became unreliable due to low*

> *sample sizes following 2001 and ended with the implemented moratorium in 2010. NYSDEC is currently evaluating the appropriateness of another adult index to determine if the relationship between life stages persists.*
>
> *The DE Co-op and NYSDEC also evaluated if YOY indices could predict returning adults. Analysts lagged adult indices to correspond with their respective YOY indices (e.g. 4-year-old adult index with 1996 YOY index and so on). Both synthetic and longitudinal cohorts were evaluated. In the Delaware River, a positive correlation was observed between the YOY and 4-7-year-old adult index; however, the relationship was not significant and had low power. In the Hudson River, a positive correlation between the YOY index and 4-year-old index was observed but it was not reported if the relationship was significant. However, power analysis in this assessment report indicates that the NYSDEC YOY index has sufficient power to detect both increasing and decreasing trends; therefore, if the relationship is significant, the YOY index has the ability to predict returning 4-year-old adults in the Hudson River.*

Indices were not synthesized using a single overall approach that could be used to develop population dynamics models. Such efforts could be conducted in the future as the time series become longer.

> *Standardized indices using a common modeling approach to account for effects on catchability were developed for surveys with appropriate environmental data time series. Bayesian analysis (Conn 2010) was applied to (1) compare and contrasts abundance patterns among indices and, if appropriate, (2) combine indices into a single, more accurate index of abundance that could be used in subsequent assessment approaches at the system, regional, or coastwide level. The analysis only supported combining indices at the system level (Delaware River YOY indices) for approaches used in this assessment.*

The Review Panel was concerned that very few estimates of uncertainty were presented with the index data. The Panel encourages the SASC to produce and present uncertainty estimates (standard errors) for all indices.

> *Measures of variance were provided for indices with repeated observations of catch rates. Power analysis was applied to these measures of variance to better understand uncertainty for indices of abundance.*

However, future efforts should focus on better determination of natural mortality, because biological reference points (BRPs) were very sensitive to the values of M used. As a first step, the panel recommends that alternate life history methods should be investigated for the calculation of M (e.g., Alverson-Carney, Pauly, Gunderson; see Quinn and Deriso 1999, section 8.3), because these methods use additional life history information such as growth and reproduction and may help to expand or narrow the range of potential M values. Second, the SASC should consider whether field work could be done to determine M experimentally. Third, the SASC should also consider a sensitivity scenario like that in the previous assessment, in which natural mortality increases with age.

> *The SAS selected the Then et al. (2014) maximum age estimator of natural mortality as published literature supports this methodology as the best available methodology for the data available in this assessment. Empirical estimates of natural mortality are not available and the SAS agrees with the review panel from the last assessment that field-based estimation of natural mortality should be attempted (e.g., a tag-recapture study) and is a high priority. Sensitivity of per-recruit reference points was evaluated again during this assessment and, as would be expected, these reference points were sensitive to natural mortality assumptions. Recent work on the performance of assessment models across varying assumed natural mortality rates indicated that an assumed age-invariant natural mortality that approximates the average natural mortality across ages performed similarly to age-varying natural mortality values (Deroba and Schueller 2013). Natural mortality assumptions were explored in the Potomac SCAA model using an age-varying natural mortality rate and a constant natural mortality rate (ages 6+) as a sensitivity run which showed little impact on the estimates.*

The Panel recommends that the SASC move towards explicitly separating natural mortality M from mortality from anthropogenic sources (Advisory Report, Section G).

> *Population models were applied to several systems that separate riverine anthropogenic mortality based on observed removals (fishery and broodstock) from assumed natural mortality (SCAA models and delay-difference models). However, there were too many data limitations to address this recommendation further (i.e., separating out unobserved anthropogenic sources of mortality such as barrier-associated mortality and ocean fishing mortality) and for other systems. Moratoria since the last assessment have further reduced data available to address this limitation (i.e., catch time series). Lack of genetic data to partition incidental catch to stock of origins will continue to prevent separating natural mortality from ocean fishing mortality. There also remains a significant data gap in barrier associated mortality, during both upstream and downstream passage.*

Consequently, the standard error of the catch curve is undoubtedly high, yet these standard errors are not reported nor are uncertainties in the catch curve considered. Future assessments should report the standard error.

> *Standard errors for total mortality estimates are provided, plotted with estimates relative to mortality reference points, and summarized for terminal three-year average female mortality estimates used to make mortality status determinations. Sensitivity analysis was also applied to total mortality estimators to inform uncertainty about data inputs and key assumptions of these estimators.*

Nevertheless, the focus of future assessments should be the development of more modern models of age-structured populations that integrate data sources and knowledge about American shad.

> *Age-structured population models were applied to the Potomac and Albemarle Sound Systems. There remain some data limitations for these models (e.g., lack of non-riverine removals, limited age data) and other systems need to improve data collection before these models can be applied.*

A potential assessment framework that the ASMFC may wish to consider is one modeled after the framework used for many North Pacific salmonid stocks. For populations where data sources are limited, simple models with very conservative input parameters are used such that a highly precautionary, risk-adverse harvest policy is developed. In areas where more information is available, more in-depth models are developed which often allows greater flexibility in the management plans and potentially higher harvests in some years.

> *The SAS explored some salmonid-type assessment approaches, particularly for semelparous stocks, but believe the need for absolute escapement rates preclude use of these models for semelparous stocks of American shad. Instead, delay-difference models were applied to semelparous stocks with open fisheries.*

The origin of the choice of F30 for American shad populations dates back to the stock assessment of 1998 (ASMFC 1998). The Panel was unable to find any rationale for the choice of the value of 30 (versus 35 or 40) and requests that future stock assessments reveal this rationale and investigate whether the choice of the value of 30 is sufficiently conservative.

> *Several contemporary lines of evidence suggest the need to maintain higher levels of spawning stock biomass per-recruit for species such as American Shad. Simulations by Clark (1993) suggests that fishing at a level between 35-45% ($F_{35\%}$-$F_{45\%}$; or in terms of Z: $Z_{35\%}$-$Z_{45\%}$) provides a high percentage of maximum sustainable yield, especially if there is uncertainty in the stock-recruitment relationship, which is the case for many American shad stocks. Clark (2002) went on to suggest that SBPR would need to be even higher for less resilient and/or data-poor stocks but could be lower for resilient and/or data-rich stocks. American shad possess many of the qualities of species traditionally considered to be less resilient and many of the individual stocks found in individual river systems remain data poor. Therefore, the SAS feels a $Z_{40\%}$ reference point is a more precautionary approach given the uncertainty dealt with in the assessment. See Section 2.5 of the assessment report and ASMFC 2017c for additional rationale of $Z_{40\%}$.*

The reference point could not be calculated for the most southerly populations that spawn only once and then die. For these populations, a method similar to that for Pacific salmon, also semelparous, could be explored (NMFS 2004).

> *The SAS explored some salmonid-type assessment approaches, particularly for semelparous stocks, but believe the need for absolute escapement rates preclude use of*

> *these models for semelparous stocks of American shad. Instead, delay-difference models were applied to semelparous stocks with open fisheries to estimate TAC reference points.*

Given the variability in gears used to capture shad, and the fact that other in-river sources of mortality were being included, the Review Panel considered this assumption appropriate for the current wide-scale assessment, but recommends that gear selectivity be investigated further in stock-specific assessments where fisheries or other sources of mortality are known to be selective.

> *Selectivity was estimated where possible using SCAA models. Given the varying maturity ogives considered in this assessment and the assumption that maturity is what determines in-river selectivity (aside from any further gear selectivity), selectivity remains a primary uncertainty.*

Although the Review Panel considered the Z30 benchmark sufficient for the region-wide comparisons presented in this assessment, this reference point is not directly linked to the management issues for many of these populations and the Review Panel encourages the development of population-specific reference points appropriate for the alleviation of the threats that exist for many of these populations.

> *Fisheries-type reference points are appropriate when stock abundance is sufficient to support fisheries; however, for populations under restoration, rebuilding, with low freshwater productivity, or affected by other sources of anthropogenic mortality (e.g. turbine mortality), reference points may need to be adjusted to compensate for those additional factors. More specifically, for populations with low freshwater productivity, a $Z_{40\%}$ criterion will not ensure population recovery to historic levels, as it does not explicitly account for this reduced production (ASMFC 2007a). More work is needed to determine appropriate system-specific reference points based on defined management objectives for some systems.*

Finally, bycatch in shad and other fisheries is almost totally unknown and needs expedited investigation in future assessments.

> *Total incidental catch estimates from ocean fisheries covered by the NEFOP have become available since the last stock assessment, but data for partitioning catch among stocks is still a considerable data limitation that needs to be addressed.*

While the available data, trend analyses, and benchmark Z30 comparisons carried out by the SASC were sufficient to provide an overview of status of shad populations in many rivers, the Review Panel recommends the development of population-specific assessment approaches that can be used to address management questions relevant to the specific population. Guidance on this recommendation is provided in TOR-G.

> *Unique population models were applied to systems that had appropriate data to support these models. Data limitations remain for other systems that could only be assessed with trend analyses and/or total mortality estimators.*

H. Describe the locations and amounts of shad and river herring bycatch in commercial fisheries for mackerel, sea herring, and other pelagic species and estimate the contribution of that bycatch to fishing mortality. The SASC members were unable to complete this task at the time of the review. The data sources are widely dispersed and not readily available. This task remains a high priority for the SASC, as bycatch could potentially represent a significant and unknown source of mortality.

> *Total incidental catch in fisheries covered by the NEFOP has been quantified, but this catch cannot be parsed into individual fisheries. Coastwide fishing mortality cannot be determined without time series of complete removals by stock, in river (recreational discards and harvest and commercial discards and harvest) and in ocean which still needs work and will not be possible for historical periods.*

The Review Panel concurs, and recommends both the implementation of archiving programs (for DNA and otoliths) and more research on otolith chemical markers.

> *Some additional research of otolith chemical markers has been completed since the last assessment to evaluate straying (*Walther et al. 2008*) and validate ageing methods (*Upton et al. 2012*). A DNA archiving program has not been addressed and remains a high priority.*

5.3.2 Data Collection Recommendations

The SASC and Technical Committee are well aware of the problem, and validation trials are in progress in a number of watersheds. The validations consist of marking otoliths of hatchery shad with OTC, releasing the fish, and monitoring for recaptures that occur several years later. This should be a substantial help in resolving some of the aging errors, and the Review Panel encourages as many such experiments as possible to be done, particularly in systems where scales are difficult to read. Once reliable aging can be done, it will enable the use of better modeling methods for more stocks.

> *Progress towards validating age determination has been made (see Section 1.1.4), but more known age data are needed especially from systems outside the Delaware. Error in identifying OTC marks needs to be quantified to understand how truly know ages are from fish identified as know age with this method. There have also been genetic microsatellite markers for parentage-based tagging developed and applied in North Carolina and natural isotopic signatures in otoliths used in Virginia that provide additional methods for age validation. Ageing error analysis suggests both scales and otoliths can be used for reliable age determination (see Section 1.1.4.3), but otoliths are preferred and paired read data from otoliths should be supplied with scale ages in the future to confirm scale-based ages are reliable.*

When the JAI includes more than one life stage, thereby integrating over these processes, it becomes unclear whether it is intended to be an index of spawner abundance during that year, or an index of year class strength that is meant to index subsequent returns as the cohort matures. Collection and analysis of size and/or age data as part of the juvenile surveys may aid in determining the utility of these data series.

> *Length data collected during the JAI seine survey in the Hudson indicate 98% of fish are YOY and the presence of "holder over" age-1+ fish is negligible.*

While habitat related improvements are being made as part of ongoing river restoration programs (e.g., up-stream passage, improvements in water quality), the Peer Review Panel suggested substantial improvements to both upstream and downstream fish passage as an area requiring remediation and research.

> *Recent peer reviewed publications continue to describe the need to improve the study of upstream and downstream passage as described in Sections 1.1.9.5, 2.7.2, 4.4.2, and 4.5. Some progress has been made in these areas, including USFWS Northeast Fish Passage Engineering Criteria (USFWS 2019), that has been regularly updated with the inclusion of new research and other sources of information as it becomes available. Research on several different entrance gate configurations for upstream shad passage is one example of new information being applied to these criteria (Mulligan et al. 2018). New analytical modeling approaches are also being applied to better understand potential impacts of routes of passage at dams/facilities at the river system level (Stich et al. 2018) and coastwide (see Sections 2.7.2 and 4.4.2). The USGS Conte Anadromous Fish Research Center continues to provide substantial technical expertise in study design, implementation, analyses and interpretation of study data for agencies dealing with FERC and fish passage projects. The USFWS Turbine Blade Strike Model Tool (Towler and Pica 2019), is a tool to help inform decisions on downstream fish passage based upon estimated impacts (mortality) in the absence of site specific tagging studies. River basin management plans are increasingly placing upstream and downstream passage impacts, needs, recommendations in the context of cumulative dam/hydropower effects and requiring passage performance measures that are quantitatively defined rather than the open ended passage terms of "safe, effective, and timely" (MEDMR and MEDIFW 2008; SRAFRC 2010; CRASC 2019).*

5.3.3 Recommendations for Fisheries and Fishery Assessments:

1. Due to the poor condition of many shad populations, future management actions to reduce total mortality are needed.

> *Moratoria have been implemented in systems without SFMPs. However, total mortality analysis indicates this is still needed (see Section 4.5 for a summary).*

2. Develop a management recovery plan for those populations where current total mortality is above the Z30 benchmark. Components of this plan could include reductions in commercial or

recreational fishery mortalities, reductions in bycatch, habitat restoration, improvements in upriver and downstream fish passage, or some combination. All stocks should have management plans that describe fishery and habitat goals and objectives for both the short term and long term. These plans should be reviewed and updated on a regular basis.

> *SFMPs have been implemented for systems with open fisheries, though management recovery plans have not been tied to mortality relative to reference points from the last assessment. Note that the reference point has changed to $Z_{40\%}$ in this assessment.*

3. Identify all fisheries where bycatch occurs, then quantify the amount and disposition of bycatch. In fisheries where bycatch is allowed, quantify the discards.

> *Total incidental catch in fisheries covered by the NEFOP has been quantified, but this catch cannot be parsed into individual fisheries. Quantification of discards is still needed for the Delaware Bay mixed-stock fishery. States need to improve observer monitoring and/or reporting in rivers and coastal fisheries not well covered by NEFOP to identify fisheries discarding shad. Quantification of discards is also needed in Bay of Fundy fisheries that encounter U.S. shad stocks.*

4. Employ observer coverage to verify the reporting rate of commercial catch and harvest, as well as bycatch and discards.

> *See response to #3 above. Progress has been made in fisheries covered by NEFOP, some coastal NC fisheries (gill net fisheries), and Potomac fisheries (bycatch reporting, not observer coverage).*

5. Identify directed harvest and bycatch losses of American shad in all fisheries. In particular, the ocean and bay waters of Atlantic Maritime Canada should be included in this investigation.

> *See previous two responses to #3 and #4 above.*

6. Future assessments will need to better separate ocean and river fishing mortality in historical data. The problem is that data from the now-closed ocean fishery are limited in regard to stock origin, age composition, and maturity of fish. There is need for better identification of stock composition in mixed-stock harvest using microchemistry techniques, genetics, and/or tagging. Modeling may help to account for ocean mortality, and efforts to locate age composition and maturity information.

> *Anthropogenic mortality from observed removals (fishery and broodstock) was estimated with SCAA models in the Potomac and Albemarle Sound. Ocean fishing mortality of adults in these models was assumed negligible or captured as part of time-invariant natural mortality. Coastwide fishing mortality cannot be determined without time series of complete removals by stock, in river (recreational discards and harvest and commercial discards and harvest) and in ocean which still needs work and will not be*

> *possible for historical periods, particularly at the stock level, due to lack of historical stock composition data from the catch.*

7. Spatially delineate between mixed-stock and Delaware stock areas within the Delaware River system.

> *This has been investigated by several researchers since the last stock assessment (see Section 1.1.2 for more detail). Most recently, an analysis was conducted by the USFWS to evaluate the composition of Delaware Bay captured American shad during the spring of 2017. Of the samples collected from the Delaware Bay in 2017, 27.1% of the 2017 samples were assigned to the Hudson River, and 72.9% were assigned to the Delaware River. Samples from American shad were also collected in 2018 and 2019 from the Delaware Bay and will be similarly analyzed to determine assignment to potential source populations, including the Hudson and Delaware Rivers.*

8. Collect annual estimates of recreational catch, total harvest, CPUE, age, size, and sex composition of fish in each fishery.

> *This has been addressed in some systems, generally where population models were applied, but not all.*

9. If in-river tagging programs (conducted in Georgia, South Carolina, and Maryland) used to estimate exploitation and population size are continued, then assumptions must be verified. Issues related to reporting rate, tag mortality and loss, and movement (fallback), which are needed to estimate exploitation, need to be addressed.

> *Some of these programs have continued and many of the assumptions have still not been verified. The SAS is comfortable with the Georgia analysis (Altamaha) to estimate trends only. See Sections 3.8.8.1 and 3.22.6.2 for additional recommendations to improve analyses.*

10. Improve analyses of mark-recapture data by using modern methods (e.g., those contained in program MARK; Williams et al. 2001) to estimate survival.

> *This has not been addressed.*

11. Monitor juvenile production in semelparous stocks. Such monitoring may indicate when recruitment failure has occurred.

> *This has been addressed in some systems (Santee-Cooper, Savannah, Winyah Bay-Great Pee Dee River, ACE Basin-Edisto River, St. Johns). Some time series were considered not useful for assessment (Table 17 and Table 19).*

12. Accurate and precise aging is a critical underpinning of shad stock assessment and a prerequisite to any substantial improvement. Validation of aging procedures using either scales or otoliths is greatly needed for most shad stocks. These methods should allow for age and

year-class identification in mature fish. To validate otoliths, it would be desirable to mark stocked larvae with OTC, alizarin, or thermal marking.

> *Progress towards validating age determination has been made (see Section 1.1.4), but more known age data are needed especially from systems outside the Delaware. Error in identifying OTC marks needs to be quantified to understand how truly know ages are from fish identified as know age with this method. There have also been genetic microsatellite markers for parentage-based tagging developed and applied in North Carolina and natural isotopic signatures in otoliths used in Virginia that provide additional methods for age validation. Ageing error analysis suggests both scales and otoliths can be used for reliable age determination (see Section 1.1.4.3), but otoliths are preferred and paired read data from otoliths should be supplied with scale ages in the future to confirm scale-based ages are reliable.*

13. Characterize passage-associated efficiency, mortality, migration delay, and sub-lethal effects on American shad at hydroelectric dams.

> *New analytical modeling approaches have been developed and are being applied to better understand potential impacts of routes of passage at dams/facilities impacts at the river system level (Stich et al. 2018) and coastwide (see Sections 2.7.2 and 4.4.2). The USGS Conte Anadromous Fish Research Center continues to provide substantial technical expertise in study design, implementation, analyses and interpretation of study data for agencies dealing with FERC and fish passage. The USFWS Turbine Blade Strike Model Tool (Towler and Pica 2019), is a new tool to quantitatively assess downstream fish passage impacts at facilities based upon user defined parameters (e.g., routing, turbine characteristics). As there are often unique project specific passage considerations, in situ studies with tagged fish are recommended. Sub-lethal effects remain not well studied given challenges of retaining control fish (juvenile) from turbine passage studies in peer-reviewed publications. More rigorously defined fish passage evaluation studies are needed as described in Section 1.1.9.5.*

14. Annually update all summary data tables of on-going data collection for use in the next assessment in the format used in this stock assessment for use in ASMFC stock assessments only.

> *The American shad FMP and associated management documents do request summarized monitoring data be provided annually with compliance reports. However, work is still needed to align the format and details of data requests for both management compliance report and stock assessment needs. Addressing the first "Data Collection" research recommendation provided in this stock assessment would facilitate work to annually update data for compliance and more efficient future assessments.*

15. Shad population modeling must be vastly expanded in the future. First, age-structured assessment models are needed to integrate the various sources of information available for shad stocks. These models have largely supplanted catch-curve analyses around the world.

Second, models that incorporate predator-prey interactions should be examined. Shad are consumed by striped bass (e.g., in Connecticut), seals, sharks, other fishes, and birds. Little is known about these effects. If statistical multi-species models cannot be developed, then perhaps Ecopath may provide some insight. Third, the ultimate goal of stock assessment of shad should be to develop a life history model that accounts for all major factors that affect the mortality, recruitment, and reproduction of shad. This model would include factors in the ocean environment such as ocean fishing, fisheries bycatch, and oceanographic processes. This model would include factors in the freshwater environment, including fish passage and related mortality, commercial and recreational fishing mortality, habitat changes, and environmental factors. Such a model would be useful to help understand which processes are most important in the sustainability of shad populations.

> *The SAS considered available data sets and the presence of active fisheries (needed to provide data for these models) to select systems believed to be the best candidates for population models. Details and limitations of these models are provided in system-specific sections. However, most systems still lack necessary data for these models, particularly after fisheries were closed and data time series were discontinued.*
>
> *The ASMFC has taken some initial steps in ecosystem modeling and ecosystem-based fisheries management, but these efforts have focused on more abundant prey species (Atlantic menhaden). These efforts are unlikely to include American shad until more progress is made with initial prey species, more American shad data are available, and there are more indications that metapopulation abundance has increased from depleted levels.*
>
> *The habitat assessment and simulation modeling analyses in this assessment (Section 2.7.2) address some components of the "life history model" part of this recommendation, but further work is needed to incorporate data time series such as indices of abundance and catch into these models for empirically-based population estimates.*

5.3.3.1 Recommendations for Habitat

1. Develop safe, timely, and effective upriver and downriver passage for adults and downriver passage for juvenile at all barriers that limit access to spawning reaches.

> *Recent peer reviewed publications continue to describe the need to improve the study of upstream and downstream passage as described in Sections 1.1.9.5, 2.7.2, 4.4.2, and 4.5. Some progress has been made in these areas, including USFWS Northeast Fish Passage Engineering Criteria (USFWS 2019), that has been regularly updated with the inclusion of new research and other sources of information as it becomes available. Research on several different entrance gate configurations for upstream shad passage is one example of new information being applied to these criteria (Mulligan et al. 2018). New analytical modeling approaches are also being applied to better understand potential impacts of routes of passage at dams/facilities at the river system level (Stich*

> *et al. 2018) and coastwide (see Sections 2.7.2 and 4.4.2). The USGS Conte Anadromous Fish Research Center continues to provide substantial technical expertise in study design, implementation, analyses and interpretation of study data for agencies dealing with FERC and fish passage projects. The USFWS Turbine Blade Strike Model Tool (Towler and Pica 2019), is a tool to help inform decisions on downstream fish passage based upon estimated impacts (mortality) in the absence of site specific tagging studies. River basin management plans are increasingly placing upstream and downstream passage impacts, needs, recommendations in the context of cumulative dam/hydropower effects and requiring passage performance measures that are quantitatively defined rather than the open ended passage terms of "safe, effective, and timely" (MEDMR and MEDIFW 2008; SRAFRC 2010; CRASC 2019).*

2. Maintain water quality and suitable habitat for all life stages of American shad in all rivers with shad populations. Refer to Amendment 1 for habitat issues pertaining to American shad and the ASMFC Anadromous Species Habitat Source Document (in prep).

> *No water quality monitoring data were analyzed by the SAS as part of this stock assessment, so it is not known to what degree this recommendation has been addressed from a coastwide perspective. System-specific water quality impacts and improvements, if available, are provided in Section 3.*

3. In rivers with flow regulation, maintain flows at levels that ensure adequate fish passage, water quality, and habitat protection.

> *Flow data were only evaluated by the SAS during this assessment in terms of effects on catchability when standardizing indices of abundance, so it is not known to what degree this recommendation has been addressed. System-specific flow management impacts and improvements, if available, are provided in Section 3.*

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7 TABLES

Table 1. Assessment approaches applied to system stocks and tributaries in the Northern Iteroparous regional metapopulation. An 'X' in columns 3-8 indicates the assessment approach was applied to the system.

System	Waterbodies	YOY Abundance Trend Analysis	Adult Abundance Trend Analysis	Mean Length Trend Analysis	Mean Length-at-Age Trend Analysis	Total Mortality	Population Model
St. Croix	St. Croix						
Nonesuch	Nonesuch						
Presumpscot	Presumpscot						
Royal	Royal						
Merrymeeting Bay	Merrymeeting Bay Cathance Abagadasset Eastern Androscoggin	X					
Kennebec	Kennebec						
Sheepscot	Sheepscot						
Orland	Orland						
Union	Union						
Ducktrap	Ducktrap						
Penobscot	Penobscot						
Narraguangus	Narraguangus						
Tunk	Tunk Stream						
Pleasant	Pleasant						
Machias/East Machias	Machias/East Machias						
Denny's	Denny's						
Mousam	Mousam						
St. George	St. George						
Medomak	Medomak						
Saco	Saco						
Webhannet	Webhannet						
Kennebunk	Kennebunk						
Sebasticook	Sebasticook						
Piscataqua	Piscataqua Salmon Falls						
Oyster	Oyster						
Exeter	Exeter						
Cocheco	Cocheco						
Winnicut	Winnicut						
Taylor	Taylor						
Lamprey	Lamprey						
Merrimack	Merrimack		X	X		X	
Neponset	Neponset						
North (Massachusetts)	North South Indian Head						
Taunton	Taunton						
Agawam	Agawam						
Jones	Jones						
Mattapoisett	Mattapoisett						
Charles	Charles						
Palmer	Palmer						
Runnins	Runnins						
Blackstone	Blackstone						

Table 1 Continued

System	Waterbodies	YOY Abundance Trend Analysis	Adult Abundance Trend Analysis	Mean Length Trend Analysis	Mean Length-at-Age Trend Analysis	Total Mortality	Population Model
Kickamuit	Kickamuit						
Hunts	Hunts						
Connecticut	Connecticut Mattabesset Salmon Pequabuck Scantic Farmington	X	X	X	X	X	X
Pawcatuck	Pawcatuck		X				
Housatonic	Housatonic						
Naugatuck	Naugatuck						
Pomperaug	Pomperaug						
Shepaug	Shepaug						
Quinnipiac	Quinnipiac						
Hammonasset	Hammonasset						
Shetucket	Shetucket						
Willimantic	Willimantic						
Natchaug	Natchaug						
Quinebaug	Quinebaug						
Moosup	Moosup						
Thames	Thames						

Table 2. Assessment approaches applied to system stocks and tributaries in the Southern Iteroparous regional metapopulation. An 'X' in columns 3-8 indicates the assessment approach was applied to the system.

System	Waterbodies	YOY Abundance Trend Analysis	Adult Abundance Trend Analysis	Mean Length Trend Analysis	Mean Length-at-Age Trend Analysis	Total Mortality	Population Model
Hudson	Hudson	X	X	X	X	X	
Tuckahoe	Cedar Swamp Creek						
Great Egg Harbor River	Great Egg Harbor River						
Hackensack	Hackensack						
Mullica	Mullica						
Passaic	Passaic						
Raritan	Raritan						
Delaware	Maurice Cohansey Cooper Crosswicks Creek Oldmans Creek Raccoon Creek Rancocas Creek Salem Woodbury Creek Delaware Lehigh Schuylkill Brandywine Christina	X	X	X	X	X	

Table 2 Continued

System	Waterbodies	YOY Abundance Trend Analysis	Adult Abundance Trend Analysis	Mean Length Trend Analysis	Mean Length-at-Age Trend Analysis	Total Mortality	Population Model
Broadkill	Broadkill						
Nanticoke	Nanticoke Marshyhope Creek	X	X	X	X	X	
Chester	Chester						
Choptank	Tuckahoe Creek Choptank						
Upper Chesapeake Bay	Susquehanna Upper Chesapeake Bay Sassafras Elk North East Bohemia	X	X	X	X	X	X
Miles	Miles						
Patapsco	Patapsco						
Bush	Bush						
Wicomico	Wicomico						
Gunpowder	Gunpowder						
Patuxent	Patuxent	X					
Potomac	Anacostia Potomac	X	X	X	X	X	X
Pocomoke	Pocomoke						
Rappahannock	Rappahannock	X	X	X	X	X	
York	York South Anna North Anna Pamunkey Mattaponi	X	X	X	X	X	
James	James Chickahominy Appomattox Nansemond	X	X	X	X	X	
Piankatank	Piankatank						
Albemarle Sound	Nottoway Blackwater Meherrin Chowan Roanoke Albemarle Sound Cashie Pasquotank Perquimans Yeopim Scuppernong Alligator	X	X	X	X	X	X
Pamlico Sound	Pamlico Sound						
Tar-Pamlico	Tar-Pamlico		X	X	X	X	
North (North Carolina)	North						
Neuse	Trent Neuse		X	X	X		X
White Oak	White Oak						
New	New						

Table 3. Assessment approaches applied to system stocks and tributaries in the Semelparous regional metapopulation. An 'X' in columns 3-8 indicates the assessment approach was applied to the system.

System	Waterbodies	YOY Abundance Trend Analysis	Adult Abundance Trend Analysis	Mean Length Trend Analysis	Mean Length-at-Age Trend Analysis	Total Mortality	Population Model
Cape Fear	Brunswick Black Cape Fear		X	X	X		X
Little	Little						
Winyah Bay	Waccamaw Great Pee Dee Winyah Bay Little Pee Dee Lynches Black Sampit Bull Creek		X	X	X		X
Santee-Cooper	Santee Cooper Lake Moultrie Lake Marion Wateree Congaree Broad Wando Ashely		X	X	X		X
ACE Basin	Ashepoo Combahee Salkehatchie Edisto		X				X
Coosawhatchie	Coosawhatchie						
Savannah	Savannah		X				X
Altamaha	Altamaha Oconee Ocmulgee		X				
Ogeechee	Ogeechee						
Satilla	Satilla						
St Marys	St. Marys						
St Johns	St. Johns Econlockhatchee Oklawaha	X	X	X			
Pellicer	Pellicer						
Tomoka	Tomoka						
Nassau	Nassau						

Table 4. Length-weight relationship data summaries, parameter estimates, and R-squared values for American shad by region and sex. Data summaries included number of data points (n) and ranges of years, weights, and lengths in the data sets. Fork length data are in millimeters and weight data are in grams.

Region	Sex	n	Minimum Year	Maximum Year	Minimum Weight	Maximum Weight	Minimum Length	Maximum Length	alpha	beta	R^2
Northern Iteroparous	Female	3,852	2005	2017	183	4,500	341	574	1.79E-04	2.59	0.54
Southern Iteroparous	Female	58,160	1972	2017	24	5,740	125	628	3.57E-05	2.87	0.61
Semelparous	Female	14,293	1979	2017	113	5,520	161	593	1.56E-07	3.76	0.75
Northern Iteroparous	Male	4,472	2005	2017	79	2,460	295	537	9.51E-05	2.68	0.69
Southern Iteroparous	Male	34,572	1972	2017	46	4,700	145	667	1.80E-06	3.35	0.71
Semelparous	Male	13,458	1979	2017	85	4,400	201	518	1.05E-07	3.82	0.81

Table 5. Results of paired scale and otolith age comparisons. Grey shading indicates a mean coefficient of variation (CV) >5% or an Evans and Hoenig (1998) symmetry test p-value <0.05. (Table continues on next page.)

	System																	
	Penobscot			Merrimack			Connecticut			Delaware			Delaware			Delaware		
	Waterbody																	
	Penobscot River			*Merrimack River*			*Connecticut River*			*Delaware River*			*Lehigh River*			*Schuylkill River*		
Year	n	mean CV	p-value	n	mean CV	p-value	n	mean CV	p-value	n	mean CV	p-value	n	mean CV	p-value	n	mean CV	p-value
1995																		
1996										76	10.23	0.000	29	12.70	0.008			
1997										73	3.50	0.144						
1998										197	7.05	0.000	37	15.47	0.162			
1999										190	9.01	0.000	87	9.19	0.000			
2000										323	10.04	0.000	96	5.31	0.301			
2001										709	8.65	0.051	96	11.06	0.000			
2002										368	8.43	0.000	95	11.12	0.000			
2003										521	8.82	0.000				24	0.00	1.000
2004										412	7.94	0.000	60	15.62	0.000	21	0.75	0.317
2005										731	11.33	0.000	13	5.69	0.368	25	0.00	1.000
2006										328	10.90	0.000	51	5.04	0.001	19	4.51	0.014
2007										315	11.59	0.000	40	18.82	0.000	24	4.63	0.480
2008				94	5.13	0.121							39	5.39	0.664	17	1.83	0.157
2009				55	5.57	0.261				359	2.78	0.003	27	1.83	0.135	24	0.65	0.317
2010				93	3.93	0.004				766	1.15	0.000	91	1.21	0.008	25	0.00	1.000
2011										380	0.75	0.297	16	0.00	1.000	24	0.99	0.157
2012										406	0.65	0.079	62	0.18	0.317	25	0.00	1.000
2013	15	8.98	0.018							437	0.12	0.025	73	0.00	1.000	24	0.00	1.000
2014	10	13.34	0.572							485	6.74	0.022	80	3.59	0.205	25	3.98	0.030
2015	74	11.03	0.008				621	5.63	0.341	267	3.18	0.239	62	4.04	0.272	4	7.77	0.157
2016	258	12.14	0.000							145	9.67	0.000	103	2.05	0.352	29	1.96	0.180
2017	52	13.90	0.000							67	8.94	0.000	97	5.30	0.000	23	4.73	0.257

Table 5 Continued

	System											
	Upper Chesapeake			**Potomac**			**Albemarle Sound**			**Nesue**		
	Waterbody											
	Susquehanna River			*Potomac River*			*Roanoke River*			*Neuse River*		
Year	n	mean CV	p-value	n	mean CV	p-value	n	mean CV	p-value	n	mean CV	p-value
1995	579	8.19	0.000									
1996	334	11.36	0.000									
1997												
1998												
1999												
2000	184	5.50	0.000	135	4.04	0.000						
2001	182	8.03	0.000									
2002	179	1.68	0.355									
2003	191	6.33	0.000									
2004	160	1.57	0.000				133	11.48	0.015			
2005	271	1.42	0.112									
2006	176	2.76	0.000	36	4.72	0.122						
2007	151	5.25	0.000	25	2.79	0.082						
2008	177	3.22	0.000	21	2.80	0.655						
2009	169	2.96	0.076							40	10.52	0.238
2010	173	2.54	0.018	67	2.68	0.092				42	10.51	0.246
2011	133	0.35	0.083	34	2.81	0.014						
2012	136	0.43	0.607	43	1.34	0.317						
2013	166	0.25	0.564	43	1.15	0.317						
2014	102	6.22	0.220	81	2.25	0.118						
2015	163	2.87	0.138									
2016	557	5.06	0.006	37	1.76	0.655						
2017	484	3.65	0.044	95	3.74	0.607						

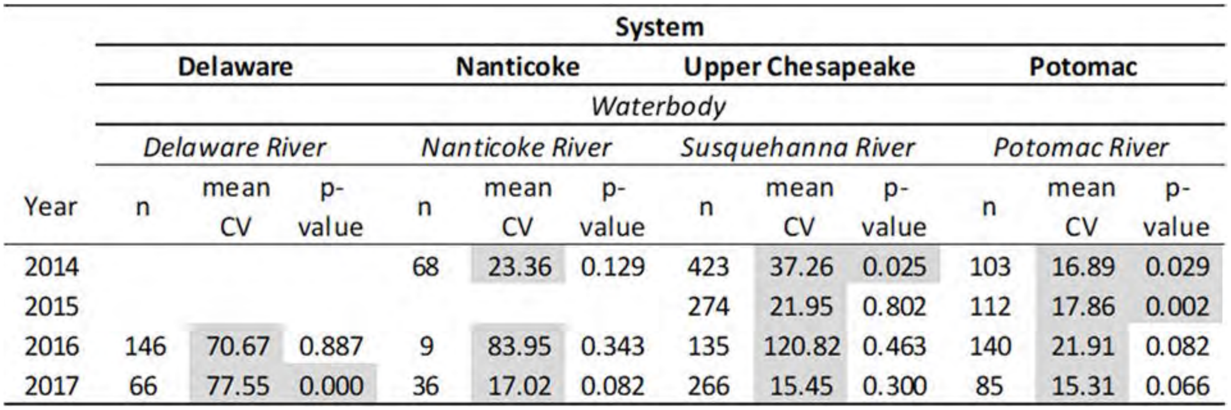
Table 6. Results of otolith and known age comparisons. Grey shading indicates a mean coefficient of variation (CV) >5% or an Evans and Hoenig (1998) symmetry test p-value <0.05.

	System														
	Delaware			**Delaware**			**Delaware**			**Potomac**			**Albemarle Sound**		
	Waterbody														
	Delaware River			*Lehigh River*			*Schuylkill River*			*Potomac River*			*Roanoke River*		
Year	n	mean CV	p-value	n	mean CV	p-value	n	mean CV	p-value	n	mean CV	p-value	n	mean CV	p-value
1998				2	0.00	1.000									
1999				49	0.00	1.000									
2000	9	1.43	0.317	78	0.40	0.157				4	0.00	1.000			
2001	7	9.18	0.025	85	0.15	0.317									
2002	2	5.44	0.317	78	3.14	0.223									
2003	12	6.55	0.261				8	15.15	0.014						
2004	1	17.68	0.317	29	6.03	0.232									
2005				4	3.21	0.317									
2006	4	0.00	1.000	2	11.79	0.317									
2007	5	2.57	0.317												
2008	1	0.00	1.000												
2009															
2010															
2011															
2012															
2013													9	8.98	0.046
2014				2	0.00	1.000							27	8.11	0.002
2015													68	3.32	0.002
2016													66	2.60	0.007
2017													101	5.66	0.842

Table 7. Results of scale and known age comparisons. Grey shading indicates a mean coefficient of variation (CV) >5% or an Evans and Hoenig (1998) symmetry test p-value <0.05.

	System												
	Delaware			**Delaware**			**Delaware**			**Potomac**			
	Waterbody												
	Delaware River			*Lehigh River*			*Schuylkill River*			*Potomac River*			
Year	n	mean CV	p-value	n	mean CV	p-value	n	mean CV	p-value	n	mean CV	p-value	
1998				2	35.36	0.157							
1999				48	2.76	0.257							
2000	9	4.60	0.564	76	4.87	0.006				4	7.86	0.157	
2001	7	7.35	0.046	82	11.71	0.000							
2002	2	31.07	0.368	78	11.40	0.000							
2003	12	14.46	0.087				9	15.71	0.008				
2004	1	28.28	0.317	29	15.89	0.001							
2005				4	3.21	0.317							
2006	4	7.86	0.157	2	24.72	0.368							
2007	2	20.57	0.368										
2008													
2009													
2010													
2011													
2012													
2013													
2014				2	0.00	1.000							
2015													
2016													
2017													

Table 8. Results of spawn mark reader comparisons. Grey shading indicates a mean coefficient of variation (CV) >5% or an Evans and Hoenig (1998) symmetry test p-value <0.05.



	System											
	Delaware			**Nanticoke**			**Upper Chesapeake**			**Potomac**		
	Waterbody											
	Delaware River			*Nanticoke River*			*Susquehanna River*			*Potomac River*		
Year	n	mean CV	p-value	n	mean CV	p-value	n	mean CV	p-value	n	mean CV	p-value
2014				68	23.36	0.129	423	37.26	0.025	103	16.89	0.029
2015							274	21.95	0.802	112	17.86	0.002
2016	146	70.67	0.887	9	83.95	0.343	135	120.82	0.463	140	21.91	0.082
2017	66	77.55	0.000	36	17.02	0.082	266	15.45	0.300	85	15.31	0.066

Table 9. Coastwide, regional-specific, and system-specific mean von Bertalanffy parameter estimates with standard deviations (sd) and 95% credible intervals.

Parameter	Mean	sd	2.5% CRI	97.5% CRI
L_∞ coastwide	477.32	11.67	454.33	499.69
K coastwide	0.44	0.30	-0.38	0.51
t_0 coastwide	-0.31	0.04	-0.40	-0.23
L_∞ northern iteroparous	489.40	2.91	483.93	495.27
L_∞ semelparous	454.26	2.44	449.67	459.20
L_∞ southern iteroparous	482.76	1.83	479.36	486.64
K northern iteroparous	0.43	0.01	0.41	0.45
K semelparous	0.49	0.01	0.47	0.50
K southern iteroparous	0.44	0.01	0.42	0.45
t_0 northern iteroparous	-0.31	0.01	-0.34	-0.29
t_0 semelparous	-0.21	0.01	-0.24	-0.18
t_0 southern iteroparous	-0.36	0.01	-0.37	-0.34
L_∞ Albemarle	469.25	3.14	463.27	475.34
L_∞ Cape Fear	480.23	4.22	472.27	488.39
L_∞ Connecticut	531.08	8.81	514.44	549.66
L_∞ Delaware	515.49	1.49	512.63	518.49
L_∞ Merrimack	499.64	2.91	494.18	505.38
L_∞ North (MA)	488.91	6.53	476.58	502.22
L_∞ Penobscot	437.98	3.31	431.74	445.01
L_∞ Potomac	463.32	2.49	458.40	468.06
L_∞ St. Johns	428.28	2.29	423.88	432.72
L_∞ Tar-Pamlico	456.94	7.64	443.36	473.36
L_∞ Upper Chesapeake Bay	508.78	2.66	503.64	513.96
K Albemarle	0.42	0.01	0.40	0.44
K Cape Fear	0.43	0.01	0.41	0.46
K Connecticut	0.33	0.02	0.30	0.36
K Delaware	0.41	0.01	0.40	0.42
K Merrimack	0.35	0.01	0.33	0.36
K North (MA)	0.38	0.02	0.34	0.43
K Penobscot	0.65	0.03	0.59	0.73
K Potomac	0.51	0.02	0.48	0.54
K St. Johns	0.54	0.01	0.51	0.56
K Tar-Pamlico	0.51	0.04	0.44	0.59
K Upper Chesapeake Bay	0.33	0.01	0.32	0.34
t_0 Albemarle	-0.32	0.01	-0.34	-0.31
t_0 Cape Fear	-0.23	0.03	-0.28	-0.17
t_0 Connecticut	-0.36	0.01	-0.38	-0.33
t_0 Delaware	-0.29	0.01	-0.30	-0.28
t_0 Merrimack	-0.36	0.03	-0.43	-0.30
t_0 North (MA)	-0.33	0.03	-0.40	-0.27
t_0 Penobscot	-0.20	0.01	-0.22	-0.18
t_0 Potomac	-0.26	0.01	-0.28	-0.25
t_0 St. Johns	-0.19	0.01	-0.21	-0.18
t_0 Tar-Pamlico	-0.29	0.03	-0.35	-0.23
t_0 Upper Chesapeake Bay	-0.62	0.01	-0.64	-0.60

Table 10. Natural mortality estimates by region and sex used in the assessment. Maximum age data for the northern iteroparous region were borrowed from the southern iteroparous region due to more prevalent and long term impacts of man-made barriers in the northern iteroparous region.

Region	Sex	n Age Samples	Maximum Age	Natural Mortality (*M*)
Northern Iteroparous	F	54,805	13	0.467
Northern Iteroparous	M	40,621	11	0.545
Semelparous	F	9,419	9	0.655
Semelparous	M	5,504	8	0.729
Southern Iteroparous	F	54,805	13	0.467
Southern Iteroparous	M	40,621	11	0.545

Table 11. Number of southern iteroparous female American shad-at-age observed as first time spawners, proportion-at-age of overall spawning run age structure, and cumulative proportion of age classes observed in the overall spawning run.

Age	Number observed as 1st time spawners	Proportion observed in run	Cumulative proportion observed in run
1	0	0.000	0.000
2	0	0.000	0.000
3	11	0.002	0.002
4	417	0.083	0.085
5	1913	0.381	0.466
6	2024	0.403	0.869
7	579	0.115	0.984
8	76	0.015	0.999
9	5	0.001	1.000

Table 12. American shad maturity-at-age by region and sex using the mortality correction approach.

Age	Semelparous		Southern Iteroparous		Northern Iteroparous	
	Female	Male	Female	Male	Female	Male
1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00
3	0.01	0.07	0.00	0.00	0.00	0.03
4	0.09	0.29	0.04	0.12	0.04	0.21
5	0.33	0.60	0.27	0.50	0.69	0.82
6	0.63	0.86	0.64	0.79	0.69	1.00
7	0.92	1.00	0.81	0.84	0.90	1.00
8	1.00	1.00	0.90	0.80	1.00	1.00
9	1.00	1.00	1.00	1.00	1.00	1.00

Table 13. Recreational catch rate data sets considered for abundance trends in the assessment.

Agency	*System*	*Survey Name*	*Index Data Treatment in Stock Assessment*	*Index Type*	*Justification for Excluding Index Data*	*Biological Data*
CT DEEP	Connecticut	Connecticut River Recreational Creel Survey	Exclude	NA	Not representative of abundance changes	No
MD DNR	Upper Chesapeake	Susquehanna River Recreational Creel Survey	Include	Nominal	NA	No
MD DNR	Upper Chesapeake	Susquehanna River Recreational Logbooks	Exclude	NA	Not representative of abundance changes	No
NC DMF	Tar-Pamlico	Central Southern Management Area Creel Survey (Tar-Pamlico)	Exclude	NA	Time series too short (<10 years)	No
NC DMF	Neuse	Central Southern Management Area Creel Survey (Neuse River)	Exclude	NA	Time series too short (<10 years)	No
NC DMF	Cape Fear	Central Southern Management Area Creel Survey (Cape Fear River)	Exclude	NA	Time series too short (<10 years)	No
NCWRC	Albemarle Sound	Central Southern Management Area Creel Survey (Roanoke River)	Exclude	NA	Not representative of abundance changes	No
SC DNR	Santee-Cooper	Cooper River Recreational Creel Survey	Include	Nominal	NA	Yes
VDGIF	James	James River Recreational Creel Survey	Exclude	NA	Not representative of abundance changes	No
VDGIF	Rappahannock	Rappahannock River Recreational Creel Survey	Exclude	NA	Not representative of abundance changes	No
FL FWC	St. Johns	St. Johns River Recreational Creel Survey	Exclude	NA	Not representative of abundance changes	No
GA DNR	Savannah	Savannah River Recreational CPUE/Monitoring (GA DNR)	Exclude	NA	Not representative of abundance changes	No
GA DNR	Ogeechee	Ogeechee River Recreational CPUE/Monitoring	Exclude	NA	Time series too short (<10 years)	No
NY DEC	Hudson	Hudson River Recreational Creel Survey	Exclude	NA	Not representative of abundance changes	No
SC DNR	Santee-Cooper	Santee River Recreational CPUE/Monitoring	Exclude	NA	Not representative of abundance changes	Yes
SC DNR	Savannah	Savannah River Recreational CPUE/Monitoring (SC DNR)	Exclude	NA	Not representative of abundance changes	No

Table 14. Commercial catch rate data sets considered for abundance trends in the assessment.

Agency	*System*	*Survey Name*	*Index Data Treatment in Stock Assessment*	*Index Type*	*Justification for Excluding Index Data*	*Biological Data*
CT DEEP	Connecticut	Connecticut River Commercial CPUE/Monitoring	Include	Modeled	NA	Yes
GA DNR	Altamaha	Altamaha River Commercial CPUE/Monitoring	Include	Nominal	NA	No
GA DNR	Savannah	Savannah River Commercial CPUE/Monitoring (GA DNR)	Include	Nominal	NA	No
MD DNR	Upper Chesapeake	Upper Chesapeake Onboard Fishery Monitoring	Include	Modeled	NA	Yes
MD DNR	Nanticoke	Nanticoke River Commercial Pound Net CPUE/Monitoring	Include	Modeled	NA	Yes
NC DMF	Albemarle Sound	Albemarle Sound Onboard Observer Program	Exclude	NA	Time series too short (<10 years)	No
NC DMF	Tar-Pamlico	Tar-Pamlico Onboard Observer Program	Exclude	NA	Time series too short (<10 years)	No
NC DMF	Neuse	Neuse River Onboard Observer Program	Exclude	NA	Time series too short (<10 years)	No
NC DMF	Cape Fear	Cape Fear River Onboard Observer Program	Exclude	NA	Time series too short (<10 years)	No
DE Co-Op	Delaware	Lewis Haul Seine Fishery CPUE/Monitoring	Include	Nominal	NA	Yes
NJ DFW	Atlantic Ocean (mixed-stock)	Atlantic Ocean Commercial Logbooks (NJ DFW)	Include	Nominal	NA	No
NJ DFW	Delaware Bay (mixed-stock)	Delaware Bay Commercial Logbooks (NJ DFW)	Include	Nominal	NA	No
DE DFW	Delaware Bay (mixed-stock)	Delaware Bay Commercial Logbooks (DE DFW)	Include	Nominal	NA	Yes
NY DEC	Hudson	Hudson River Commercial Gill Net CPUE/Monitoring	Include	Modeled	NA	Yes
PRFC	Potomac	Potomac River Commercial Pound Net CPUE/Monitoring	Include	Nominal	NA	No
NC DMF	Albemarle Sound	Albemarle Sound Commercial CPUE/Monitoring	Include	Nominal	NA	Yes
NC DMF	Tar-Pamlico	Tar-Pamlico Commercial CPUE/Monitoring	Include	Nominal	NA	Yes
NC DMF	Neuse	Neuse River Commercial CPUE/Monitoring	Include	Nominal	NA	Yes
NC DMF	Cape Fear	Cape Fear River Commercial CPUE/Monitoring	Include	Nominal	NA	Yes
NC DMF	Atlantic Ocean (mixed-stock)	Atlantic Ocean Commercial CPUE/Monitoring (NC DMF)	Include	Nominal	NA	Yes
SC DNR	Winyah Bay	Black River Commercial CPUE/Monitoring	Include	Nominal	NA	No
SC DNR	Winyah Bay	Great Pee Dee River Commercial CPUE/Monitoring	Include	Nominal	NA	Yes
SC DNR	Winyah Bay	Waccamaw River Commercial CPUE/Monitoring	Include	Nominal	NA	Yes
SC DNR	Santee-Cooper	Santee River Commercial CPUE/Monitoring	Include	Nominal	NA	Yes
SC DNR	ACE Basin	Edisto River Commercial CPUE/Monitoring	Include	Nominal	NA	Yes

Table 14 Continued

Agency	*System*	*Survey Name*	*Index Data Treatment in Stock Assessment*	*Index Type*	*Justification for Excluding Index Data*	*Biological Data*
SC DNR	Savannah	Savannah River Commercial CPUE/Monitoring (SC DNR)	Include	Nominal	NA	Yes
VMRC	Chesapeake Bay (mixed-stock)	Chesapeake Bay Commercial Pound Net Discard Logbooks (VMRC)	Exclude	NA	No reliable effort data	No
FL FWC	Atlantic Ocean (mixed-stock)	Atlantic Ocean Historic Commercial CPUE/Monitoring (FL FWC)	Exclude	NA	Not representative of abundance changes	No
MD DNR	Atlantic Ocean (mixed-stock)	Atlantic Ocean Historic Commercial CPUE/Monitoring (MD DNR)	Exclude	NA	Not representative of abundance changes	No
MD DNR	Chesapeake Bay (mixed-stock)	Chesapeake Bay Historic Commercial CPUE/Monitoring (MD DNR)	Exclude	NA	Not representative of abundance changes	No
MD DNR	Potomac	Potomac River Historic Commercial CPUE/Monitoring	Exclude	NA	Not representative of abundance changes	No
MD DNR	Patuxent	Patuxent River Historic Commercial CPUE/Monitoring	Exclude	NA	Not representative of abundance changes	No
MD DNR	Pocomoke	Pocomoke River Historic Commercial CPUE/Monitoring	Exclude	NA	Not representative of abundance changes	No
MD DNR	Wicomico	Wicomico River Historic Commercial CPUE/Monitoring	Exclude	NA	Not representative of abundance changes	No
MD DNR	Nanticoke	Nanticoke River Historic Commercial CPUE/Monitoring	Exclude	NA	Not representative of abundance changes	No
MD DNR	Choptank	Choptank River Historic Commercial CPUE/Monitoring	Exclude	NA	Not representative of abundance changes	No
MD DNR	Miles	Miles River Historic Commercial CPUE/Monitoring	Exclude	NA	Not representative of abundance changes	No
MD DNR	Chester	Chester River Historic Commercial CPUE/Monitoring	Exclude	NA	Not representative of abundance changes	No
MD DNR	Upper Chesapeake	Sassafras River Historic Commercial CPUE/Monitoring	Exclude	NA	Not representative of abundance changes	No
MD DNR	Upper Chesapeake	Elk River Historic Commercial CPUE/Monitoring	Exclude	NA	Not representative of abundance changes	No
MD DNR	Upper Chesapeake	Susquehanna River Historic Commercial CPUE/Monitoring	Exclude	NA	Not representative of abundance changes	No

Table 15. Fishery-independent gill net surveys considered for abundance trends in the assessment.

Agency	*System*	*Survey Name*	*Index Data Treatment in Stock Assessment*	*Index Type*	*Justification for Excluding Index Data*	*Biological Data*
PFBC	Delaware	Smithfield Beach Gill Net Survey	Include	Modeled	NA	Yes
MD DNR	Upper Chesapeake	Upper Chesapeake Striped Bass Spawning Stock Survey	Exclude	NA	Average annual proportion positive <5%	Yes
MD DNR	Potomac	Potomac River Striped Bass Spawning Stock Survey	Include	Modeled	NA	Yes
VIMS	James	James River Adult Gill Net Survey (VIMS)	Include	Modeled	NA	Yes
VIMS	York	York River Adult Gill Net Survey	Include	Modeled	NA	Yes
VIMS	Rappahannock	Rappahannock River Adult Gill Net Survey	Include	Modeled	NA	Yes
NC DMF	Albemarle Sound	Albemarle Sound Independent Gill Net Survey	Include	Nominal	NA	Yes
NC DMF	Neuse	Neuse River Independent Gill Net Survey	Exclude	NA	Not representative of abundance changes	Yes
NC DMF	Cape Fear	Cape Fear River Independent Gill Net Survey	Exclude	NA	Not representative of abundance changes	Yes
NC DMF	New	New River Independent Gill Net Survey	Exclude	NA	Not representative of abundance changes	Yes
NC DMF	Tar-Pamlico	Tar-Pamlico Independent Gill Net Survey	Exclude	NA	Not representative of abundance changes	Yes
SC DNR	Winyah Bay	Waccamaw River Adult Gill Net Survey	Exclude	NA	Time series too short (<10 years)	Yes
SC DNR	Santee-Cooper	Santee River Adult Gill Net Survey	Include	Nominal	NA	Yes
SC DNR	ACE Basin	Edisto River Adult Gill Net Survey	Exclude	NA	Not representative of abundance changes	Yes

Table 15 Continued

Agency	*System*	*Survey Name*	*Index Data Treatment in Stock Assessment*	*Index Type*	*Justification for Excluding Index Data*	*Biological Data*
SC DNR	ACE Basin	Combahee River Adult Gill Net Survey	Exclude	NA	Not representative of abundance changes	Yes
GA DNR	Altamaha	Altamaha River Tagging Survey	Include	Nominal	NA	No
VDGIF	James	James River Gill Net Survey (VDGIF)	Exclude	NA	Not representative of abundance changes	No
VDGIF	Pamunkey	Pamunkey River Gill Net Survey	Exclude	NA	Not representative of abundance changes	No
MD DNR	Potomac	Potomac River Broodstock Gill Net Collections	Exclude	NA	Not representative of abundance changes	Yes
MD DNR	Choptank	Choptank River Restoration Adult Gill Net Survey	Exclude	NA	Not representative of abundance changes	No
ICPRB	Potomac	Potomac River Shad Egg Collections (ICPRB)	Exclude	NA	No data available	Yes
VDGIF	Potomac	Potomac River Shad Egg Collections (VDGIF)	Exclude	NA	No data available	Yes
DC DOEE	Potomac	Potomac River Stock Enhancement	Exclude	NA	No data available	Yes
USFWS/PFBC	Potomac	Potomac River Shad Egg Collections (USFWS/PFBC)	Exclude	NA	No data available	Yes
NJ DFW	Delaware Bay (mixed-stock)	Delaware Bay Striped Bass Tagging Survey	Exclude	NA	Not representative of abundance changes	No

Table 16. Fishery-independent electrofishing surveys considered for abundance trends in the assessment.

Agency	*System*	*Survey Name*	*Index Data Treatment in Stock Assessment*	*Index Type*	*Justification for Excluding Index Data*	*Biological Data*
FL FWC	St. Johns	St. Johns River Spawning Ground Electrofishing Survey	Include	Modeled	NA	Yes
GA DNR	Ogeechee	Ogeechee River Electrofishing Survey	Exclude	NA	Time series too short (<10 years)	Yes
GA DNR	Savannah	Savannah River Electrofishing Survey	Exclude	NA	Time series too short (<10 years)	Yes
NCWRC	Cape Fear	Cape Fear River Adult Spawning Area Electrofishing Survey	Include	Modeled	NA	Yes
NCWRC	Neuse	Neuse River Adult Spawning Area Electrofishing Survey	Include	Modeled	NA	Yes
NCWRC	Tar-Pamlico	Tar River Adult Spawning Area Electrofishing Survey	Exclude	NA	<10 collections made per year	Yes
NCWRC	Albemarle Sound	Roanoke River Adult Spawning Area Electrofishing Survey	Include	Modeled	NA	Yes
NCWRC	Albemarle Sound	Roanoke River YOY Electrofishing Survey	Exclude	NA	<10 collections made per year	Yes
VDGIF	James	Appomattox River Boat Electrofishing Survey	Exclude	NA	Too few annual positive observations (<2)	Yes
VDGIF	James	Chickahominy River Boat Electrofishing Survey	Exclude	NA	Too few annual positive observations (<2)	Yes
VDGIF	James	James River Boat Electrofishing Survey	Include	Modeled	NA	Yes
VDGIF	York	Mattaponi River Boat Electrofishing Survey	Exclude	NA	Needs further research for combining into a representative system-wide index	Yes
VDGIF	York	North Anna River Boat Electrofishing Survey	Exclude	NA	Time series too short (<10 years)	Yes

Table 16 Continued

Agency	*System*	*Survey Name*	*Index Data Treatment in Stock Assessment*	*Index Type*	*Justification for Excluding Index Data*	*Biological Data*
VDGIF	York	Pamunkey River Boat Electrofishing Survey	Exclude	NA	Time series too short (<10 years)	Yes
VDGIF	York	South Anna River Boat Electrofishing Survey	Exclude	NA	Needs further research for combining into a representative system-wide index	Yes
VDGIF	Rappahannock	Rappahannock River Boat Electrofishing Survey	Include	Modeled	NA	Yes
MD DNR	Patuxent	Patuxent River Restoration Adult Electrofishing Survey	Include	Modeled	NA	Yes
MD DNR	Choptank	Choptank River Restoration Adult Electrofishing Survey	Exclude	NA	Not representative of abundance changes	No
PFBC	Delaware	Lehigh River Electrofishing Survey	Exclude	NA	Too few annual positive observations (<2)	Yes
Philadelphia Water Department	Delaware	Schuylkill River Electrofishing Survey	Exclude	NA	No data available	Yes
DE DFW	Nanticoke	Nanticoke River Electrofishing Survey	Include	Nominal	NA	Yes
MA DMF	North	Indian Head River Electrofishing Survey	Exclude	NA	Time series too short (<10 years)	Yes
MA DMF	North	South River Electrofishing Survey	Exclude	NA	Time series too short (<10 years)	Yes
PFBC	Delaware	Raubsville Electrofishing Survey	Exclude	NA	Not representative of abundance changes	No
NY DEC	Hudson	Hudson River Spawning Stock Electrofishing Survey	Exclude	NA	Not representative of abundance changes	Yes
RI DEM	Pawcatuck	Pawcatuck River Electrofishing Survey	Exclude	NA	Not representative of abundance changes	No

Table 17. Fishery-independent seine surveys considered for abundance trends in the assessment.

Agency	*System*	*Survey Name*	*Index Data Treatment in Stock Assessment*	*Index Type*	*Justification for Excluding Index Data*	*Biological Data*
ME DMR	Merrymeeting Bay	Merrymeeting Bay Seine Survey	Include	Nominal	NA	No
RI DEM	Pawcatuck	Pawcatuck River Seine Survey	Exclude	NA	No data available	No
RI DEM	Narragansett Bay (mixed-stock)	Narragansett Bay Seine Survey	Exclude	NA	No data available	No
RI DEM	RI Coastal Ponds (mixed-stock)	Rhode Island Coastal Ponds Seine Survey	Exclude	NA	Not representative of abundance changes	No
CT DEEP	Connecticut	Connecticut River Juvenile Shad Seine Survey	Include	Nominal	NA	No
NY DEC	Hudson	Hudson River Spawning Stock Haul Seine Survey	Include	Modeled	NA	Yes
NY DEC	Hudson	Hudson River YOY 3/8" Seine Survey	Include	Modeled	NA	Yes
Hudson River Generating Companies	Hudson	Hudson River Utility YOY Seine Survey	Include	Nominal	NA	
NJ DFW	Delaware	Tidal Delaware River Striped Bass Seine Survey	Include	Modeled	NA	Yes
NJ DFW	Delaware	Non-Tidal Delaware River Juvenile Seine Survey	Include	Modeled	NA	
DE DFW	Nanticoke	Nanticoke River Juvenile Haul Seine Survey	Include	Nominal	NA	Yes
PFBC	Upper Chesapeake	Columbia Haul Seine Survey	Exclude	NA	No reliable effort data	Yes
DC DOEE	Potomac	Potomac River Juvenile Seine Survey	Exclude	NA	No data available	Yes
MD DNR	Potomac	Potomac River Striped Bass Juvenile Seine Survey	Include	Modeled	NA	Yes
MD DNR	Upper Chesapeake	Upper Chesapeake Striped Bass Juvenile Seine Survey	Include	Modeled	NA	Yes
MD DNR	Nanticoke	Nanticoke River Striped Bass Juvenile Seine Survey	Exclude	*NA*	Not representative of abundance changes	Yes
MD DNR	Choptank	Choptank River Striped Bass Juvenile Seine Survey	Exclude	*NA*	Not representative of abundance changes	Yes
MD DNR	Choptank	Choptank River Restoration Juvenile Seine Survey	Exclude	NA	No data available	No
MD DNR	Patuxent	Patuxent River Restoration Juvenile Seine Survey	Exclude	NA	Not representative of abundance changes	No
MD DNR	Nanticoke	Marshyhope Creek Restoration Juvenile Seine Survey	Exclude	NA	Not representative of abundance changes	No

Table 17 Continued

Agency	*System*	*Survey Name*	*Index Data Treatment in Stock Assessment*	*Index Type*	*Justification for Excluding Index Data*	*Biological Data*
VIMS	James	James River Juvenile Seine Survey	Include	Nominal	NA	No
VIMS	York	York River Juvenile Seine Survey	Include	Nominal	NA	No
VIMS	Rappahannock	Rappahannock River Juvenile Seine Survey	Include	Nominal	NA	No
NC DMF	Albemarle Sound	Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey	Include	Modeled	NA	No
DE DFW	Delaware	Christina River Juvenile Haul Seine Survey	Exclude	*NA*	Time series too short (<5 years)	No
GA DNR	Altamaha	Altamaha River Juvenile Seine Survey	Exclude	*NA*	Not representative of abundance changes	No
GA DNR	Savannah	Savannah River Juvenile Seine Survey (GA DNR)	Exclude	*NA*	Not representative of abundance changes	No
GA DNR	Ogeechee	Ogeechee River Juvenile Seine Survey	Exclude	*NA*	Not representative of abundance changes	No
SC DNR	Santee-Cooper	Congaree River Juvenile Seine Survey	Exclude	*NA*	Needs further research for combining into a representative system-wide index	No
SC DNR	Santee-Cooper	Wateree River Juvenile Seine Survey	Exclude	*NA*	Needs further research for combining into a representative system-wide index	No
SC DNR	Santee-Cooper	Upper Santee River Juvenile Seine Survey	Exclude	*NA*	Needs further research for combining into a representative system-wide index	No
SC DNR	Winyah Bay	Great Pee Dee River Juvenile Seine Survey	Exclude	*NA*	Not representative of abundance changes	No
SC DNR	Savannah	Savannah River Juvenile Seine Survey (SC DNR)	Exclude	*NA*	Not representative of abundance changes	No
SC DNR	ACE Basin	Edisto River Juvenile Seine Survey	Exclude	*NA*	Not representative of abundance changes	No

Table 18. Fishery-independent trawl surveys considered for abundance trends in the assessment.

Agency	*System*	*Survey Name*	*Index Data Treatment in Stock Assessment*	*Index Type*	*Justification for Excluding Index Data*	*Biological Data*
CT DEEP	Atlantic Ocean (mixed-stock)	Long Island Sound Trawl Survey	Include	Nominal	NA	No
DE DFW	Delaware Bay (mixed-stock)	Delaware Bay 30' Trawl Survey	Include	Modeled	NA	No
DE DFW	Delaware Bay (mixed-stock)	Delaware Bay 16' Trawl Survey	Exclude	NA	Average annual proportion positive <5%	No
ME DMR	Atlantic Ocean (mixed-stock)	Maine/New Hampshire Trawl Survey	Include	Modeled	NA	No
NOAA Fisheries	Atlantic Ocean (mixed-stock)	Northeast Fisheries Science Center Bottom Trawl Survey	Include	Nominal	NA	Yes
NJ DFW	Atlantic Ocean (mixed-stock)	New Jersey Ocean Trawl Survey	Include	Modeled	NA	Yes
RI DEM	Atlantic Ocean (mixed-stock)	Rhode Island Coastal Trawl Survey	Include	Modeled	NA	No
VIMS	Atlantic Ocean (mixed-stock)	Northeast Area Monitoring and Assessment Program Trawl Survey	Include	Modeled	NA	Yes

Table 19. Other fishery-independent surveys considered for abundance trends in the assessment.

Agency	*System*	*Survey Name*	*Index Data Treatment in Stock Assessment*	*Index Type*	*Justification for Excluding Index Data*	*Biological Data*
Hudson River Generating Companies	Hudson	Hudson River Utility Post-Yolk Sac Larvae Survey	Include	Nominal	NA	No
Hudson River Generating Companies	Hudson	Hudson River Utility Egg Survey	Include	Nominal	NA	No
Hudson River Generating Companies	Hudson	Hudson River Utility Yolk Sac Larvae Survey	Exclude	NA	Not representative of abundance changes	No
PFBC	Upper Chesapeake	Holtwood Lift Netting Survey	Exclude	NA	Not representative of abundance changes	Yes
MD DNR	Upper Chesapeake	Susquehanna Hook-and-Line Survey	Include	Modeled	NA	Yes
DC DOEE	Potomac	Potomac River Juvenile Pushnet Survey	Include	Nominal	NA	No
FL FWC	St. Johns	St. Johns River Juvenile Pushnet Survey	Include	Modeled	NA	No
University of Maine	Penobscot	University of Maine Biological Sampling	NA	NA	NA	Yes

Table 20. Fish counts considered for abundance trends in the assessment.

Agency	*System*	*Survey Name*	*Index Data Treatment in Stock Assessment*	*Index Type*	*Justification for Excluding Index Data*	*Biological Data*
USFWS/MassWildlife	Merrimack	Essex Dam Fish Lift Counts	Include	Nominal	NA	Yes
RI DEM	Pawcatuck	Potter Hill Fishway Count	Include	Nominal	NA	Yes
Holyoke Gas and Electric	Connecticut	Holyoke Dam Fish Lift Counts	Include	Nominal	NA	Yes
PFBC	Delaware	Easton Dam Fishway Count	Include	Nominal	NA	No
PFBC	Delaware	Chain Dam Fishway Count	Include	Nominal	NA	No
Philadelphia Water Department	Delaware	Fairmount Fishway Count	Include	Nominal	NA	No
PFBC	Upper Chesapeake	Holtwood Passage Count	Exclude	NA	Not representative of abundance changes	No
PFBC	Upper Chesapeake	Safe Harbor Passage Count	Exclude	NA	Not representative of abundance changes	Yes
PFBC	Upper Chesapeake	York Haven Passage Count	Exclude	NA	Not representative of abundance changes	No
Normandeau Associates, Inc.	Upper Chesapeake	Conowingo Dam Fish Lift Count	Exclude	NA	Not representative of abundance changes	Yes
VDGIF	James	Bosher's Dam Fishway Count	Include	Nominal	NA	No
SC DNR	Santee-Cooper	St. Stephen Locks Passage Count	Exclude	NA	Not representative of abundance changes	Yes
ME DMR	Merrymeeting Bay	Brunswick Fishway Count	Exclude	NA	Not representative of abundance changes	No
Brookfield Renewable Energy	Saco	Saco River Fish Count	Exclude	NA	Not representative of abundance changes	No
ME DMR	Kennebec	Kennebec River Fish Count	Exclude	NA	Not representative of abundance changes	No
ME DMR	Penobscot	Penobscot River Fish Count	Exclude	NA	Not representative of abundance changes	No
NJ DFW	Raritan	Raritan River Fishway Count	Exclude	NA	Not representative of abundance changes	No

Table 21. Results of the Mann-Kendall test for trends fishery-independent and fishery-dependent survey indices. n = sample size, S is the Mann-Kendall test statistic, and p-value is the two-tailed probability. Significant results are shaded. The sign of the test statistic indicates the direction of the trend.

Data Type	Category	Region	System	Waterbody	Program	Time Series				2005+			
						Years	n	S	p-value	Years	n	S	p-value
FI	CPUE	NI	Merrymeeting Bay	Merrymeeting Bay	Merrymeeting Bay Seine Survey	**1979-2017**	**35**	**253**	**0.000**	2005-2017	13	-28	0.100
FI	Run Counts	NI	Merrimack	Merrimack	Essex Dam Fish Lift Counts	**1983-2017**	**33**	**176**	**0.007**	**2005-2017**	**11**	**31**	**0.020**
FI	Run Counts	NI	Pawcatuck	Pawcatuck	Potter Hill Fishway Count	**1980-2017**	**38**	**-294**	**0.000**	**2005-2017**	**13**	**35**	**0.038**
FD	CPUE	NI	Connecticut	Connecticut	Connecticut River Commercial CPUE	1995-2017	23	31	0.428	2005-2017	13	10	0.583
FI	JAI	NI	Connecticut	Connecticut	Connecticut River Juvenile Shad Seine Survey	1978-2017	40	-24	0.789	2005-2017	13	8	0.669
FI	Run Counts	NI	Connecticut	Connecticut	Holyoke Dam Fish Lift Counts	1975-2017	43	-13	0.900	**2005-2017**	**13**	**60**	**0.000**
FD	CPUE	SI	Hudson	Hudson	Hudson River Commercial Gill Net CPUE	1980-2001	22	8	0.843				
FI	CPUE	SI	Hudson	Hudson	Hudson River Utility Egg Survey	**1974-2015**	**42**	**-398**	**0.000**	2005-2015	11	-11	0.436
FI	CPUE	SI	Hudson	Hudson	Hudson River Utility Post-Yolk Sac Larvae Survey	**1974-2015**	**42**	**-412**	**0.000**	2005-2015	11	12	0.390
FI	CPUE	SI	Hudson	Hudson	Hudson River Spawning Stock Haul Seine Survey	**1988-2017**	**29**	**-178**	**0.001**	2005-2017	13	2	0.951
FI	JAI	SI	Hudson	Hudson	Hudson River YOY 3/8" Seine Survey	**1980-2017**	**35**	**-337**	**0.000**	2005-2017	13	-6	0.760
FI	CPUE	SI	Delaware	Delaware	Lewis Haul Seine Fishery CPUE	**1925-2017**	**93**	**1117**	**0.000**	**2005-2017**	**13**	**40**	**0.017**
FI	JAI	SI	Delaware	Delaware	Non-Tidal Delaware River Juvenile Seine Survey	1980-2017	26	-19	0.692	2005-2017	9	4	0.754
FI	CPUE	SI	Delaware	Delaware	Smithfield Beach Gill Net Survey	**1990-2017**	**28**	**-108**	**0.035**	2005-2017	13	20	0.246
FI	JAI	SI	Delaware	Delaware	Tidal Delaware River Striped Bass Seine Survey	1987-2017	31	39	0.518	2005-2017	13	12	0.502
FI	Run Counts	SI	Delaware	Lehigh	Chain Dam Fishway Count	**1994-2012**	**15**	**-43**	**0.038**	**2005-2012**	**7**	**-15**	**0.035**
FI	Run Counts	SI	Delaware	Lehigh	Easton Dam Fishway Count	1994-2012	19	-7	0.834	2005-2012	8	4	0.711
FI	Run Counts	SI	Delaware	Schuylkill	Fairmount Fishway Count	2004-2017	12	22	0.150	2005-2017	11	15	0.276
FI	CONN	SI	Delaware	Delaware	DE JAI (Conn Method)	1987-2017	31	1	1.000	2005-2017	13	12	0.502
FD	CPUE	SI	Nanticoke	Nanticoke	Nanticoke River Commercial Pound Net CPUE	1996-2017	20	-20	0.538	2005-2017	12	-4	0.837
FI	JAI	SI	Nanticoke	Nanticoke	Nanticoke River Juvenile Haul Seine Survey	1999-2017	19	-4	0.916	**2005-2017**	**13**	**-45**	**0.007**
FI	CPUE	SI	Nanticoke	Nanticoke	Nanticoke River Electrofishing Survey	2002-2017	16	18	0.444	2005-2017	13	18	0.300
FI	CPUE	SI	Upper Chesapeake Bay	Susquehanna	Susquehanna Hook-and-Line Survey	1982-2017	34	101	0.138	2005-2017	12	8	0.631
FI	CPUE	SI	Upper Chesapeake Bay	Upper Chesapeake Bay	Susquehanna River Recreational Creel Survey	2001-2017	14	-23	0.228	2005-2017	10	11	0.371
FD	CPUE	SI	Upper Chesapeake Bay	Upper Chesapeake Bay	Upper Chesapeake Onboard Fishery Monitoring	**1980-2001**	**20**	**116**	**0.000**				
FI	JAI	SI	Upper Chesapeake Bay	Upper Chesapeake Bay	Upper Chesapeake Striped Bass Juvenile Seine Survey	1959-2017	56	211	0.125	2005-2017	13	10	0.583
FI	CPUE	SI	Pautuxent	Patuxent	Patuxent River Restoration Adult Electrofishing Survey	2001-2014	14	-19	0.324	2005-2014	10	15	0.210
FD	CPUE	SI	Potomac	Potomac	Potomac River Commercial Pound Net CPUE	**1999-2017**	**19**	**89**	**0.002**	2005-2017	13	20	0.246
FI	JAI	SI	Potomac	Potomac	Potomac River Striped Bass Juvenile Seine Survey	**1959-2017**	**56**	**533**	**0.000**	2005-2017	13	10	0.583
FI	CPUE	SI	Potomac	Potomac	Potomac River Striped Bass Spawning Stock Survey	**1985-2017**	**26**	**219**	**0.000**	2005-2017	13	28	0.100
FI	CPUE	SI	Rappahannock	Rappahannock	Rappahannock River Boat Electrofishing Survey	1998-2017	16	-12	0.620	2007-2017	10	-11	0.371
FI	CPUE	SI	Rappahannock	Rappahannock	Rappahannock River Adult Gill Net Survey	1998-2017	20	58	0.064	2005-2017	13	16	0.360
FI	CPUE	SI	Rappahannock	Rappahannock	Rappahannock River Adult Gill Net Survey (Weight)	1998-2017	20	48	0.127	2005-2017	13	14	0.428
FI	CPUE	SI	Rappahannock	Rappahannock	Rappahannock River Juvenile Seine Survey	**1980-2017**	**38**	**279**	**0.000**	**2005-2017**	**13**	**40**	**0.017**
FI	CPUE	SI	York	Mattaponi	York River Juvenile Seine Survey (Mattaponi River Stations)	1980-2017	38	-100	0.213	2005-2017	13	5	0.807
FI	CPUE	SI	York	Pamunkey	York River Juvenile Seine Survey (Pamunkey River Stations)	1980-2017	38	-36	0.658	**2005-2017**	**13**	**33**	**0.048**
FI	CPUE	SI	York	York	York River Juvenile Seine Survey (York River Stations)	1980-2017	38	-127	0.113	2005-2017	13	9	0.625
FI	CPUE	SI	York	York	York River Adult Gill Net Survey	**1998-2017**	**20**	**-96**	**0.002**	2005-2017	13	-24	0.161
FI	CPUE	SI	York	York	York River Adult Gill Net Survey (Weight)	**1998-2017**	**20**	**-106**	**0.001**	2005-2017	13	-26	0.127
FI	Run Counts	SI	James	James	Bosher's Dam Fishway Count	1999-2017	19	-43	0.142	2005-2017	13	-4	0.855
FI	CPUE	SI	James	James	James River Boat Electrofishing Survey	2000-2017	18	27	0.325	2005-2017	13	10	0.583
FI	CPUE	SI	James	James	James River Adult Gill Net Survey (VIMS)	1998-2017	20	-18	0.581	2005-2017	13	-4	0.855
FI	CPUE	SI	James	James	James River Adult Gill Net Survey (Weight)	1998-2017	20	-22	0.496	2005-2017	13	-10	0.583
FI	CPUE	SI	James	James	James River Juvenile Seine Survey	1980-2017	38	125	0.095	2005-2017	13	-1	1.000

Table 21 Continued

						Time Series				2005+			
Data Type	Category	Region	System	Waterbody	Program	Years	n	S	p-value	Years	n	S	p-value
FD	CPUE	SI	Albemarle Sound	Albemarle Sound	Albemarle Sound Commercial CPUE	**1994-2017**	**24**	**156**	**0.000**	**2005-2017**	**13**	**34**	**0.044**
FI	JAI	SI	Albemarle Sound	Albemarle Sound	Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey	**1996-2017**	**22**	**74**	**0.039**	**2005-2017**	**13**	**35**	**0.038**
FI	CPUE	SI	Albemarle Sound	Albemarle Sound	Albemarle Sound Independent Gill Net Survey	**1993-2017**	**25**	**128**	**0.003**	2005-2017	13	10	0.583
FI	CPUE	SI	Albemarle Sound	Roanoke	Roanoke River Adult Spawning Area Electrofishing Survey	2001-2017	17	-6	0.837	2005-2017	13	-22	0.200
FD	CPUE	SI	Tar-Pamlico	Tar-Pamlico	Tar-Pamlico Commercial CPUE	1994-2017	24	-8	0.862	2005-2017	13	-24	0.161
FD	CPUE	SI	Neuse	Neuse	Neuse River Commercial CPUE	1994-2017	24	18	0.673	2005-2017	13	-16	0.360
FI	CPUE	SI	Neuse	Neuse	Neuse River Adult Spawning Area Electrofishing Survey	2000-2017	18	27	0.325	**2005-2017**	**13**	**40**	**0.017**
FD	CPUE	SE	Cape Fear	Cape Fear	Cape Fear River Commercial CPUE	**1994-2017**	**24**	**128**	**0.002**	**2005-2017**	**13**	**44**	**0.009**
FI	CPUE	SE	Cape Fear	Cape Fear	Cape Fear River Adult Spawning Area Electrofishing Survey	2001-2017	17	2	0.967	**2005-2017**	**13**	**40**	**0.017**
FD	CPUE	SE	Winyah Bay	Black	Black River Commercial CPUE	2001-2017	17	46	0.064	**2005-2017**	**13**	**38**	**0.024**
FD	CPUE	SE	Winyah Bay	Great Pee Dee	Great Pee Dee River Commercial CPUE	2001-2017	17	-30	0.232	2005-2017	13	0	1.000
FD	CPUE	SE	Winyah Bay	Waccamaw	Waccamaw River Commercial CPUE	2001-2016	15	-33	0.113	2005-2016	11	7	0.640
FD	CPUE	SE	Santee-Cooper	Santee	Santee River Commercial CPUE	2001-2017	17	-30	0.232	2005-2017	13	-4	0.855
FI	CPUE	SE	Santee-Cooper	Cooper	Cooper River Recreational Creel Survey	**2000-2016**	**17**	**76**	**0.002**	**2005-2016**	**12**	**32**	**0.034**
FI	CPUE	SE	Santee-Cooper	Santee	Santee River Adult Gill Net Survey	2008-2017	10	-7	0.592	2008-2017	10	-7	0.592
FD	CPUE	SE	ACE Basin	Edisto	Edisto River Commercial CPUE	2001-2017	17	28	0.266	2005-2017	13	18	0.300
FD	CPUE	SE	Savannah	Savannah	Savannah River Commercial CPUE (SC DNR)	2001-2017	17	44	0.077	2005-2017	13	24	0.161
FD	CPUE	SE	Savannah	Savannah	Savannah River Commercial CPUE (GA DNR)	2001-2017	17	-48	0.053	2005-2017	13	-30	0.077
FD	CPUE	SE	Altamaha	Altamaha	Altamaha River Commercial CPUE	**2002-2017**	**16**	**46**	**0.043**	2005-2017	13	6	0.760
FI	CPUE	SE	Altamaha	Altamaha	Altamaha River Tagging Survey	**1982-2017**	**36**	**295**	**0.000**	**2005-2017**	**13**	**41**	**0.014**
FI	JAI	SE	St Johns	St. Johns	St. Johns River Juvenile Pushnet Survey	2007-2017	11	23	0.087	2007-2017	11	23	0.087
FI	CPUE	SE	St Johns	St. Johns	St. Johns River Spawning Ground Electrofishing Survey	2003-2017	15	35	0.092	**2005-2017**	**13**	**40**	**0.017**
FI	CPUE	MS	Mixed Stock	Long Island Sound	Long Island Sound Trawl Survey (Spring)	1984-2017	34	-117	0.085	2005-2017	13	-2	0.951
FI	CPUE	MS	Mixed Stock	Long Island Sound	Long Island Sound Trawl Survey (Fall)	1984-2017	33	-108	0.097	2005-2017	12	20	0.193
FD	CPUE	MS	Mixed Stock	Delaware Bay	Delaware Bay Commercial Logbooks (NJ DFW)	**2000-2017**	**18**	**-107**	**0.000**	**2005-2017**	**13**	**-50**	**0.003**
FD	CPUE	MS	Mixed Stock	Delaware Bay	Delaware Bay Commercial Logbooks (DE DFW)	**1989-2017**	**29**	**-160**	**0.003**	2005-2017	13	-4	0.854
FI	CPUE	MS	Mixed Stock	Delaware Bay	Delaware Bay 30' Trawl Survey	1966-2017	34	23	0.744	2005-2017	13	-24	0.161
FI	CPUE	MS	Mixed Stock	Atlantic Ocean	Maine/New Hampshire Trawl Survey (Spring)	2001-2017	17	36	0.149	2005-2017	13	6	0.760
FI	CPUE	MS	Mixed Stock	Atlantic Ocean	Maine/New Hampshire Trawl Survey (Fall)	2000-2017	18	-15	0.596	2005-2017	13	-14	0.428
FI	CPUE	MS	Mixed Stock	Atlantic Ocean	Northeast Fisheries Science Center Bottom Trawl Survey (R/V Albatross; Spring)	1979-2008	30	91	0.108	2005-2008	4	2	0.734
FI	CPUE	MS	Mixed Stock	Atlantic Ocean	Northeast Fisheries Science Center Bottom Trawl Survey (R/V Albatross; Spring)	1979-2008	30	14	0.817	2005-2008	4	-2	0.734
FI	CPUE	MS	Mixed Stock	Atlantic Ocean	Northeast Fisheries Science Center Bottom Trawl Survey (R/V Albatross; Fall)	1979-2008	30	47	0.412	2005-2008	4	4	0.308
FI	CPUE	MS	Mixed Stock	Atlantic Ocean	Northeast Fisheries Science Center Bottom Trawl Survey (R/V Albatross; Fall)	1979-2008	30	40	0.486	2005-2008	4	2	0.734
FI	CPUE	MS	Mixed Stock	Atlantic Ocean	Northeast Fisheries Science Center Bottom Trawl Survey (R/V Bigelow; Spring)	2009-2017	9	-6	0.602	2009-2017	9	-6	0.602
FI	CPUE	MS	Mixed Stock	Atlantic Ocean	Northeast Fisheries Science Center Bottom Trawl Survey (R/V Bigelow; Spring)	2009-2017	9	6	0.602	2009-2017	9	6	0.602
FI	CPUE	MS	Mixed Stock	Atlantic Ocean	Northeast Fisheries Science Center Bottom Trawl Survey (R/V Bigelow; Fall)	2009-2017	8	14	0.108	2009-2017	8	14	0.108
FI	CPUE	MS	Mixed Stock	Atlantic Ocean	Northeast Fisheries Science Center Bottom Trawl Survey (R/V Bigelow; Fall)	2009-2017	8	16	0.063	2009-2017	8	16	0.063
FI	CPUE	MS	Mixed Stock	Atlantic Ocean	Rhode Island Coastal Trawl Survey (April Segment)	**1979-2017**	**34**	**223**	**0.001**	**2005-2017**	**13**	**38**	**0.024**
FI	CPUE	MS	Mixed Stock	Atlantic Ocean	Rhode Island Coastal Trawl Survey (Monthly Segment)	**1990-2017**	**28**	**150**	**0.003**	**2005-2017**	**13**	**36**	**0.033**
FD	CPUE	MS	Mixed Stock	Atlantic Ocean	Atlantic Ocean Commercial Logbooks (NJ DFW)	**2000-2013**	**13**	**-46**	**0.006**	**2005-2013**	**8**	**-20**	**0.019**
FI	CPUE	MS	Mixed Stock	Atlantic Ocean	New Jersey Ocean Trawl Survey	1989-2017	29	14	0.807	2005-2017	13	14	0.428
FI	CPUE	MS	Mixed Stock	Atlantic Ocean	Northeast Area Monitoring and Assessment Program Trawl Survey	**2007-2017**	**9**	**24**	**0.016**	**2007-2017**	**9**	**24**	**0.016**
FD	CPUE	MS	Mixed Stock	Atlantic Ocean	Atlantic Ocean Commercial CPUE (NC DMF)	1994-2004	11	3	0.876				

Table 22. Results of the Mann-Kendall test for trends in mean length by waterbody and sex. n = sample size, S is the Mann-Kendall test statistic, and p-value is the two-tailed probability. Significant results are shaded. The sign of the test statistic indicates the direction of the trend.

					Male			Female		
Region	System	Waterbody	Program	Years	n	S	p-value	n	S	p-value
Northern Iteroparous	Connecticut	Connecticut River	Connecticut River Commercial Fishery Monitoring	1995-2012	13	-8	0.669	15	11	0.621
		Connecticut River	Holyoke Dam Fish Lift Counts	1997-2017	18	-37	0.173	19	-33	0.263
	Merrimack	Merrimack River	Essex Dam Fish Lift Counts	2005-2017	**13**	**-52**	**0.002**	**13**	**-60**	**0.000**
Southern Iteroparous	Albemarle Sound	Albemarle Sound	Albemarle Sound Commercial Fishery Moinitoring	1970-2017	**38**	**-259**	**0.001**	**41**	**-406**	**0.000**
		Albemarle Sound	Albemarle Sound Independent Gill Net Survey	2004-2017	12	14	0.373	12	-6	0.732
		Roanoke River	Roanoke River Adult Spawning Area Electrofishing Survey	2000-2017	18	-21	0.449	16	-36	0.115
	Delaware	Delaware River	Smithfield Beach Gill Net Survey	1996-2017	22	-45	0.215	**22**	**-73**	**0.042**
		Lehigh River	Lehigh River Electrofishing Survey	1996-2017	13	-18	0.300			
	Hudson	Hudson River	Hudson River Commercial Gill Net Fishery Monitoring	1980-2009	25	-58	0.183	**30**	**-179**	**0.001**
		Hudson River	Hudson River Spawning Stock Haul Seine and Electrofishing Surveys	1985-2017	32	-104	0.095	**32**	**-192**	**0.002**
	James	James River	James River Boat Electrofishing Survey	1995-2017	12	-16	0.304	10	3	0.858
		James River	James River Adult Gill Net Survey (VIMS)	1998-2017				19	17	0.576
	Nanticoke	Nanticoke River	Nanticoke River Electrofishing Survey	2002-2017	15	19	0.373	12	2	0.945
		Nanticoke River	Nanticoke River Commercial Pound Net Fishery Monitoring	1988-2017	23	-15	0.712	17	-10	0.711
	Neuse	Neuse River	Neuse River Commercial Fishery Moinitoring	1977-2017	**17**	**-54**	**0.029**	**29**	**-160**	**0.003**
	Potomac	Potomac River	Potomac River Shad Egg Collections (VDGIF)	2004-2017	14	-1	1.000	**14**	**-43**	**0.021**
		Potomac River	Potomac River Striped Bass Spawning Stock Survey	2002-2017	13	-2	0.951	15	-21	0.322
	Rappahannock	Rappahannock River	Rappahannock River Adult Gill Net Survey	1998-2017				20	4	0.922
	Tar-Pamlico	Tar River	Tar River Adult Spawning Area Electrofishing Survey	2000-2017	18	11	0.705	18	25	0.363
		Tar-Pamlico River	Tar-Pamlico Commercial Fishery Moinitoring	1975-2017	10	-11	0.371	**29**	**-162**	**0.003**
	Upper Chesapeake Bay	Susquehanna River	Conowingo Dam Fish Lift Count	2000-2017	**18**	**-65**	**0.015**	**18**	**-71**	**0.008**
		Susquehanna River	Susquehanna Hook-and-Line Survey	1981-2017	35	115	0.105	**34**	**-161**	**0.018**
		Upper Chesapeake Bay	Upper Chesapeake Onboard Fishery Monitoring	1980-2001	**22**	**-107**	**0.003**	**22**	**-109**	**0.002**
	York	York River	York River Adult Gill Net Survey	1998-2017				20	14	0.673
Semelparous	Cape Fear	Cape Fear River	Cape Fear River Commercial Fishery Moinitoring	1983-2017	10	-13	0.283	**20**	**-74**	**0.018**
		Cape Fear River	Cape Fear River Adult Spawning Area Electrofishing Survey	2001-2017	17	8	0.773	17	-18	0.484
	Santee-Cooper	Cooper River	Cooper River Recreational Creel Survey	2000-2017	18	49	0.069	**18**	**61**	**0.023**
		Santee River	Santee River Commercial Fishery Monitoring	1979-2017				**17**	**-58**	**0.019**
		Santee River	Santee River Recreational Fishery Monitoring	2006-2017	11	17	0.213	11	23	0.087
		Santee River	St. Stephen Locks Passage Count	2000-2017	15	-25	0.235	11	9	0.533
	St Johns	St. Johns River	St. Johns River Spawning Ground Electrofishing Survey	2003-2017	**15**	**71**	**0.001**	**15**	**73**	**0.000**
	Winyah Bay	Waccamaw River	Waccamaw River Commercial Fishery Monitoring	1979-2017				**14**	**-57**	**0.002**

Table 23. Results of the Mann-Kendall test for trends in mean length-at-age over time for both sexes using scales. n = sample size, S is the Mann-Kendall test statistic, and p-value is the two-tailed probability. Significant results are shaded. The sign of the test statistic indicates the direction of the trend.

					Female				Male			
Region	System	Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Northern Iteroparous	Connecticut	Connecticut River	Connecticut River Commercial Fishery Monitoring	3					1996-2011	6	8	0.181
				4	1995-2012	15	14	0.519	1995-2011	13	-4	0.855
				5	1995-2012	15	5	0.843	1995-2011	13	-8	0.669
				6	1995-2012	15	5	0.843	1995-2011	12	-12	0.449
				7	1995-2012	6	-7	0.260				
			Holyoke Dam Fish Lift Counts	3	2011-2017	5	0	1.000	2000-2017	18	32	0.240
				4	2000-2017	17	12	0.650	2000-2017	18	-13	0.649
				5	2000-2017	18	-37	0.173	2000-2017	18	-33	0.225
				6	2000-2017	18	-71	0.008	2000-2017	16	-58	0.010
				7	2002-2017	7	-9	0.230	2007-2017	6	3	0.707
Southern Iteroparous	Albemarle Sound	Albemarle Sound	Albemarle Sound Commercial Fishery Moinitoring	3	1982-2006	5	-4	0.462	1972-2014	18	-31	0.256
				4	1972-2014	29	-115	0.032	1972-2014	36	-332	0.000
				5	1972-2017	40	-470	0.000	1972-2014	36	-254	0.001
				6	1970-2017	41	-484	0.000	1972-2014	35	-211	0.003
				7	1970-2017	41	-438	0.000	1972-2014	33	-213	0.001
				8	1970-2017	35	-193	0.006	1972-2014	19	-29	0.327
				9	1970-2017	17	-6	0.837	1979-2014	3	-3	1.000
			Albemarle Sound Independent Gill Net Survey	3	2004-2017	7	-13	0.072	2004-2017	10	-1	1.000
				4	2004-2017	12	-35	0.019	2004-2017	12	-32	0.034
				5	2004-2017	12	-24	0.115	2004-2017	12	-16	0.304
				6	2004-2017	12	-20	0.193	2007-2017	10	17	0.152
				7	2004-2017	12	-30	0.047	2004-2017	10	-1	1.000
				8	2004-2017	10	-29	0.012				
		Roanoke River	Roanoke River Adult Spawning Area Electrofishing Survey	3					2002-2010	9	6	0.602
				4					2000-2010	11	19	0.161
				5					2000-2010	11	17	0.213
				6					2000-2010	10	18	0.127
				7					2000-2004	5	10	0.027
				8					2000-2002	3	3	1.000
	Delaware	Delaware River	Smithfield Beach Gill Net Survey	3	1998-2006	3	-1	1.000	1997-2015	10	1	1.000
				4	1996-2017	21	-38	0.264	1996-2016	20	-84	0.007
				5	1996-2017	21	-100	0.003	1996-2016	20	-50	0.112
				6	1996-2017	21	-116	0.001	1996-2016	20	-74	0.018
				7	1997-2017	20	-86	0.006	2000-2016	11	-28	0.035
				8	2005-2017	9	2	0.917				
				9	2009-2017	4	6	0.089				
		Lehigh River	Lehigh River Electrofishing Survey	3					1999-2017	10	-17	0.152
				4					1999-2017	13	-34	0.044
				5					1999-2017	13	-18	0.300
				6					2000-2017	10	-5	0.721
				7					2012-2014	3	3	1.000
	Hudson	Hudson River	Hudson River Commercial Gill Net Fishery Monitoring	3					1982-1992	3	1	1.000
				4	1980-1995	15	15	0.488	1980-1995	12	18	0.244
				5	1980-1995	16	-26	0.260	1980-1995	13	18	0.300
				6	1980-1995	16	-30	0.192	1980-1995	13	0	1.000
				7	1980-1995	16	-20	0.392	1980-1995	13	-4	0.855
				8	1980-1995	16	-26	0.260	1980-1995	13	-2	0.951
				9	1980-1995	16	18	0.444	1981-1995	11	9	0.533
				10	1981-1995	13	26	0.127	1982-1989	8	20	0.019
				11	1982-1991	8	22	0.009	1983-1987	4	0	1.000
				12	1984-1990	5	2	0.806				
			Hudson River Spawning Stock Haul Seine and Electrofishing Surveys	3	1985-2016	6	-3	0.707	1985-2017	19	28	0.345
				4	1985-2017	21	-110	0.001	1985-2017	21	-54	0.110
				5	1985-2017	22	-115	0.001	1985-2017	21	-60	0.075
				6	1985-2017	22	-103	0.004	1985-2017	21	-66	0.050
				7	1985-2017	22	-125	0.000	1985-2017	21	-94	0.005
				8	1985-2017	21	-114	0.001	1985-2017	15	-59	0.004
				9	1985-2014	17	-64	0.009	1985-2014	7	-11	0.133
				10	1985-2014	10	-11	0.371	1985-1997	5	-8	0.086
				11	1985-1989	5	-2	0.806				

Table 23 Continued

				Female					Male			
Region	System	Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Southern Iteroparous	James	James River	James River Adult Gill Net Survey (VIMS)	3	2002-2011	6	1	1.000				
				4	2002-2015	14	5	0.827				
				5	2002-2017	15	-13	0.553				
				6	2002-2017	15	-15	0.488				
				7	2002-2017	15	-15	0.488				
				8	2002-2017	13	-40	0.017				
				9	2003-2015	8	-6	0.536				
				10	2002-2008	4	0	1.000				
	Nanticoke	Nanticoke River	Nanticoke River Electrofishing Survey	3	2004-2013	4	-2	0.734	2003-2017	15	-1	1.000
				4	2004-2017	9	-12	0.251	2003-2017	15	-1	1.000
				5	2004-2017	11	-17	0.213	2003-2017	15	5	0.843
				6	2004-2017	11	-5	0.755	2003-2017	15	15	0.488
				7	2005-2017	10	9	0.474	2003-2017	14	5	0.827
				8	2005-2017	7	1	1.000	2005-2014	5	0	1.000
				9	2007-2013	3	-3	1.000				
			Nanticoke River Commercial Pound Net Fishery Monitoring	2					1992-1995	4	2	0.734
				3	1988-1997	7	-7	0.368	1988-2016	19	11	0.726
				4	1988-2012	14	-7	0.743	1988-2016	20	-25	0.436
				5	1988-2012	14	-7	0.743	1988-2016	20	-26	0.417
				6	1988-2012	14	-5	0.827	1988-2016	20	-38	0.230
				7	1988-2012	14	-27	0.155	1988-2016	12	-26	0.086
				8	1988-2003	10	-8	0.530	1989-2016	6	-8	0.181
	Neuse	Neuse River	Neuse River Commercial Fishery Moinitoring	3					1977-2006	5	4	0.462
				4	1977-2014	18	-43	0.112	1977-2006	10	-9	0.474
				5	1977-2017	27	-167	0.001	1977-2006	10	-5	0.721
				6	1977-2017	27	-211	0.000	1977-2003	9	8	0.466
				7	1977-2017	25	-165	0.000	1977-2003	4	-4	0.308
				8	1988-2017	16	-40	0.079				
	Potomac	Potomac River	Potomac River Striped Bass Spawning Stock Survey	3	2007-2015	3	1	1.000	2003-2017	7	14	0.048
				4	2002-2017	11	-3	0.876	2003-2017	11	-5	0.755
				5	2002-2017	14	-35	0.063	2003-2017	12	-28	0.064
				6	2002-2017	14	-15	0.443	2003-2017	12	-14	0.373
				7	2002-2017	14	-17	0.381	2003-2016	9	-8	0.466
				8	2002-2016	10	-26	0.025	2003-2013	3	-1	1.000
				9	2003-2007	4	2	0.734				
	Rappahannock	Rappahannock River	Rappahannock River Adult Gill Net Survey	3	2002-2012	7	6	0.448				
				4	2002-2017	15	27	0.198				
				5	2002-2017	16	0	1.000				
				6	2002-2017	16	-28	0.224				
				7	2002-2017	16	-34	0.137				
				8	2002-2017	14	-29	0.125				
				9	2002-2014	9	-16	0.118				
				10	2002-2013	7	1	1.000				
	Tar-Pamlico	Tar River	Tar River Adult Spawning Area Electrofishing Survey	2					2001-2008	4	4	0.308
				3					2000-2010	11	1	1.000
				4	2000-2010	11	3	0.876	2000-2010	11	-1	1.000
				5	2000-2010	11	1	1.000	2000-2010	11	3	0.876
				6	2000-2010	10	-11	0.371	2000-2007	7	3	0.764
				7	2000-2009	6	5	0.452	2004-2007	4	2	0.734
		Tar-Pamlico River	Tar-Pamlico Commercial Fishery Moinitoring	3	2003-2005	3	1	1.000				
				4	1975-2012	17	-12	0.650				
				5	1975-2017	27	-199	0.000				
				6	1975-2017	27	-199	0.000				
				7	1975-2017	27	-173	0.000				
				8	2002-2017	14	-7	0.742				
				9	2008-2013	3	-3	1.000				

Table 23 Continued

Region	System	Waterbody	Program	Female					Male			
				Age	Years	n	S	p-value	Years	n	S	p-value
Southern Iteroparous	Upper Chesapeake Bay	Susquehanna River	Conowingo Dam Fish Lift Count	3	2000-2014	5	-6	0.221	2000-2017	17	-62	0.012
				4	2000-2017	17	-82	0.001	2000-2017	18	-91	0.001
				5	2000-2017	18	-77	0.004	2000-2017	18	-83	0.002
				6	2000-2017	18	-71	0.008	2000-2017	17	-58	0.019
				7	2000-2017	18	-67	0.012	2002-2016	7	-8	0.288
				8	2002-2016	7	-5	0.548				
				9	2003-2010	3	3	1.000				
			Susquehanna Hook-and-Line Survey	2					1987-1999	5	4	0.462
				3	1986-2017	13	7	0.714	1982-2017	33	178	0.006
				4	1984-2017	34	95	0.163	1982-2017	35	-3	0.977
				5	1984-2017	34	-187	0.006	1982-2017	35	-269	0.000
				6	1984-2017	34	-322	0.000	1984-2017	32	-214	0.001
				7	1984-2016	29	-180	0.001	1991-2016	15	-49	0.018
				8	1992-2015	14	-39	0.037	2005-2013	3	-1	1.000
				9	1998-2014	9	-26	0.009	1999-2013	3	-1	1.000
		Upper Chesapeake Bay	Upper Chesapeake Onboard Fishery Monitoring	2					1981-1991	4	-5	0.149
				3	1985-2001	6	-3	0.697	1980-2001	19	-66	0.023
				4	1980-2001	20	-78	0.012	1980-2001	21	-86	0.010
				5	1980-2001	20	-72	0.021	1980-2001	21	-110	0.001
				6	1980-2001	20	-90	0.004	1980-2001	20	-42	0.183
				7	1980-2001	16	-48	0.034	1990-2001	10	-8	0.530
				8	1991-2001	8	-8	0.386				
	York	York River	York River Adult Gill Net Survey	3	1998-2007	9	11	0.295				
				4	1998-2015	18	9	0.762				
				5	1998-2017	20	22	0.496				
				6	1998-2017	20	-30	0.347				
				7	1998-2017	20	-20	0.538				
				8	1998-2017	19	-63	0.030				
				9	1998-2016	16	-50	0.027				
				10	1998-2014	13	-11	0.541				
				11	2006-2008	3	-1	1.000				
Semelparous	Cape Fear	Cape Fear River	Cape Fear River Commercial Fishery Moinitoring	3	2004-2008	4	-4	0.308				
				4	1984-2016	18	-38	0.161				
				5	1984-2017	20	-104	0.001				
				6	1984-2017	20	-112	0.000				
				7	1984-2017	17	-66	0.007				
				8	2003-2017	15	-37	0.075				
			Cape Fear River Adult Spawning Area Electrofishing Survey	3					2001-2010	10	-7	0.592
				4					2001-2010	10	3	0.858
				5					2001-2010	10	3	0.858
				6					2001-2009	8	6	0.536
				7					2001-2005	4	6	0.089
	Santee-Cooper	Santee River	Santee River Commercial Fishery Monitoring	3	2001-2017	9	8	0.466				
				4	1979-2017	16	36	0.115				
				5	1979-2017	16	-12	0.620				
				6	1979-1985	5	0	1.000				
				7	1981-1985	3	3	1.000				
	Winyah Bay	Waccamaw River	Waccamaw River Commercial Fishery Monitoring	3	2003-2014	6	1	1.000				
				4	1979-2014	14	15	0.443				
				5	1979-2014	13	-28	0.100				
				6	1979-1985	7	3	0.764				
				7	1982-1985	4	2	0.734				

Table 24. Results of the Mann-Kendall test for trends in mean length-at-age over time for both sexes using otoliths. n = sample size, S is the Mann-Kendall test statistic, and p-value is the two-tailed probability. Significant results are shaded. The sign of the test statistic indicates the direction of the trend.

					Female				Male			
Region	System	Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Northern Iteroparous	Merrimack	Merrimack River	Essex Dam Fish Lift Counts	3					2008-2017	7	-5	0.548
				4	2008-2017	9	-2	0.917	2008-2017	10	-17	0.152
				5	2008-2017	10	-11	0.371	2008-2017	10	-13	0.283
				6	2008-2017	10	-13	0.283	2008-2017	10	-15	0.210
				7	2008-2017	10	-21	0.074	2008-2017	10	-9	0.474
				8	2009-2016	7	-4	0.649	2008-2016	8	-14	0.108
				9	2008-2014	6	-1	1.000	2009-2014	4	-2	0.734
				10					2010-2014	4	2	0.734
Southern Iteroparous	Delaware	Delaware River	Smithfield Beach Gill Net Survey	3	1996-2016	8	2	0.902	1997-2016	11	-11	0.436
				4	1996-2017	22	-15	0.693	**1996-2017**	**22**	**-103**	**0.004**
				5	**1996-2017**	**22**	**-83**	**0.021**	1996-2017	22	-43	0.236
				6	**1996-2017**	**22**	**-91**	**0.011**	1996-2017	22	-45	0.215
				7	**1996-2017**	**22**	**-93**	**0.009**	1996-2017	18	-1	1.000
				8	1996-2017	19	-19	0.529	2000-2015	8	-14	0.108
				9	2002-2016	6	1	1.000				
		Lehigh River	Lehigh River Electrofishing Survey	3					1999-2017	8	12	0.174
				4					1999-2017	13	-8	0.669
				5					1999-2017	13	-8	0.669
				6					1999-2017	12	-16	0.304
				7					2004-2015	5	-2	0.806
	Upper Chesapeake Bay	Susquehanna River	Conowingo Dam Fish Lift Count	3	2000-2016	5	-1	1.000	**2000-2017**	**16**	**-66**	**0.003**
				4	**2000-2017**	**17**	**-70**	**0.004**	**2000-2017**	**18**	**-85**	**0.001**
				5	**2000-2017**	**18**	**-65**	**0.015**	**2000-2017**	**18**	**-53**	**0.049**
				6	**2000-2017**	**18**	**-75**	**0.005**	**2000-2017**	**18**	**-63**	**0.019**
				7	**2000-2017**	**18**	**-57**	**0.034**	2001-2016	9	8	0.466
				8	2002-2016	10	-11	0.371	2003-2005	3	1	1.000

Table 25. Results of the power analysis by survey for linear and exponential trends in American shad abundance indices over a ten-year period. Power was detected as the probability of detecting a 50% change following the methods of Gerrodette (1987). Method refers to whether the index represents a nominal (N) or standardized (S) index of relative abundance.

								Linear Trend		Exponential Trend	
System	**Waterbody**	**Survey**	**Years**	**Life Stage**	**Method**	**SFMP**	**PSE**	**-50%**	**+50%**	**-50%**	**+50%**
St Johns	St. Johns River	St. Johns River Juvenile Pushnet Survey	2007-2017	YOY	S	Yes	0.167	0.97	0.70	0.99	0.73
		St. Johns River Spawning Ground Electrofishing Survey	2003-2017	Adult	S	Yes	0.174	0.96	0.68	0.98	0.70
Altamaha	Altamaha River	Altamaha River Commercial CPUE	2002-2017	Adult	N	No	0.058	1.00	1.00	1.00	1.00
Savannah	Savannah River	Savannah River Commercial CPUE (GA DNR)	2001-2017	Adult	N	Yes	0.105	1.00	0.97	1.00	0.97
		Savannah River Commercial CPUE (SC DNR)	2001-2017	Adult	N	Yes	0.600	0.26	0.15	0.31	0.17
ACE Basin	Edisto River	Edisto River Commercial CPUE	2001-2017	Adult	N	Yes	1.628	0.10	0.08	0.14	0.09
Santee-Cooper	Cooper River	Cooper River Recreational Creel Survey	2000-2017	Adult	N	Yes	0.062	1.00	1.00	1.00	1.00
	Santee River	Santee River Adult Gill Net Survey	2008-2017	Adult	N	Yes	0.214	0.88	0.53	0.91	0.55
		Santee River Commercial CPUE	2001-2017	Adult	N	Yes	1.680	0.10	0.08	0.14	0.09
Winyah Bay	Waccamaw River	Waccamaw River Commercial CPUE	2001-2017	Adult	N	Yes	0.808	0.18	0.12	0.23	0.13
	Black River	Black River Commercial CPUE	2001-2017	Adult	N	Yes	0.986	0.15	0.10	0.19	0.12
	Great Pee Dee River	Great Pee Dee River Commercial CPUE	2001-2017	Adult	N	Yes	1.631	0.10	0.08	0.14	0.09
Cape Fear	Cape Fear River	Cape Fear River Adult Spawning Area Electrofishing Survey	2001-2017	Adult	S	No	0.223	0.85	0.50	0.89	0.52
Neuse	Neuse River	Neuse River Adult Spawning Area Electrofishing Survey	2000-2017	Adult	S	Yes	0.156	0.99	0.76	0.99	0.78
Albemarle Sound	Albemarle Sound	Albemarle Sound Independent Gill Net Survey	1993-2017	Adult	N	Yes	0.112	1.00	0.95	1.00	0.96
	Roanoke River	Roanoke River Adult Spawning Area Electrofishing Survey	2001-2017	Adult	S	Yes	0.167	0.97	0.71	0.99	0.73
	Albemarle Sound	Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey	1996-2017	YOY	S	No	0.430	0.40	0.21	0.46	0.23

Table 25 Continued

								Linear Trend		Exponential Trend	
System	**Waterbody**	**Survey**	**Years**	**Life Stage**	**Method**	**SFMP**	**PSE**	**-50%**	**+50%**	**-50%**	**+50%**
James	James River	James River Boat Electrofishing Survey	2000-2017	Adult	S	No	0.167	0.97	0.71	0.99	0.73
		James River Adult Gill Net Survey (VIMS)	1998-2017	Adult	S	No	0.167	0.97	0.70	0.99	0.73
		James River Juvenile Seine Survey	1980-2017	YOY	N	No	4.085	0.07	0.06	0.10	0.08
York	York River	York River Adult Gill Net Survey	1998-2017	Adult	S	No	0.163	0.98	0.72	0.99	0.74
	Mattaponi River	York River Juvenile Seine Survey (Mattaponi River Stations)	1980-2017	YOY	N	No	0.950	0.16	0.10	0.20	0.12
	York River	York River Juvenile Seine Survey (York River Stations)	1994-2017	YOY	N	No	1.632	0.10	0.08	0.14	0.09
	Pamunkey River	York River Juvenile Seine Survey (Pamunkey River Stations)	1980-2017	YOY	N	No	2.625	0.08	0.07	0.12	0.08
Rappahannock	Rappahannock River	Rappahannock River Adult Gill Net Survey	1998-2017	Adult	S	No	0.156	0.99	0.76	0.99	0.78
		Rappahannock River Boat Electrofishing Survey	1998-2017	Adult	S	No	1.223	0.12	0.09	0.17	0.11
		Rappahannock River Juvenile Seine Survey	1980-2017	YOY	N	No	2.030	0.09	0.07	0.13	0.09
Potomac	Potomac River	Potomac River Striped Bass Spawning Stock Survey	1985-2017	Adult	S	No	0.391	0.46	0.24	0.52	0.26
		Potomac River Striped Bass Juvenile Seine Survey	1959-2017	YOY	S	No	0.450	0.38	0.20	0.44	0.22
Patuxent	Patuxent River	Patuxent River Restoration Adult Electrofishing Survey	2001-2017	Adult	S	No	0.258	0.75	0.41	0.81	0.43
Upper Chesapeake Bay	Susquehanna River	Susquehanna Hook-and-Line Survey	1982-2017	Adult	S	No	0.165	0.98	0.71	0.99	0.74
	Upper Chesapeake Bay	Upper Chesapeake Onboard Fishery Monitoring	1980-2001	Adult	S	No	0.247	0.78	0.44	0.83	0.46
		Susquehanna River Recreational Creel Survey	2001-2017	Adult	N	No	0.338	0.55	0.29	0.62	0.31
		Upper Chesapeake Striped Bass Juvenile Seine Survey	1959-2017	YOY	S	No	0.590	0.27	0.15	0.32	0.17

Table 25 Continued

								Linear Trend		Exponential Trend	
System	**Waterbody**	**Survey**	**Years**	**Life Stage**	**Method**	**SFMP**	**PSE**	**-50%**	**+50%**	**-50%**	**+50%**
Nanticoke	Nanticoke River	Nanticoke River Commercial Pound Net CPUE	1996-2017	Adult	S	No	0.306	0.63	0.33	0.69	0.35
Delaware	Delaware River	Smithfield Beach Gill Net Survey	1990-2017	Adult	S	Yes	0.136	1.00	0.85	1.00	0.87
		Tidal Delaware River Striped Bass Seine Survey	1987-2017	YOY	S	Yes	0.170	0.97	0.69	0.98	0.71
		Non-Tidal Delaware River Juvenile Seine Survey	1980-2017	YOY	S	Yes	0.230	0.83	0.48	0.88	0.50
Hudson	Hudson River	Hudson River YOY 3/8" Seine Survey	1980-2017	YOY	S	No	0.090	1.00	0.99	1.00	0.99
		Hudson River Utility Egg Survey	1974-2015	Egg	N	No	0.240	0.80	0.45	0.85	0.48
		Hudson River Commercial Gill Net CPUE	1980-2001	Adult	S	No	0.258	0.75	0.41	0.81	0.43
		Hudson River Spawning Stock Haul Seine Survey	1988-2017	Adult	S	No	0.370	0.49	0.26	0.56	0.27
		Hudson River Utility Post-Yolk Sac Larvae Survey	1974-2015	Post Yolk-Sac Larval	N	No	0.397	0.45	0.24	0.51	0.25
Connecticut	Connecticut River	Connecticut River Commercial CPUE	1995-2017	Adult	S	No	0.061	1.00	1.00	1.00	1.00
		Connecticut River Juvenile Shad Seine Survey	1978-2017	YOY	N	Yes	0.211	0.88	0.53	0.92	0.56
Merrymeeting Bay	Merrymeeting Bay	Merrymeeting Bay Seine Survey	1979-2017	YOY	N	No	0.189	0.94	0.62	0.96	0.64
Mixed-Stock Surveys	Delaware Bay	Delaware Bay Commercial Logbooks (NJ DFW)	2000-2017	Adult	N	No	0.113	1.00	0.94	1.00	0.95
		Delaware Bay 30' Trawl Survey	1966-2017		S	No	0.601	0.26	0.15	0.31	0.17
	Long Island Sound	Long Island Sound Trawl Survey (Spring)	1984-2017		N	No	0.224	0.85	0.49	0.89	0.52
		Long Island Sound Trawl Survey (Fall)	1984-2017		N	No	0.280	0.69	0.37	0.75	0.39

Table 25 Continued

								Linear Trend		Exponential Trend	
System	**Waterbody**	**Survey**	**Years**	**Life Stage**	**Method**	**SFMP**	**PSE**	**-50%**	**+50%**	**-50%**	**+50%**
Mixed-Stock Surveys	Atlantic Ocean	NEFSC Bottom Trawl Survey (R/V Bigelow; Fall) - Number	2009-2017		N	No	0.215	0.87	0.52	0.91	0.55
		NEFSC Bottom Trawl Survey (R/V Bigelow; Fall) - Weight	2009-2017		N	No	0.243	0.80	0.45	0.85	0.47
		Atlantic Ocean Commercial Logbooks (NJ DFW)	2000-2013	Adult	N	No	0.253	0.77	0.42	0.82	0.44
		NEFSC Bottom Trawl Survey (R/V Bigelow; Spring) - Number	2009-2017		N	No	0.256	0.76	0.42	0.81	0.44
		Rhode Island Coastal Trawl Survey (Monthly Segment)	1990-2017		S	No	0.254	0.77	0.42	0.82	0.44
		NEFSC Bottom Trawl Survey (R/V Bigelow; Spring) - Weight	2009-2017		N	No	0.257	0.76	0.41	0.81	0.43
		Maine/New Hampshire Trawl Survey (Spring)	2001-2017		S	No	0.271	0.72	0.38	0.77	0.41
		NEFSC Bottom Trawl Survey (R/V Albatross; Spring) - Number	1976-2008		N	No	0.275	0.71	0.38	0.76	0.40
		NEFSC Bottom Trawl Survey (R/V Albatross; Spring) - Weight	1976-2008		N	No	0.333	0.56	0.29	0.63	0.31
		NEAMAP Trawl Survey	2007-2017		S	No	0.365	0.50	0.26	0.56	0.28
		NEFSC Bottom Trawl Survey (R/V Albatross; Fall) - Number	1975-2008		N	No	0.402	0.44	0.23	0.50	0.25
		NEFSC Bottom Trawl Survey (R/V Albatross; Fall) - Weight	1975-2008		N	No	0.409	0.43	0.23	0.49	0.24
		New Jersey Ocean Trawl Survey	1989-2017		S	No	0.525	0.31	0.17	0.36	0.19
		Maine/New Hampshire Trawl Survey (Fall)	2000-2017		S	No	0.921	0.16	0.11	0.20	0.12
		Rhode Island Coastal Trawl Survey (April Segment)	1979-2017		S	No	1.443	0.11	0.08	0.15	0.10

Table 26. American shad natural mortality rates used in Thompson-Bell spawning stock biomass per-recruit and egg per-recruit models.

Region	Age invariant Natural mortality*
Northern Iteroparous	0.47
Southern Iteroparous	0.47
Semelparous	0.65
Sensitivity analysis	0.30
	0.50
	0.70

Age	Age variant M**
1	0.51
2	0.37
3	0.29
4	0.25
5	0.23
6	0.21
7	0.20
8	0.20
9	0.19
10	0.19
11	0.19
12	0.19
13	0.19
14	0.19

*Then et al (2015)

**Boudreau and Dickie (1989) and Dickie et al (1987)

Table 27. Regional life history data used as inputs to the Thompson-Bell spawning stock biomass per-recru models.

Age	M			Maturity			Weight at age			Batch F	
	Northern Iteroparous	Southern Iteroparous	Semelparous	Northern Iteroparous	Southern Iteroparous	Semelparous	Northern Iteroparous	Southern Iteroparous	Semelparous	Northern Iteroparous	
1	0.47	0.47	0.65	0%	0%	0%	0.24	0.25	0.12	3623	2
2	0.47	0.47	0.65	0%	0%	0%	0.62	0.67	0.46	13228	1
3	0.47	0.47	0.65	0%	0%	1%	0.95	1.05	0.83	23902	2
4	0.47	0.47	0.65	4%	4%	9%	1.19	1.32	1.11	32553	3
5	0.47	0.47	0.65	69%	27%	33%	1.34	1.51	1.29	38619	4
6	0.47	0.47	0.65	69%	64%	63%	1.44	1.62	1.40	42567	5
7	0.47	0.47	0.65	90%	81%	92%	1.50	1.69	1.46	45033	5
8	0.47	0.47	0.65	100%	90%	100%	1.54	1.73	1.50	46539	5
9	0.47	0.47	0.65	100%	100%	100%	1.56	1.75	1.52	47446	6
10	0.47	0.47	0.65	100%	100%		1.57	1.76		47988	6
11	0.47	0.47	0.65	100%	100%		1.58	1.77		48311	6
12	0.47	0.47	0.65	100%	100%		1.58	1.78		48502	6
13	0.47	0.47	0.65	100%	100%		1.58	1.78		48616	6

* Batch fecundity derived from the following $\log_{10}$ batch fecundity and $\log_{10}$ weight relationships reported in Olney and McBride (2003): Northern iteroparous: $Y = 0.239 + 1.39X$; Southern iteroparous: $Y = -0.54 + 1.64X$; Semelparous: $Y = -1.45 + 1.96X$

Table 28. Results of biological reference point, $Z_{40\%}$ from Thompson-Bell spawning stock biomass per-recruit and egg per-recruit models for regional American shad.

		$Z_{40\%}$	
Region	**M**	**EPR**	**SBPR**
Northern Iteroparous	0.47	0.99	1.00
Southern Iteroparous	0.47	1.04	1.07
Semelparous	0.65	1.52	1.43

Table 29. Results of sensitivity of the Thompson-Bell spawning stock biomass per-recruit and egg per-recruit models to variation in *M* with Southern iteroparous regional inputs held constant.

		$F_{40\%}$		$Z_{40\%}$	
Type of sensitivity analyses	***M***	**EPR**	**SBPR**	**EPR**	**SBPR**
Natural mortality	0.30	0.42	0.43	0.72	0.73
	0.50	0.62	0.65	1.12	1.15
	0.70	0.88	0.93	1.58	1.63
Natural mortality age variant	see Table 26	0.34	0.35		

Table 30. Results of sensitivity of the Thompson-Bell spawning stock biomass per-recruit to model parameters c (proportion of *F* occurring prior to spawning) and d (proportion of *M* occurring prior to spawning) with Southern iteroparous regional inputs (*M*, maturity at age, and weight at age) held constant.

Type of sensitivity analyses	*c*	*d*	$Z_{40\%}$
Model parameters *c* and *d*	1.00	1.00	1.07
	1.00	0.50	1.07
	1.00	0.00	1.07
	0.50	1.00	1.29
	0.50	0.50	1.29
	0.50	0.00	1.29
	0.00	1.00	1.83
	0.00	0.50	1.83
	0.00	0.00	1.83

Table 31. Results of sensitivity of the Thompson-Bell spawning stock biomass per-recruit to variation river-specific inputs (maturity at age and weight at age) with *M* held constant at $M = 0.47$.

Type of sensitivity analyses	River system	$Z_{40\%}$
River specific inputs	Hudson R.	0.93
	Delaware R.	1.09
	Nanticoke R.	0.99
	Upper Chesapeake	1.05
	Potomac R.	1.05
	Rappahannock R.	0.99
	York R.	1.00
	James R.	1.02
	Albemarle Sound	1.06
	Tar-Pamlico	1.09

Table 32. Age composition data sets available for use in total mortality estimation. Recruitment refers to the observed peak-#s-at-age based on aggregated data by sex and structure for a given monitoring program. Shown are the years available for cross-sectional analysis for each survey in the black shaded region, after application of the filtering criteria.

System	Monitoring Program	Structure	Sex	Recruitment	1983 -- 2017
Tar-Pamlico Sound	Tar River Adult Spawning Area Electrofishing Survey	Scale	Female	5	□□□□□□□□□□□□□□□□□■□□□■■■■□■□□□□□□□□
			Male	4	□□□□□□□□□□□□□□□□□■■■□■■■■□□□□□□□□□□
Albemarle Sound	Roanoke River Adult Spawning Area Electrofishing Survey	Scale	Female	5	□□□□□□□□□□□□□□□□□□□■■■■□□□■■□□□□□□□
			Male	4	□□□□□□□□□□□□□□□□□■■■■■■■□■■■□□□□□□□
	Albemarle Sound Commercial Monitoring	Scale	Female	6	□□□□□□□□□□□□□□□□□□■■■□■■■■■■■■■■■■■
	Albemarle Sound Independent Gill Net Survey	Scale	Female	6	□□□□□□□□□□□□□□□□□□□□□■■■■■■■■■■■■■■
			Male	4	□□□□□□□□□□□□□□□□□□□□□■■■■■■■■■■■■■■
James River	James River Adult Gill Net Survey (VIMS)	Scale	Female	5	□□□□□□□□□□□□□□□□□□□■■■■■■■■■■■■■■□■
York River	York River Adult Gill Net Survey	Scale	Female	5	□□□□□□□□□□□□□□□■■■■■■■■■■■■■■■■■■■■
Rappahannock River	Rappahannock River Adult Gill Net Survey	Scale	Female	5	□□□□□□□□□□□□□□□□□□□■■■■■■■■■■■■■■■■
Potomac River	Combined Potomac Broodstock Collections	Otolith	Female	5	□□□□□□□□□□□□□□□□□■□□□□□■■■□■□■■■□■■
		Scale	Female	5	□□□□□□□□□□□□□□□□□■□□□■■■■■□■■■■■■■■
			Male	5	□□□□□□□□□□□□□□□□□□□□□■□□□■□■□■■■■■■
	Potomac River Striped Bass Spawning Stock Survey	Scale	Female	6	□□□□□□□□□□□□□□□□□□□□■■■□□□□□□□■■□■□
			Male	5	□□□□□□□□□□□□□□□□□□□□□□□□□■□□□□■■■■□

Table 32 Continued

System	Monitoring Program	Structure	Sex	Recruitment	1983																																		2017
Upper Chesapeake Bay	Conowingo Dam Fish Lift Count	Otolith	Female	5													■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■						
			Male	4													■	■	■		■	■	■	■	■						■	■			■				
		Scale	Female	5									■	■	■		■	■				■	■	■	■	■	■	■	■		■	■	■						
	Susquehanna Hook-and-Line Survey	Scale	Female	5		■	■					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
			Male	4		■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Nanticoke River	Nanticoke River Commercial Pound Net Monitoring	Scale	Female	5							■	■	■	■	■	■	■	■				■		■	■									■					
			Male	4							■	■	■	■	■	■	■	■	■	■				■	■				■		■		■	■		■		■	
Delaware River	Lehigh River Electrofishing Survey	Scale	Female	5																		■	■	■						■				■		■			■
	Lewis Haul Seine Fishery Monitoring	Scale	Female	5																										■		■		■	■	■			
	Smithfield Beach Gill Net Survey	Otolith	Female	6															■	■	■	■	■	■	■	■	■		■	■	■	■		■	■	■	■	■	■
			Male	5															■	■		■	■	■	■	■	■		■	■	■		■	■	■	■	■	■	■
		Scale	Female	6														■	■	■	■	■	■	■	■	■	■		■		■	■	■	■	■	■		■	■
			Male	5																		■	■		■		■		■		■		■	■	■	■	■	■	
Hudson River	Hudson River Spawning Stock Haul Seine and Electrofishing Surveys	Scale	Female	5	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■											■	■	■	■	■	■
			Male	5		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■											■		■	■	■	■
Connecticut River	Holyoke Dam Fish Lift Counts	Scale	Female	5																				■					■					■		■	■	■	■
			Male	4																		■	■		■	■	■	■	■	■	■	■	■	■		■	■	■	■
Merrimack River	Essex Dam Fish Lift Counts	Otolith	Female	6																										■	■	■	■	■	■	■	■	■	
			Male	5																										■	■	■	■	■	■	■	■	■	■
		Scale	Female	5																							■	■	■										
			Male	4																							■	■	■										

Table 33. Instantaneous total mortality (*Z*) as estimated by weighted linear regression on synthetic cohorts by system, monitoring program, structure, sex, and year. Provided is the $Z_{40\%}$ biological reference point (BRP), *Z* estimate (*Z*) with lower (LCI; lower bound is censored to 0 if raw lower bound was <0) and upper (UCI) bounds of a 95% CI, and a three year average *Z* (3-yr Avg.; right aligned) when 3 or more consecutive years were included in the analysis. Table continues on next several pages.

							Z Estimate			
System	**Source**	**Structure**	**Sex**	**Year**	**BRP**	**n**	**LCI**	**Z**	**UCI**	**3-yr Avg.**
Merrimack	Essex Dam Fish Lift Counts	Otolith	Female	2008	1	59		1.69		
				2009	1	66	0.41	0.80	1.19	
				2010	1	61	0.24	1.35	2.46	1.28
				2011	1	101	0.31	0.85	1.39	1.00
				2012	1	38	0.43	0.68	0.93	0.96
				2013	1	59	0.18	1.27	2.36	0.93
				2014	1	90	0.06	0.92	1.78	0.96
				2015	1	47	0.26	0.37	0.48	0.85
				2016	1	85	1.14	2.47	3.80	1.25
			Male	2008	1	93	0.35	1.07	1.79	
				2009	1	69	0.37	0.68	0.99	
				2010	1	45	0.57	1.13	1.69	0.96
				2011	1	102	0.20	0.55	0.90	0.79
				2012	1	124	0.12	0.86	1.60	0.85
				2013	1	60	0.20	1.08	1.96	0.83
				2014	1	89	0.22	0.79	1.36	0.91
				2015	1	124	0.76	1.24	1.72	1.04
				2016	1	78	0.00	1.52	3.37	1.18
				2017	1	105	0.00	0.73	1.57	1.16
		Scale	Female	2005	1	83	0.00	0.31	0.85	
				2006	1	64	0.53	0.99	1.45	
				2007	1	73	0.73	1.03	1.33	0.78
			Male	2005	1	98	0.00	0.26	0.76	
				2006	1	58	0.28	0.79	1.30	
				2007	1	87	0.77	0.99	1.21	0.68

Table 33 Continued

							Z Estimate			
System	**Source**	**Structure**	**Sex**	**Year**	**BRP**	**n**	**LCI**	**Z**	**UCI**	**3-yr Avg.**
Connecticut	Holyoke Dam Fish Lift Counts	Scale	Female	2002	1	281	1.36	2.20	3.04	
				2007	1	234	0.00	1.40	4.35	
				2012	1	270	0.29	1.87	3.45	
				2014	1	161	1.01	1.19	1.37	
				2015	1	215	0.24	1.77	3.30	
				2016	1	236	0.40	1.73	3.06	1.56
				2017	1	281	0.10	0.70	1.30	1.40
			Male	2000	1	280	0.00	1.71	4.01	
				2001	1	271	0.32	1.91	3.50	
				2003	1	204	0.00	1.40	4.15	
				2004	1	170	0.00	0.87	4.65	
				2005	1	63	0.00	0.21	1.08	0.83
				2006	1	91	0.00	0.70	2.55	0.59
				2007	1	234	0.00	0.87	2.24	0.59
				2008	1	255	0.00	0.77	2.02	0.78
				2009	1	201	0.00	1.16	2.65	0.93
				2010	1	231	0.49	1.42	2.35	1.12
				2011	1	217	0.45	1.03	1.61	1.20
				2012	1	543	0.00	1.22	2.49	1.22
				2014	1	292	0.63	1.46	2.29	
				2015	1	217	0.00	0.80	2.29	
				2016	1	339	0.43	1.31	2.19	1.19
				2017	1	386	0.00	0.58	1.88	0.90

Table 33 Continued

							Z Estimate			
System	**Source**	**Structure**	**Sex**	**Year**	**BRP**	**n**	**LCI**	**Z**	**UCI**	**3-yr Avg.**
Hudson	Hudson River Spawning Stock Haul Seine and Electrofishing Surveys	Scale	Male	1984	1.07	63	0.27	0.60	0.93	
				1985	1.07	102	0.55	0.71	0.87	
				1986	1.07	137	0.72	0.80	0.88	0.70
				1987	1.07	146	0.44	0.57	0.70	0.69
				1988	1.07	180	0.70	0.80	0.90	0.72
				1989	1.07	128	0.34	0.58	0.82	0.65
				1990	1.07	41	0.39	0.84	1.29	0.74
				1991	1.07	54	0.74	1.03	1.32	0.82
				1992	1.07	308	1.42	1.77	2.12	1.21
				1993	1.07	222	0.95	1.28	1.61	1.36
				1994	1.07	46	0.86	1.34	1.82	1.46
				1995	1.07	127	0.95	1.06	1.17	1.23
				1996	1.07	89	1.38	1.42	1.46	1.27
				1997	1.07	42	0.92	1.63	2.34	1.37
				1998	1.07	65	1.10	1.28	1.46	1.44
				1999	1.07	102	1.12	1.46	1.80	1.46
				2000	1.07	88	1.05	1.92	2.79	1.55
				2001	1.07	251	0.75	1.05	1.35	1.48
				2012	1.07	33	0.19	0.44	0.69	
				2014	1.07	58	0.46	0.64	0.82	
				2015	1.07	97	1.08	1.24	1.40	
				2016	1.07	74	0.69	1.33	1.97	1.07
				2017	1.07	69	0.30	0.77	1.24	1.11

Table 33 Continued

							Z Estimate			
System	**Source**	**Structure**	**Sex**	**Year**	**BRP**	**n**	**LCI**	**Z**	**UCI**	**3-yr Avg.**
Hudson	Hudson River Spawning Stock Haul Seine and Electrofishing Surveys	Scale	Female	1983	1.07	47	0.37	0.47	0.57	
				1984	1.07	53	0.00	0.25	0.50	
				1985	1.07	82	0.17	0.33	0.49	0.35
				1986	1.07	181	0.38	0.52	0.66	0.37
				1987	1.07	199	0.39	0.54	0.69	0.46
				1988	1.07	287	0.45	0.58	0.71	0.55
				1989	1.07	189	0.34	0.50	0.66	0.54
				1990	1.07	59	0.26	0.57	0.88	0.55
				1991	1.07	87	0.38	0.79	1.20	0.62
				1992	1.07	411	0.64	0.97	1.30	0.78
				1993	1.07	139	0.34	0.64	0.94	0.80
				1994	1.07	77	0.89	1.01	1.13	0.87
				1995	1.07	387	0.77	1.25	1.73	0.97
				1996	1.07	87	0.78	0.85	0.92	1.04
				1997	1.07	62	0.22	0.49	0.76	0.86
				1998	1.07	103	0.78	0.97	1.16	0.77
				1999	1.07	150	0.83	1.06	1.29	0.84
				2000	1.07	147	1.25	1.44	1.63	1.16
				2001	1.07	351	0.76	1.03	1.30	1.18
				2012	1.07	132	0.13	0.51	0.89	
				2013	1.07	128	0.18	0.65	1.12	
				2014	1.07	107	0.51	0.71	0.91	0.62
				2015	1.07	175	0.37	0.74	1.11	0.70
				2016	1.07	73	0.25	0.66	1.07	0.70
				2017	1.07	66	0.00	0.36	1.26	0.59

Table 33 Continued

							Z Estimate			
System	**Source**	**Structure**	**Sex**	**Year**	**BRP**	**n**	**LCI**	**Z**	**UCI**	**3-yr Avg.**
Delaware	Smithfield Beach Gill Net Survey	Scale	Female	1996	1.07	214	1.00	1.24	1.48	
				1997	1.07	41	0.00	0.88	2.31	
				1998	1.07	121	1.07	1.74	2.41	1.29
				1999	1.07	138	0.00	1.35	2.94	1.32
				2000	1.07	163	0.00	0.96	2.40	1.35
				2001	1.07	483	0.18	1.45	2.72	1.25
				2002	1.07	233	0.00	1.12	2.77	1.18
				2003	1.07	270	0.00	0.93	2.06	1.17
				2004	1.07	259	0.19	1.29	2.39	1.11
				2005	1.07	438	0.00	0.55	1.46	0.92
				2007	1.07	136	0.50	1.41	2.32	
				2009	1.07	204	0.42	0.91	1.40	
				2010	1.07	398	1.73	2.05	2.37	
				2011	1.07	325	0.00	0.50	3.32	1.15
				2012	1.07	298	0.00	0.83	1.85	1.13
				2013	1.07	308	0.00	0.54	1.64	0.62
				2014	1.07	355	0.00	0.21	0.98	0.53
				2016	1.07	68	0.00	0.34	1.16	
				2017	1.07	64	0.00	0.33	1.25	
			Male	2000	1.07	110	0.74	1.70	2.66	
				2001	1.07	110		2.41		
				2003	1.07	165	1.78	2.05	2.32	
				2005	1.07	209	0.00	1.64	3.69	
				2007	1.07	86	0.62	1.58	2.54	
				2009	1.07	57	0.82	1.21	1.60	
				2011	1.07	60	0.00	0.58	3.75	
				2012	1.07	105	0.00	0.93	2.14	
				2013	1.07	127	0.00	0.68	2.67	0.73
				2014	1.07	96	0.00	0.99	2.54	0.87
				2015	1.07	114	0.49	1.19	1.89	0.95
				2016	1.07	68	0.07	0.44	0.81	0.87

Table 33 Continued

							Z Estimate			
System	**Source**	**Structure**	**Sex**	**Year**	**BRP**	**n**	**LCI**	**Z**	**UCI**	**3-yr Avg.**
Delaware	Smithfield Beach Gill Net Survey	Otolith	Female	1997	1.07	568	0.24	1.35	2.46	
				1998	1.07	54	0.06	0.73	1.40	
				1999	1.07	36	0.00	0.29	0.90	0.79
				2000	1.07	131	0.35	1.19	2.03	0.74
				2001	1.07	200	1.38	1.61	1.84	1.03
				2002	1.07	169	1.11	1.36	1.61	1.39
				2003	1.07	218	1.04	1.60	2.16	1.52
				2004	1.07	140	0.00	1.19	2.49	1.38
				2005	1.07	184	1.31	1.63	1.95	1.47
				2007	1.07	231	1.31	1.85	2.39	
				2008	1.07	252	1.08	1.91	2.74	
				2009	1.07	139	1.03	1.44	1.85	1.73
				2010	1.07	65	1.52	1.70	1.88	1.68
				2012	1.07	197	0.00	0.75	3.00	
				2013	1.07	261	0.24	1.45	2.66	
				2014	1.07	246	0.00	1.46	4.30	1.22
				2015	1.07	145	0.55	0.88	1.21	1.26
				2016	1.07	207	0.84	1.58	2.32	1.31
				2017	1.07	144	0.00	1.44	3.30	1.30
			Male	1997	1.07	469	0.75	1.45	2.15	
				1998	1.07	59	0.92	1.27	1.62	
				2000	1.07	102	0.34	1.36	2.38	1.36
				2001	1.07	125	1.06	1.50	1.94	1.38
				2002	1.07	123	0.38	0.98	1.58	1.28
				2003	1.07	153	0.47	1.10	1.73	1.19
				2004	1.07	125	1.42	1.47	1.52	1.18
				2005	1.07	230	0.03	1.25	2.47	1.27
				2007	1.07	220	0.49	1.52	2.55	
				2008	1.07	206	0.00	0.68	1.78	
				2009	1.07	65	0.65	1.11	1.57	1.10
				2011	1.07	62	0.00	0.61	3.76	
				2012	1.07	104	0.07	0.87	1.67	
				2013	1.07	127	0.00	0.68	2.67	0.72
				2014	1.07	93	0.00	0.56	1.28	0.70
				2015	1.07	124	1.04	1.44	1.84	0.89
				2016	1.07	115	0.00	0.92	2.63	0.97
				2017	1.07	158	1.02	1.42	1.82	1.26

Table 33 Continued

System	Source	Structure	Sex	Year	BRP	n	Z Estimate LCI	 Z	 UCI	3-yr Avg.
Delaware	Lehigh River Electrofishing Survey	Scale	Female	2000	1.07	32	0.00	0.98	2.22	
				2001	1.07	32	0.69	0.82	0.95	
				2002	1.07	45	0.00	1.12	2.46	0.97
				2008	1.07	32	0.00	0.20	0.79	
				2012	1.07	31	0.06	0.20	0.34	
				2014	1.07	40	0.00	0.32	1.54	
				2017	1.07	41	0.81	1.04	1.27	
	Lewis Haul Seine Fishery Monitoring	Scale	Female	2008	1.07	40	0.17	0.65	1.13	
				2010	1.07	106	0.57	0.84	1.11	
				2012	1.07	71	0.14	0.81	1.48	
				2013	1.07	223	0.64	1.19	1.74	
				2014	1.07	136	0.29	1.47	2.65	1.16

Table 33 Continued

System	Source	Structure	Sex	Year	BRP	n	Z Estimate LCI	Z Estimate Z	Z Estimate UCI	3-yr Avg.
Nanticoke	Nanticoke River Commercial Pound Net Monitoring	Scale	Female	1989	1.07	75	0.33	0.73	1.13	
				1990	1.07	122	1.01	1.17	1.33	
				1991	1.07	148	0.38	0.98	1.58	0.96
				1992	1.07	65	0.00	0.07	0.26	0.74
				1993	1.07	80	0.34	0.55	0.76	0.53
				1994	1.07	34	0.98	1.00	1.02	0.54
				1995	1.07	44	0.00	0.96	2.30	0.84
				1996	1.07	35	0.08	0.17	0.26	0.71
				2000	1.07	50	0.13	1.18	2.23	
				2002	1.07	38	0.00	0.29	1.56	
				2003	1.07	41	0.00	0.58	1.29	
				2012	1.07	53	0.07	0.68	1.29	
			Male	1989	1.07	195	1.50	1.66	1.82	
				1990	1.07	146	0.17	1.11	2.05	
				1991	1.07	179	0.31	0.97	1.63	1.25
				1992	1.07	61	0.00	0.40	0.93	0.83
				1993	1.07	111	0.11	0.50	0.89	0.62
				1994	1.07	70	0.62	1.04	1.46	0.65
				1995	1.07	64	0.00	0.93	1.94	0.82
				1996	1.07	58	0.07	0.65	1.23	0.87
				1997	1.07	44	0.65	0.92	1.19	0.83
				1998	1.07	33	0.20	0.69	1.18	0.75
				2002	1.07	74	0.00	0.65	1.36	
				2003	1.07	72	0.00	0.10	0.78	
				2007	1.07	38	0.34	1.14	1.94	
				2009	1.07	53	0.00	1.11	2.32	
				2011	1.07	39	0.48	1.13	1.78	
				2012	1.07	106	0.00	0.78	1.78	
				2014	1.07	38	0.00	0.16	0.71	
				2016	1.07	33	0.00	0.36	0.85	

Table 33 Continued

System	Source	Structure	Sex	Year	BRP	n	Z Estimate LCI	Z Estimate Z	Z Estimate UCI	3-yr Avg.
Upper Chesapeake Bay	Susquehanna Hook-and-Line Survey	Scale	Male	1984	1.07	46	0.69	1.14	1.59	
				1987	1.07	212	0.00	1.69	3.61	
				1988	1.07	113	0.45	1.63	2.81	
				1989	1.07	150	0.46	1.21	1.96	1.51
				1990	1.07	167	0.26	1.28	2.30	1.37
				1991	1.07	174	0.00	0.80	1.88	1.10
				1992	1.07	160	0.00	0.90	1.87	0.99
				1993	1.07	143	0.33	0.97	1.61	0.89
				1994	1.07	255	0.00	1.00	2.30	0.96
				1995	1.07	296	0.00	0.62	1.90	0.86
				1996	1.07	194	0.00	0.68	1.44	0.77
				1997	1.07	306	0.98	1.23	1.48	0.84
				1998	1.07	120	0.22	1.13	2.04	1.01
				1999	1.07	450	0.62	1.70	2.78	1.35
				2000	1.07	448	0.00	1.63	3.38	1.49
				2001	1.07	382	0.02	1.15	2.28	1.49
				2002	1.07	348	0.00	0.49	1.05	1.09
				2003	1.07	436	0.37	0.87	1.37	0.84
				2004	1.07	143	0.00	0.37	1.76	0.58
				2005	1.07	141	0.38	0.78	1.18	0.67
				2006	1.07	113	0.59	1.13	1.67	0.76
				2007	1.07	168	0.73	1.35	1.97	1.09
				2008	1.07	53	0.07	0.88	1.69	1.12
				2009	1.07	349	0.78	1.47	2.16	1.23
				2010	1.07	222	0.28	1.11	1.94	1.15
				2011	1.07	50	0.00	0.42	1.35	1.00
				2012	1.07	99	0.00	0.16	0.81	0.56
				2013	1.07	162	0.00	0.35	1.04	0.31
				2014	1.07	196	0.00	0.67	1.64	0.39
				2015	1.07	133	0.00	0.67	1.52	0.56
				2016	1.07	222	0.00	0.75	2.09	0.70
				2017	1.07	100	0.00	1.20	2.68	0.87

Table 33 Continued

System	Source	Structure	Sex	Year	BRP	n	Z Estimate LCI	Z Estimate Z	Z Estimate UCI	3-yr Avg.
Upper Chesapeake Bay	Susquehanna Hook-and-Line Survey	Scale	Female	1984	1.07	37	0.81	1.01	1.21	
				1985	1.07	48	0.04	1.11	2.18	
				1990	1.07	86	0.87	1.29	1.71	
				1991	1.07	147	0.00	1.12	2.42	
				1992	1.07	183	0.12	1.02	1.92	1.14
				1993	1.07	66	0.00	0.56	1.43	0.90
				1994	1.07	143	0.71	1.18	1.65	0.92
				1995	1.07	260	0.18	1.46	2.74	1.07
				1996	1.07	163	0.00	0.95	2.21	1.20
				1997	1.07	180	0.83	1.30	1.77	1.24
				1998	1.07	102	0.88	1.27	1.66	1.17
				1999	1.07	222	0.93	1.67	2.41	1.41
				2000	1.07	162	1.28	1.66	2.04	1.53
				2001	1.07	421	0.12	1.28	2.44	1.54
				2002	1.07	382	0.07	0.92	1.77	1.29
				2003	1.07	273	0.15	0.76	1.37	0.99
				2004	1.07	195	0.70	1.35	2.00	1.01
				2005	1.07	201	0.00	0.99	2.04	1.03
				2006	1.07	112	0.65	0.90	1.15	1.08
				2007	1.07	200	0.66	1.42	2.18	1.10
				2008	1.07	53	0.91	1.40	1.89	1.24
				2009	1.07	133	0.94	1.37	1.80	1.40
				2010	1.07	112	0.80	1.69	2.58	1.49
				2011	1.07	108	0.15	1.23	2.31	1.43
				2012	1.07	72	0.00	0.49	1.75	1.14
				2013	1.07	132	0.04	0.48	0.92	0.73
				2014	1.07	224	0.05	0.79	1.53	0.59
				2015	1.07	103	0.83	1.17	1.51	0.81
				2016	1.07	128	0.14	1.30	2.46	1.09

Table 33 Continued

							Z Estimate			
System	**Source**	**Structure**	**Sex**	**Year**	**BRP**	**n**	**LCI**	**Z**	**UCI**	**3-yr Avg.**
Upper Chesapeake Bay	Conowingo Dam Fish Lift Count	Scale	Female	1991	1.07	90	0.00	0.61	1.52	
				1992	1.07	122	0.00	0.79	1.90	
				1993	1.07	39	0.00	0.67	1.50	0.69
				1995	1.07	227	0.43	1.02	1.61	
				1996	1.07	122	0.12	1.51	2.90	
				2000	1.07	40	0.00	1.05	2.41	
				2001	1.07	66	1.30	1.69	2.08	
				2002	1.07	95	0.40	0.94	1.48	1.23
				2003	1.07	78	0.63	1.14	1.65	1.26
				2004	1.07	43	0.07	0.69	1.31	0.92
				2005	1.07	41	0.10	0.79	1.48	0.87
				2006	1.07	38	1.04	1.55	2.06	1.01
				2007	1.07	51	0.00	1.07	2.73	1.14
				2009	1.07	37	1.17	1.28	1.39	
				2010	1.07	39		2.89		
				2011	1.07	36	0.00	0.60	1.99	1.59

Table 33 Continued

							Z Estimate			
System	**Source**	**Structure**	**Sex**	**Year**	**BRP**	**n**	**LCI**	**Z**	**UCI**	**3-yr Avg.**
Upper Chesapeake Bay	Conowingo Dam Fish Lift Count	Otolith	Female	1995	1.07	221	1.10	1.15	1.20	
				1996	1.07	98	1.28	1.37	1.46	
				1997	1.07	50	0.00	1.06	2.34	1.19
				1998	1.07	49	0.24	1.27	2.30	1.23
				1999	1.07	61	1.10	1.47	1.84	1.27
				2000	1.07	43	0.35	1.14	1.93	1.29
				2001	1.07	93	0.19	1.17	2.15	1.26
				2002	1.07	97	0.35	0.86	1.37	1.06
				2003	1.07	89	0.00	0.77	1.72	0.93
				2004	1.07	43	0.00	0.66	1.33	0.76
				2005	1.07	41	0.10	0.79	1.48	0.74
				2006	1.07	40	1.10	1.10	1.10	0.85
				2007	1.07	50	0.00	0.64	2.94	0.84
				2009	1.07	33	1.23	1.24	1.25	
				2010	1.07	39		2.46		
				2011	1.07	35	0.00	0.56	1.99	1.42
			Male	1995	1.07	339	0.33	1.15	1.97	
				1996	1.07	200	0.16	1.03	1.90	
				1997	1.07	106	1.28	1.43	1.58	1.20
				1999	1.07	81	1.23	1.66	2.09	
				2000	1.07	114	1.14	1.38	1.62	
				2001	1.07	82	0.00	0.85	1.75	1.30
				2002	1.07	58	0.00	0.58	1.39	0.94
				2003	1.07	86	0.44	0.86	1.28	0.76
				2009	1.07	84	1.01	1.31	1.61	
				2010	1.07	56	0.00	0.86	2.81	
				2013	1.07	42	0.45	1.15	1.85	

Table 33 Continued

System	Source	Structure	Sex	Year	BRP	n	Z Estimate LCI	Z Estimate Z	Z Estimate UCI	3-yr Avg.
Potomac	Potomac River Striped Bass Spawning Stock Survey	Scale	Female	2003	1.07	55	0.30	0.81	1.32	
				2004	1.07	33	0.00	0.93	2.14	
				2005	1.07	32	0.68	1.27	1.86	1.00
				2013	1.07	41	0.00	0.58	1.34	
				2014	1.07	58	0.98	1.26	1.54	
				2016	1.07	31	1.24	1.42	1.60	
			Male	2008	1.07	32	0.26	2.36	4.46	
				2013	1.07	61	0.00	0.34	1.00	
				2014	1.07	41	0.00	0.04	0.79	
				2015	1.07	35	0.26	0.66	1.06	0.35
				2016	1.07	54	1.29	1.29	1.29	0.66

Table 33 Continued

							Z Estimate			
System	**Source**	**Structure**	**Sex**	**Year**	**BRP**	**n**	**LCI**	**Z**	**UCI**	**3-yr Avg.**
Potomac	Combined Potomac Broodstock Collections	Otolith	Female	2000	1.07	57	0.31	0.97	1.63	
				2006	1.07	87	0.33	0.49	0.65	
				2007	1.07	33	0.00	0.21	0.63	
				2008	1.07	66	0.00	0.51	1.67	0.40
				2010	1.07	35	0.22	0.67	1.12	
				2012	1.07	32	0.28	0.99	1.70	
				2013	1.07	30	0.00	0.78	1.97	
				2014	1.07	42	0.00	0.19	0.57	0.65
				2016	1.07	85	0.03	0.43	0.83	
				2017	1.07	98	0.09	1.28	2.47	
		Scale	Female	2000	1.07	50	0.81	1.44	2.07	
				2004	1.07	52	0.09	0.71	1.33	
				2005	1.07	54	0.00	0.37	1.20	
				2006	1.07	58	0.31	0.73	1.15	0.60
				2007	1.07	84	0.74	1.44	2.14	0.85
				2008	1.07	84	0.83	1.23	1.63	1.13
				2010	1.07	106	0.31	0.72	1.13	
				2011	1.07	51	0.00	0.62	1.36	
				2012	1.07	118	0.40	0.84	1.28	0.73
				2013	1.07	122	0.27	0.70	1.13	0.72
				2014	1.07	146	0.00	0.44	1.21	0.66
				2015	1.07	136	0.00	1.27	3.04	0.80
				2016	1.07	190	0.39	0.92	1.45	0.88
				2017	1.07	188	0.38	1.15	1.92	1.11
		Scale	Male	2004	1.07	34	0.00	0.71	2.31	
				2008	1.07	55	0.00	2.31	5.14	
				2010	1.07	78	0.79	1.23	1.67	
				2012	1.07	90	0.92	0.93	0.94	
				2013	1.07	98	0.00	0.69	1.42	
				2014	1.07	141	0.00	0.71	1.80	0.78
				2015	1.07	120	0.52	0.88	1.24	0.76
				2016	1.07	91	0.40	0.83	1.26	0.81
				2017	1.07	77	0.55	1.29	2.03	1.00

Table 33 Continued

System	Source	Structure	Sex	Year	BRP	n	Z Estimate LCI	 Z	 UCI	3-yr Avg.
Rappahannock	Rappahannock River Adult Gill Net Survey	Scale	Female	2002	1.07	111	0.14	0.57	1.00	
				2003	1.07	300	0.85	0.89	0.93	
				2004	1.07	267	0.63	0.90	1.17	0.79
				2005	1.07	161	0.46	0.75	1.04	0.85
				2006	1.07	115	0.73	0.98	1.23	0.88
				2007	1.07	90	0.68	1.09	1.50	0.94
				2008	1.07	147	0.71	0.85	0.99	0.97
				2009	1.07	237	0.89	1.12	1.35	1.02
				2010	1.07	75	0.20	0.81	1.42	0.93
				2011	1.07	226	0.81	1.17	1.53	1.03
				2012	1.07	260	0.87	1.06	1.25	1.01
				2013	1.07	294	0.86	1.02	1.18	1.08
				2014	1.07	306	0.77	1.10	1.43	1.06
				2015	1.07	83	0.26	0.57	0.88	0.90
				2016	1.07	41	0.00	0.21	1.58	0.63
				2017	1.07	82	0.00	0.73	1.67	0.50

Table 33 Continued

							Z Estimate			
System	**Source**	**Structure**	**Sex**	**Year**	**BRP**	**n**	**LCI**	**Z**	**UCI**	**3-yr Avg.**
York	York River Adult Gill Net Survey	Scale	Female	1998	1.07	534	0.80	1.03	1.26	
				1999	1.07	235	0.61	0.84	1.07	
				2000	1.07	201	0.92	1.14	1.36	1.00
				2001	1.07	382	1.01	1.09	1.17	1.02
				2002	1.07	356	0.44	0.85	1.26	1.03
				2003	1.07	452	0.48	0.76	1.04	0.90
				2004	1.07	624	0.31	0.62	0.93	0.74
				2005	1.07	256	0.17	0.51	0.85	0.63
				2006	1.07	104	0.41	0.69	0.97	0.61
				2007	1.07	184	0.78	0.93	1.08	0.71
				2008	1.07	145	0.79	1.04	1.29	0.89
				2009	1.07	144	0.44	0.83	1.22	0.93
				2010	1.07	198	0.51	0.77	1.03	0.88
				2011	1.07	189	0.51	1.00	1.49	0.87
				2012	1.07	121	0.92	1.08	1.24	0.95
				2013	1.07	186	0.52	0.89	1.26	0.99
				2014	1.07	341	0.69	0.86	1.03	0.94
				2015	1.07	40	0.39	0.77	1.15	0.84
				2016	1.07	41	0.00	0.18	1.22	0.60
				2017	1.07	31	0.19	0.63	1.07	0.53

Table 33 Continued

							Z Estimate			
System	**Source**	**Structure**	**Sex**	**Year**	**BRP**	**n**	**LCI**	**Z**	**UCI**	**3-yr Avg.**
James	James River Adult Gill Net Survey (VIMS)	Scale	Female	2002	1.07	255	0.39	0.74	1.09	
				2003	1.07	390	0.87	1.08	1.29	
				2004	1.07	304	0.82	0.89	0.96	0.90
				2005	1.07	289	0.57	0.86	1.15	0.94
				2006	1.07	57	0.94	1.77	2.60	1.17
				2007	1.07	139	1.08	1.45	1.82	1.36
				2008	1.07	58	0.67	0.99	1.31	1.40
				2009	1.07	121	0.41	0.75	1.09	1.06
				2010	1.07	338	0.78	1.15	1.52	0.96
				2011	1.07	294	0.76	1.09	1.42	1.00
				2012	1.07	167	0.77	1.18	1.59	1.14
				2013	1.07	176	0.71	0.99	1.27	1.09
				2014	1.07	305	0.59	0.79	0.99	0.99
				2015	1.07	32	0.00	0.51	1.08	0.76
				2017	1.07	77	0.00	0.68	1.54	

Table 33 Continued

System	Source	Structure	Sex	Year	BRP	n	Z Estimate LCI	Z Estimate Z	Z Estimate UCI	3-yr Avg.
Albemarle Sound	Albemarle Sound Independent Gill Net Survey	Scale	Female	2004	1.07	53	0.24	1.30	2.36	
				2005	1.07	43	0.00	1.03	2.13	
				2006	1.07	38	0.22	0.75	1.28	1.03
				2007	1.07	72	0.00	1.26	2.55	1.01
				2008	1.07	52	0.68	0.72	0.76	0.91
				2009	1.07	68	0.00	1.21	2.63	1.06
				2010	1.07	49	0.45	0.84	1.23	0.92
				2011	1.07	42	0.26	0.94	1.62	1.00
				2012	1.07	34	1.08	1.39	1.70	1.06
				2013	1.07	85	0.34	0.91	1.48	1.08
				2014	1.07	67	0.10	0.60	1.10	0.97
				2015	1.07	86	0.00	0.65	1.59	0.72
				2016	1.07	81	0.00	0.84	1.84	0.70
				2017	1.07	82	0.04	0.99	1.94	0.83
			Male	2004	1.07	101	0.17	0.79	1.41	
				2005	1.07	80	0.68	0.82	0.96	
				2006	1.07	116	0.00	0.59	1.37	0.73
				2007	1.07	173	0.00	0.59	1.37	0.67
				2008	1.07	139	0.00	0.31	1.21	0.50
				2009	1.07	131	0.00	0.47	0.95	0.46
				2010	1.07	134	0.00	0.01	0.80	0.26
				2011	1.07	103	0.00	0.33	0.83	0.27
				2012	1.07	214	0.00	0.54	1.29	0.29
				2013	1.07	158	0.00	0.10	0.72	0.32
				2014	1.07	138	0.00	0.33	1.03	0.32
				2015	1.07	119	0.01	0.41	0.81	0.28
				2016	1.07	57	0.00	0.42	1.39	0.39
				2017	1.07	59	0.00	0.39	0.79	0.41

Table 33 Continued

System	Source	Structure	Sex	Year	BRP	n	Z Estimate LCI	Z	UCI	3-yr Avg.
Albemarle Sound	Albemarle Sound Commercial Monitoring	Scale	Female	2001	1.07	70	1.60	1.82	2.04	
				2002	1.07	49	0.00	0.83	2.12	
				2003	1.07	71	0.00	0.79	2.00	1.15
				2005	1.07	50	0.00	1.15	2.57	
				2006	1.07	45	0.40	1.01	1.62	
				2007	1.07	79	0.00	1.34	2.87	1.17
				2008	1.07	83	0.16	0.79	1.42	1.05
				2009	1.07	76	0.00	1.20	2.82	1.11
				2010	1.07	77	0.38	0.92	1.46	0.97
				2011	1.07	63	0.23	1.00	1.77	1.04
				2012	1.07	30	1.19	1.39	1.59	1.10
				2013	1.07	89	0.41	1.02	1.63	1.14
				2014	1.07	84	0.00	0.44	1.14	0.95
				2015	1.07	109	0.00	0.76	1.88	0.74
				2016	1.07	137	0.00	0.33	1.62	0.51
				2017	1.07	95	0.00	0.85	1.90	0.65

Table 33 Continued

							Z Estimate			
System	**Source**	**Structure**	**Sex**	**Year**	**BRP**	**n**	**LCI**	**Z**	**UCI**	**3-yr Avg.**
Albemarle Sound	Roanoke River Adult Spawning Area Electrofishing Survey	Scale	Female	2002	1.07	60	0.00	0.49	0.98	
				2003	1.07	87	0.71	1.11	1.51	
				2004	1.07	34	0.00	0.20	0.67	0.60
				2005	1.07	34	0.35	0.45	0.55	0.59
				2009	1.07	55	0.81	0.96	1.11	
				2010	1.07	52	0.24	0.91	1.58	
			Male	2000	1.07	132	0.00	0.30	1.31	
				2001	1.07	232	0.00	0.12	0.67	
				2002	1.07	164	0.20	0.56	0.92	0.33
				2003	1.07	119	0.18	0.86	1.54	0.51
				2004	1.07	75	0.25	0.52	0.79	0.65
				2005	1.07	91	1.22	1.39	1.56	0.92
				2006	1.07	76	0.00	1.22	3.03	1.04
				2008	1.07	60	0.23	0.98	1.73	
				2009	1.07	74	0.01	1.14	2.27	
				2010	1.07	79	0.06	0.81	1.56	0.98

Table 33 Continued

System	Source	Structure	Sex	Year	BRP	n	Z Estimate			3-yr Avg.
							LCI	Z	UCI	
Tar-Pamlico	Tar River Adult Spawning Area Electrofishing Survey	Scale	Female	2000	1.07	42	0.29	1.23	2.17	
				2004	1.07	46	0.59	0.72	0.85	
				2005	1.07	64	0.14	0.69	1.24	
				2006	1.07	74	0.48	1.03	1.58	0.81
				2007	1.07	58	0.46	0.90	1.34	0.87
				2009	1.07	36	0.89	1.34	1.79	
			Male	2000	1.07	143	0.00	1.29	2.70	
				2001	1.07	107	0.88	1.65	2.42	
				2002	1.07	97	0.00	1.39	2.79	1.44
				2004	1.07	53	0.40	0.93	1.46	
				2005	1.07	110	0.89	1.12	1.35	
				2006	1.07	72	0.00	0.77	1.72	0.94
				2007	1.07	109	0.43	0.94	1.45	0.94

Table 34. Reported adult American shad upstream passage rates (efficiencies), refer to summary for definitions.

Rate	Summary	Citation
73.1%	A low slope (1:15) vertical slot section at the John Day fishway (Columbia River) – (scale/size of fishway is unlike anything on Aast Coast).	Weaver et al. 1972
2-25%	Passage rate of shad that have entered the Cabot Station fishway (ice harbor)	Sullivan 2004
50%	Generalized paradigm statement, considered "excellent" for conventional fishway designs	Haro and Castro-Santos 2012; Larnier and Travade 2002
75%	Generalized paradigm statement, considered "exceptional" for conventional fishway designs	Haro and Castro-Santos 2012; Larnier and Travade 2002
42%	Holyoke in 1980 ("overall" – attraction and passability) –	Groux et al. 2015 (citing Barry and Kynard 1986)
67%	Holyoke in 1981 ("overall" – attraction and passability)	Groux et al. 2015 (citing Barry and Kynard 1986)
80.5 and 77.1%	Holyoke in 2011 and 2012 (of fish arrived within 1 km)	Castro-Santos et al. 2016
7 and 26%	Turners Falls gatehouse in 2008 and 2010 ("overall" – attraction and passability)	Groux et al. 2015
7 and 11%	Lowell (Boott Fishway) in 2002 and 2011 ("overall" – attraction and passability)	Groux et al. 2015
45 and 26%	Conowingo in 2010 and in 2012 ("overall" – attraction and passability)	Groux et al. 2015
34 and 11%	Holtwood in 2001 and 2008 ("overall" – attraction and passability)	Groux et al. 2015
15%	York Haven in 2010 ("overall" – attraction and passability)	Groux et al. 2015
43.2 – 81.7% Mean 67.7%	Range of annual shad passage efficiency at Vernon dam (2012 – 2018), based on 90% (USGS study results) arrival from shad passed at previous Gatehouse Fishway.	CRASC 2018

Table 35. Reported adult American shad downstream passage (mortality) rates (note Conowingo Study is survival) refer to summary for definitions.

Rate	Summary	Citation
10-12%	Immediate post passage mortality in Kaplan and mixed flow turbines	Heisey et al. 1992
24.2%	Immediate post passage mortality larger Kaplan	Bell and Kynard 1985
46.3% (90% C.I.: ±34.7%)	Immediate post passage mortality at the Annapolis tidal generating station in 1985	Hogans and Melvin 1985
21.3% (90% C.I: ±15.2)	Immediate post mortality at the Annapolis tidal generating station in 1986 with improved capture and handling methods over the 1985 study	Hogans 1987
SURVIVAL rates – Francis Turbine (1 hr) rate was 93% (90% CI of ± 4.2%); 48 hr rate was 88.3% (90% CI ± 10.5%)……**Kaplan** turbine (1 hr) rate 86.3% (CI ±5.8%); 48 hr 84.1% (±9.9%). Injury free rate 76.2 and 75.4% respectively.	Conowingo Study (large turbines, slow rpms) **note study fish were “fresh” uprunning adults NOT spent downrunners. Rates are SURVIVAL. Power company study, so agency had concerns (e.g., fresh uprunners)	Exelon 2012
Survival rate – 81.4% estimate include route assignments and mortality from bypass use	Turners Falls Project - The USFWS Model was set to study determined routing data (15% spill and 49% bypass), 36% entrained in units - Cabot. Mort rate includes radio tag data that 7.7% fish killed via bypass. No delayed mortality estimated. Cabot has large slow Francis Units.	USFWS 2019 (Turbine Blade Strike Model)

Table 36. Reported juvenile American shad downstream passage rates (mortality), (note Vernon Project Study is Survival rates), refer to summary for definitions. Please note that in many cases the inability to retain control fish from balloon tag field studies for estimates of "delayed" mortality. Because of this fact, field study mortality estimates are minimum values that would be expected to be higher with additional delayed mortality. Delayed mortality is reasoned based upon injury rate monitoring for turbine passed fished.

Rate	Summary	Citation
3% (24 hr) and 6% (48hr)	Short-term (<24hr) large Kaplan turbines at Safe Harbor (large unit slow RPM)	Heisey et al. 1992
0.0% (95% CI ± 14.5%) at 35% wicket gate open and 2.7% (± 16.2%) for 100% gate open	Study done at Holyoke Dam, Hadley Falls Power Station	Mather et al. 1994
46.3% (for clupeids)	Large Stratflo low-head tidal turbine	Stokesbury and Dadswell 1991
23.4% (95% C.I.: 6.1% to 58.8%)	Large Stratflo low-head tidal turbine, with corrective analyses for handling, believed to improve accuracy from Stokesbury and Dadswell 1991	Gibson and Myers 2002
95% (1 hr) 90%CI ± 3.3%	Cabot Station, terminus of Turners Falls Power Canal, larger Francis Turbine, balloon tagging study	FirstLight 2016
67.8% (± 5.0%) and 76.6% (± 4.8%)	Station 1, two different smaller Francis turbines off the Turners Falls Power Canal, balloon tagging study results	Firstlight 2016
Francis unit – 1hr **SURVIVAL** rate 91.7% (CI ± 5.5%) and Kaplan unit 95.2% (CI ±4.7%). reported injury rate of 4.5% and 4.3% for two units types	Balloon tag study at Vernon Hydroelectric project for relicense study, conducted by Normandeau Associates	TransCanada 2016

Table 37. Amount of American shad habitat (river kilometers) in Maine waters (USFWS 1983). Rivers are listed in order of descending habitat kilometers.

River/Watershed	Current (though may be limited)	Current Assumed	Historical	Historical Assumed	Uncertain	Total
Penobscot Watershed	399.6		354.0	32.7		786.3
Kennebec Watershed	300.4		107.2			407.6
Salmon Falls/Piscataqua River	59.8	8.1	8.9	108.1		184.9
Sheepscot River	178.8					178.8
Narraguagus River	38.9			35.6	60.4	134.9
Royal River	106.2					106.2
Androscoggin River	48.3		17.4	34.8		100.5
Saco River	49.1			50.6		99.7
East Machias River	18.8			67.0		85.7
Pleasant River	72.1					72.1
Scarborough Marsh/Nonesuch R.	70.4					70.4
St. George River	65.5					65.5
St. Croix River	61.8					61.8
Kennebunk River	47.0					47.0
Dennys River	34.8				10.7	45.5
Presumpscot River	22.0			22.2		44.2
Tunk Stream	20.2				16.8	37.1
Ducktrap River					22.8	22.8
Webhanet River	8.9					8.9
Union River	7.9					7.9
Pennamaquan River					7.6	7.6
Mousam River	6.3					6.3
Little River	5.5					5.5
Grand Total	**1622.3**	**8.1**	**487.5**	**351.0**	**118.2**	**2587.2**

Table 38. Number of American shad larvae raised at the Waldoboro Hatchery and stocked in Maine rivers, 1992-2018.

Year	Saco River	Medomak River	Androscoggin River	Main Stem Kennebec River	Sebasticook River	Kennebec River System[a]	Merry Meeting Bay Complex[b]
1992	0	230000	0	0	0	0	0
1993	0	61000	0	194400	0	194400	194400
1994	0	30460	0	58800	0	58800	58800
1995	0	318290	0	479612	0	479612	479612
1996	0	327495	0	339319	320000	659319	659319
1997	414201	208240	0	1615603	474313	2089916	2089916
1998	408575	269043	0	1381723	744163	2125886	2125886
1999	151774	17626	316967	1944712	839500	2784212	3101179
2000	259090	145900	522000	3374325	500004	3874329	4396329
2001	313560	213	308556	1496454	618879	2115333	2423889
2002	0	11143	295725	1571856	1013852	2585708	2881433
2003	0	0	1269842	5989358	1857184	7846542	9116384
2004	0	0	538613	4548947	382217	4931164	5469777
2005	0	0	96551	1105343	0	1105343	1201894
2006	0	0	0	262,131	0	262,131	262,131
2007	0	0	0	9,082,178	0	9,082,178	9,082,178
2008	0	0	712,286	1,396,689	288,507	1,685,196	2,397,482
2009	0	0	0	0	0	0	0
2010	0	0	0	0	0	0	0
2011	0	0	0	0	0	0	0
2012	0	0	0	0	0	0	0
2013	0	0	0	0	0	0	0
2014	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0
2018	0	0	0	0	0	0	0
Total	**1,547,200**	**1,619,410**	**4,060,540**	**34,841,450**	**7,038,619**	**41,880,069**	**45,940,609**

[a] Sebasticook and main stem Kennebec rivers.

[b] Androscoggin, Sebasticook, and main stem Kennebec Rivers.

Table 39. Percent of hatchery fish in samples of age-0 American shad from the Kennebec and Androscoggin rivers and Merrymeeting Bay, Maine.

Year	Kennebec		Androscoggin		Merrymeeting Bay	
	Sample Size	Percent Marked	Sample Size	Percent Marked	Sample Size	Percent Marked
2000	9	22.2	5	20	-	-
2001	199	8.0	-	-	-	-
2002	68	13.2	19	5.3	-	-
2003	42	16.7	8	62.5	100	10
2004	97	7.2	71	25.4	100	6
2005	451	2.4	-	-	150	2

Table 40. Reported commercial landings of American shad from Maine state and federal waters.

Year	Pounds	Kg
1887	1,095,720	497,019
1888	839,256	380,687
1889		
1890		
1891		
1892		
1893		
1894		
1895		
1896	366,738	166,352
1897		
1898	1,152,000	522,547
1899		
1900	820,400	372,133
1901	731,000	331,582
1902	773,400	350,814
1903	1,143,600	518,737
1904	1,259,400	571,264
1905	1,087,200	493,154
1906	470,200	213,283
1907	873,400	396,174
1908	1,881,800	853,584
1909	980,350	444,687
1910	847,200	384,290
1911	1,386,400	628,871
1912	3,296,000	1,495,066
1913	2,088,400	947,298
1914	2,086,200	946,300
1915		
1928	110,149	49,964
1929	36,123	16,385
1930	88,635	40,205
1931	157,763	71,561
1932	107,891	48,939
1933	178,901	81,149
1934		
1935	13,000	5,897
1936		
1937	9,300	4,218
1938	11,900	5,398
1939	9,266	4,203
1940	32,164	14,590
1941	47,800	21,682
1942	160,374	72,746
1943	360,923	163,715
1944	452,549	205,276
1945	637,620	289,224
1946	1,106,800	502,044
1947	304,395	138,074
1948	2,552	1,158
1949	4,908	2,226
1950	2,427	1,101
1951	76,164	34,548
1952	50,450	22,884
1953	27,294	12,381
1954	1,981	899
1955	6,570	2,980
1956	2,011	912
1957	7,613	3,453
1958	10,098	4,580
1959	1,635	742
1960	311	141
1961	154	70
1962	65	29
1963		
1964		
1965		
1966	2,072	940
1967	125	57
1968	2,311	1,048
1969		
1970		
1971		
1972		
1973		
1974	588	267
1975	34,669	15,726
1976	14,855	6,738
1977	22,100	10,025
1978	24,500	11,113
1979	18,600	8,437
1980	27,958	12,682
1981	90,600	41,096
1982	25,883	11,741
1983	38,700	17,554
1984	33,414	15,157
1985	16,000	7,258
1986	23,012	10,438
1987	26,400	11,975
1988	31,881	14,461
1989	46,498	21,091
1990	11,804	5,354
1991	1,991	903
1992	1,450	658
1993		
1994	1,051	477
1995		
1996	354	161
1997	2222	1,008
1998	1326	601
1999	291	132
2000	87	39
2001	461	209
2002		
2003	54	24
2004	18	8
2005	159	72
2006	713	323
2007	399	181
2008	38	17
2009	2075	941
2010	272	123
2011	536	243
2012	80	36
2013	17	8
2014		
2015		
2016	162	73
2017		
2018		

Table 41. Upstream passage of American over the lowermost dam on the Androscoggin, Saco, Kennebec, Sebasticook and Penobscot rivers 1981 – 2018.

	American Shad				
Year	Androscoggin	Saco	Kennebec	Sebasticook	Penobscot
1981					
1982					
1983					
1984					
1985					
1986					
1987					
1988					
1989					
1990	1				
1991	0				
1992	0				
1993	1	882			
1994	1	399			
1995	3	580			
1996	2	837			
1997	2	1,104			
1998	5	1,374			
1999	87	4,994			
2000	88	1,323			
2001	26	2,570			
2002	11	1,014			
2003	7	1,227			
2004	12	1,627			
2005	0	744			
2006	3	883	0		
2007	6	1,428	18		
2008	1	1,491	0		
2009	0	278	0	8	
2010	22	3,663	39	2	
2011	0	3,338	12	54	
2012	11	6,419	5	163	
2013	14	6,171	0	114	
2014	0	2,580	1	26	809
2015	58	6,171	26	47	1,806
2016	1,096	16,926	830	18	7,862
2017	1	3,727	213	64	3,868
2018	32	4,107	437	26	3,958
Min	**0**	**278**	**0**	**2**	**809**
Max	**1,096**	**16,926**	**830**	**163**	**7,862**
Ave	**51**	**2,918**	**122**	**52**	**3,661**
Total	**1,490**	**75,857**	**1,581**	**522**	**18,303**

Table 42. American shad number-at-age and length data for the Androscoggin River in Merrymeeting Bay, Maine.

Sex	Age	Number-at-Age					Mean Total Length (mm)														
							2000			2001			2002			2003			2004*		
		2000	2001	2002	2003	2004	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Males	3	1					490														
	4	6		2		3	471	439	494				427	420	433				455	452	460
	5	5	1	2	4	5	482	441	520	462			488	463	512	451	400	461	459	438	475
	6	2	3	1	1		489	483	495	474	430	510	502	502	502	495	495	495			
Females	4	10				1													463	463	463
	5	14		1		2							495	495	495				488	480	495
	6	2	2			1				535	514	555							560	560	560
	7	1	2							534	509	558									
	8																				
	9			1									527	527	527						
Unknown	4			1						502			445	445	445						
	5		1	1	2								505	505	505	470	470	470			
	6		1	1						482			527	527	527						
All	3	1	0	0	0	0															
	4	16	0	3	0	4															
	5	19	2	4	6	7															
	6	4	6	2	1	1															
	7	1	2	0	0	0															
	8																				
	9	0	0	1	0	0															
Mean Age All		**4.7**	**6.0**	**5.3**	**5.1**	**4.8**															

*No shad were measured after 2005

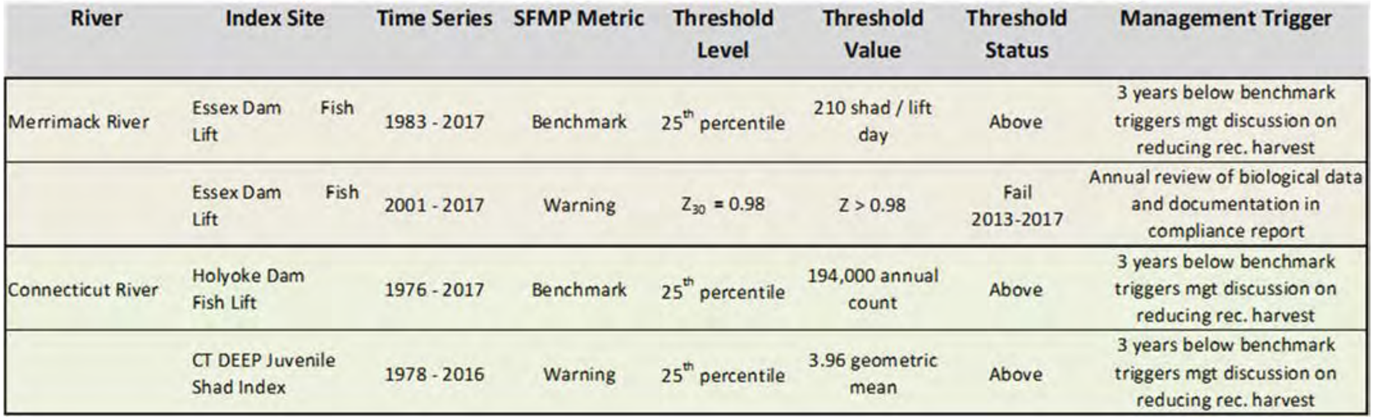
Table 43. Merrymeeting Bay Seine Survey number of observations (n), index values (numbers), and CVs.

Year	n	Index	CV	Year	n	Index	CV
1979	45	0.10	0.55	1999	108	0.51	0.28
1980	57	NA	NA	2000	111	0.29	0.27
1981	58	NA	NA	2001	129	0.20	0.27
1982	59	NA	NA	2002	127	0.45	0.16
1983	53	NA	NA	2003	114	0.94	0.13
1984	45	0.29	0.31	2004	105	1.02	0.13
1985	42	0.68	0.19	2005	112	1.07	0.11
1986	62	0.22	0.29	2006	120	1.75	0.08
1987	60	0.63	0.19	2007	119	1.98	0.07
1988	100	0.52	0.21	2008	104	1.59	0.08
1989	92	0.23	0.29	2009	111	1.63	0.08
1990	98	0.51	0.18	2010	114	1.66	0.08
1991	88	0.25	0.26	2011	117	1.30	0.09
1992	79	0.26	0.26	2012	118	1.21	0.10
1993	76	0.10	0.56	2013	120	1.95	0.07
1994	93	0.09	0.40	2014	120	1.53	0.09
1995	110	0.16	0.29	2015	112	0.96	0.10
1996	89	0.21	0.30	2016	116	0.83	0.11
1997	110	0.09	0.43	2017	110	1.29	0.09
1998	112	0.06	0.61				

Table 44. American shad counts at the Merrimack River (Essex Dam Fish Lift, Lawrence), Massachusetts, 1983–2018. Note: "*" excludes the 2005 and 2006 counts because high flows caused the lift to be inoperable for much of the spawning run.

Year	Merrimack River
1983	5,629
1984	5,497
1985	12,793
1986	18,173
1987	16,909
1988	12,359
1989	7,875
1990	6,013
1991	16,098
1992	20,796
1993	8,599
1994	4,349
1995	13,861
1996	11,322
1997	22,661
1998	27,891
1999	56,461
2000	72,800
2001	76,717
2002	54,586
2003	55,620
2004	36,593
2005	6,382
2006	1,205
2007	15,876
2008	25,116
2009	23,199
2010	10,442
2011	13,835
2012	21,396
2013	37,149
2014	38,107
2015	89,467
2016	67,528
2017	62,846
2018	29,069
Time series average	29,342*

Table 45. Summary of Massachusetts American Shad Sustainable Fishery Management Plan metrics and thresholds for 2018 plan update.



River	Index Site	Time Series	SFMP Metric	Threshold Level	Threshold Value	Threshold Status	Management Trigger
Merrimack River	Essex Dam Fish Lift	1983 - 2017	Benchmark	25th percentile	210 shad / lift day	Above	3 years below benchmark triggers mgt discussion on reducing rec. harvest
	Essex Dam Fish Lift	2001 - 2017	Warning	$Z_{30} = 0.98$	$Z > 0.98$	Fail 2013-2017	Annual review of biological data and documentation in compliance report
Connecticut River	Holyoke Dam Fish Lift	1976 - 2017	Benchmark	25th percentile	194,000 annual count	Above	3 years below benchmark triggers mgt discussion on reducing rec. harvest
	CT DEEP Juvenile Shad Index	1978 - 2016	Warning	25th percentile	3.96 geometric mean	Above	3 years below benchmark triggers mgt discussion on reducing rec. harvest

Table 46. American shad counts at the Essex Dam Lift on the Merrimack River, Lawrence, MA. The lift data source is the USFWS Central NE Fishery Office. The discharge data source is the USGS National Water Information System, Station No. 01100000.

Year	American Shad (No.)	Shad Count Index (No.)	Lift Days (No.)	Shad per Lift Day	Lifts (No.)	Lift Start Date	Lift End Date	Mean Q April	Mean Q May	Mean Q June	Mean Q July
1983	5,629	5,629	54	104.2		5/9/1983	7/9/1983	23,870	16,980	9,277	2,158
1984	5,497	5,497	42	130.9		5/9/1984	7/31/1984	27,650	16,240	23,660	7,606
1985	12,793	12,793	54	236.9		5/1/1985	7/22/1985	8,150	5,705	2,665	1,982
1986	18,173	18,173	54	336.5	506	5/2/1986	7/25/1986	14,070	5,842	7,782	4,368
1987	16,909	16,909	54	313.1	467	5/15/1987	7/23/1987	37,440	10,020	6,198	4,837
1988	12,359	12,359	54	228.9	485	5/9/1988	7/15/1988	12,480	14,080	4,061	3,563
1989	7,875	7,875	54	145.8		5/1/1989	7/28/1989	17,120	18,990	11,250	3,758
1990	6,013	6,013	54	111.4		5/1/1990	7/31/1990	16,750	14,840	7,128	3,187
1991	16,098	16,098	54	298.1		5/1/1991	7/14/1991	12,520	9,242	3,310	1,613
1992	20,796	20,796	54	385.1		5/4/1992	7/31/1992	12,350	8,774	7,046	3,850
1993	8,599	8,599	54	159.2		5/10/1993	7/15/1993	31,730	6,829	3,361	1,334
1994	4,349	4,349	54	80.5		5/2/1994	7/9/1994	23,330	13,020	3,951	2,324
1995	13,861	13,861	54	256.7		5/1/1995	7/9/1995	6,979	6,077	3,243	1,687
1996	11,322	11,322	54	209.7	325	5/20/1996	7/12/1996	24,300	21,270	5,834	8,611
1997	22,661	22,661	57	397.6	412	5/6/1997	7/7/1997	25,600	13,070	4,158	3,737
1998	27,891	27,891	57	489.3	443	5/4/1998	7/22/1998	15,790	10,900	20,940	8,730
1999	56,461	56,461	64	882.2	632	4/28/1999	7/2/1999	10,860	5,748	1,994	1,765
2000	72,800	72,800	65	1120.0	618	5/1/2000	7/7/2000	23,170	12,660	7,469	3,515
2001	76,717	76,717	65	1180.3	501	5/7/2001	7/20/2001	26,020	7,375	8,390	2,750
2002	54,586	54,586	65	839.8	558	4/29/2002	7/12/2002	12,310	11,920	8,273	2,173
2003	55,620	55,620	77	722.3		5/10/2003	7/3/2003	20,750	12,010	7,939	2,559
2004	36,593	36,593	77	475.2		4/29/2004	7/15/2004	22,730	11,930	5,850	3,397
2005	6,382		81			5/12/2005	7/19/2005	26,860	15,800	12,240	6,385
2006	1,205		46			4/17/2006	5/12/2006	7,554	27,810	22,410	9,813
2007	15,876	15,876	73	217.5		5/10/2007	7/16/2007	29,380	14,680	6,354	3,558
2008	25,116	25,116	64	392.4		5/13/2008	7/14/2008	26,640	11,910	3,638	6,668
2009	23,199	23,199	89	260.7		4/20/2009	7/17/2009	19,930	8,757	9,806	15,340
2010	10,442	10,442	83	125.8		4/24/2010	7/15/2010	23,600	5,670	3,497	1,895
2011	13,835	13,835	73	189.5		5/2/2011	7/15/2011	22,230	15,130	6,410	2,550
2012	21,396	21,396	87	245.9		4/16/2012	7/13/2012	6,298	10,730	10,060	1,968
2013	37,149	37,149	89	417.4		4/15/2013	7/12/2013	14,390	8,069	12,880	11,370
2014	38,107	38,107	80	476.3		4/22/2014	7/10/2014	25,700	11,580	5,401	6,099
2015	89,467	89,467	89	1005.2		4/20/2015	7/17/2015	17,850	5,128	5,751	5,034
2016	67,528	67,528	86	785.2		4/21/2016	7/15/2016	8,463	5,225	2,779	1,604
2017	62,846	62,846	89	706.1		4/17/2017	7/14/2017	22,160	16,880	11,030	5,458
Mean		29,350		422							
Median		20,796		313							
25th %		12,359		210							

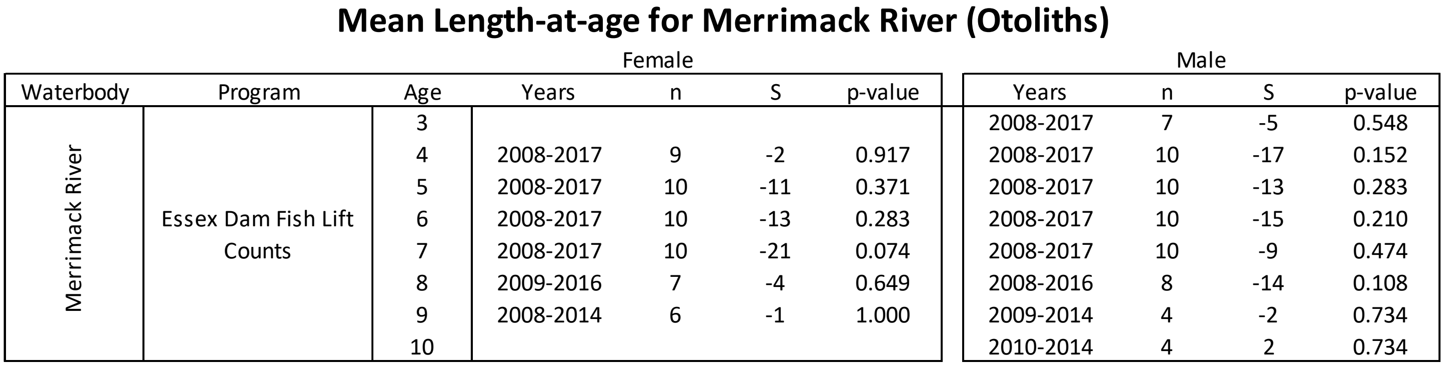
Table 47. American shad age, growth, and sex statistics for adult returns at the Merrimack River (1991–2018). Ageing switched from scale-based to otolith-based in 2009. Source: 2018 ASMFC River Herring and American Shad MA Compliance Report.

						Ratio	Mean Age		Mean FL (mm)		Mean Wgt (kg)		C - R	
Year	Sample #	N (male)	N (Female)	% Male	% Female	(M:F)	Male	Female	Male	Female	Male	Female	Z	S
1991	107	61	46	57.0	43.0	1.3:1.0	4.7	5.3	434	475	1.13	1.59	Unk	Unk
1992	48	23	25	46.0	54.0	0.9:1.0	4.4	5.2	Unk	Unk	Unk	Unk	Unk	Unk
1993	32	6	26	19.0	81.0	0.2:1.0	4.5	5.0	Unk	Unk	Unk	Unk	Unk	Unk
1995	160	101	59	63.0	37.0	1.7:1.0	Unk	Unk	404	465	0.91	1.50	Unk	Unk
1999	212	146	66	69.0	31.0	2.2:1.0	4.8	5.6	406	450	0.91	1.32	Unk	Unk
2000	217	103	114	47.5	52.5	0.9:1.0	4.7	5.6	422	467	1.00	1.50	Unk	Unk
2001	204	115	89	56.4	43.6	1.3:1.0	6.0	6.6	427	471	1.04	1.47	0.87	0.42
2002	199	79	120	39.7	60.3	0.8:1.0	5.7	6.3	432	482	1.10	1.69	0.95	0.39
2003	115	39	76	39.7	60.3	0.5:1.0	5.9	6.7	439	499	1.16	1.92	0.75	0.47
2004	257	152	119	45.5	54.5	1.3:1.0	5.8	6.5	433	482	1.08	1.59	0.79	0.45
2005	200	105	95	52.5	47.5	1.1:1.0	5.9	6.1	443	477	1.11	1.51	1.02	0.36
2006	178	79	99	44.4	55.6	0.8:1.0	4.9	5.7	407	468	0.96	1.49	0.87	0.42
2007	212	99	113	46.7	53.3	0.9:1.0	4.4	5.1	429	464	1.16	1.55	0.81	0.45
2008	227	113	114	49.8	50.2	1.0:1.0	5.4	5.6	427	464	1.10	1.43	0.95	0.38
2009	214	96	118	44.9	55.1	0.8:1.0	5.9	6.5	429	461	1.08	1.38	0.85	0.43
2010	181	65	116	36.0	64.0	0.6:1.0	5.1	5.6	412	455	1.04	1.53	0.88	0.41
2011	258	148	110	57.0	43.0	1.3:1.0	5.7	6.6	408	452	1.01	1.39	0.76	0.47
2012	243	155	88	63.8	36.2	1.8:1.0	5.1	5.5	404	436	0.95	1.28	1.00	0.37
2013	144	69	75	48.0	52.0	0.9:1.0	5.3	5.9	407	451	0.93	1.40	1.50	0.20
2014	302	158	144	52.0	48.0	1.1:1.0	5.1	5.8	403	449	0.92	1.36	1.22	0.29
2015	357	175	182	49.0	51.0	0.9:1.0	4.9	5.4	402	445	0.92	1.35	1.20	0.30
2016	225	91	134	40.0	60.0	0.7:1.0	5.3	5.7	400	437	0.90	1.31	2.50	0.10
2017	246	115	131	47.0	53.0	0.9:1.0	5.5	5.9	409	443	0.92	1.32	1.68	0.19
2018	214	92	122	43.0	57.0	0.8:1.0	5.4	6.0	405	444	0.88	1.29	1.10	0.30

Table 48. Repeat spawning percentage (RSP) of sub-sampled American shad collected at the Essex Dam fish-lift, Merrimack River, 2004-2017 (Source: 2018 ASMFC River Herring and American Shad MA Compliance Report). The numbers in parentheses following RSP are the years of repeat spawning, with RSP (0) for virgin shad.

YEAR	*N*	*RSP (0)*	*RSP (1)*	*RSP (2)*	*RSP (3)*	*RSP (4)*	*RSP (5)*	*RSP (6)*	*Z($_{RPS}$)*	*S($_{RPS}$)*
2004	243	53	23	13	6	4	1	0	0.77	0.46
2005	182	53	25	13	8	2	0	0	0.81	0.44
2006	175	66	22	8	4	0	0	0	0.94	0.39
2007	208	76	15	7	1	0	0	0	1.25	0.29
2008	211	84	7	5	3	0	0	0	1.11	0.33
2009	151	32	45	15	5	3	1	0	1.02	0.36
2010	181	38	43	15	3	1	1	0	1.20	0.30
2011	259	58	19	13	8	2	0	0	0.82	0.44
2012	178	69	21	7	3	1	0	0	1.16	0.31
2013	144	64	26	7	3	1	0	0	1.13	0.32
2014	254	61	31	6	1	0	0	0	1.34	0.26
2015	292	78	12	9	1	0	0	0	1.45	0.23
2016	225	63	22	12	3	0	0	0	1.40	0.25
2017	244	62	24	14	0	0	1	0	1.10	0.33

Table 49. Mean length-at-age for Merrimack River (otoliths).



Mean Length-at-age for Merrimack River (Otoliths)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Merrimack River	Essex Dam Fish Lift Counts	3					2008-2017	7	-5	0.548
		4	2008-2017	9	-2	0.917	2008-2017	10	-17	0.152
		5	2008-2017	10	-11	0.371	2008-2017	10	-13	0.283
		6	2008-2017	10	-13	0.283	2008-2017	10	-15	0.210
		7	2008-2017	10	-21	0.074	2008-2017	10	-9	0.474
		8	2009-2016	7	-4	0.649	2008-2016	8	-14	0.108
		9	2008-2014	6	-1	1.000	2009-2014	4	-2	0.734
		10					2010-2014	4	2	0.734

Table 50. American shad stocked in the Pawcatuck River, RI, 1972-2017.

Year	Fertilized Eggs	Hatched Fry	Stocked Adults*
1972	57,000		
1973	147,500		
1974	64,000		
1975		12,000	374
1976		40,000	2,500
1977		75,000	2,000
1978		94,000	2,100
1979		97,000	3,500
1980		50,000	4,700
1981			3,281
1982			1,667
1983			2,953
1984			859
1985			500
2009			1,077
2010		919,703	
2011		284,745	
2012		2,157,163	
2013		3,520,812	
2014		2,504,704	
2015		1,384,101	
2016		1,072,252	
2017		583,364	

* Source-the Connecticut River

Table 51. Fish counts from the Potter Hill Fishway Trap on the Pawcatuck River.

Year	Index	Year	Index
1980	165	1999	2,149
1981	882	2000	608
1982	644	2001	774
1983	491	2002	768
1984	2,163	2003	243
1985	4,219	2004	301
1986	3,000	2005	151
1987	724	2006	92
1988	580	2007	44
1989	533	2008	70
1990	904	2009	69
1991	1,900	2010	44
1992	2,119	2011	78
1993	797	2012	156
1994	270	2013	279
1995	740	2014	72
1996	1,508	2015	159
1997	2,061	2016	169
1998	936	2017	331

Table 52. Connecticut River Commercial CPUE number of observations (n), proportion positive observations, index values (weight), and CVs.

Year	n	Proportion Positive	Index	CV
1995	239	1.00	145.36	0.06
1996	168	1.00	187.41	0.07
1997	116	1.00	383.28	0.07
1998	176	1.00	256.90	0.05
1999	124	1.00	181.65	0.06
2000	123	1.00	477.06	0.06
2001	143	1.00	882.10	0.11
2002	216	1.00	756.09	0.06
2003	226	1.00	713.28	0.06
2004	226	1.00	364.97	0.06
2005	218	1.00	424.56	0.07
2006	185	1.00	444.05	0.10
2007	205	1.00	597.02	0.07
2008	204	1.00	228.90	0.05
2009	202	1.00	173.62	0.05
2010	135	1.00	185.34	0.06
2011	133	1.00	245.97	0.07
2012	166	1.00	482.64	0.06
2013	150	1.00	483.97	0.06
2014	163	1.00	433.93	0.07
2015	131	1.00	408.61	0.08
2016	131	1.00	316.52	0.09
2017	111	1.00	491.50	0.06

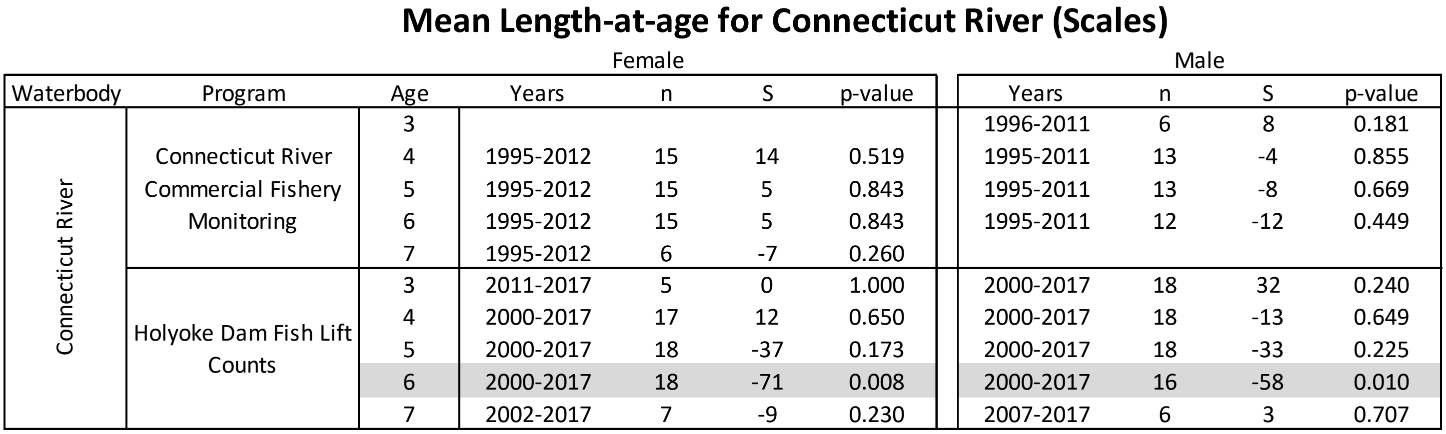
Table 53. Holyoke Dam Fish Lift Counts (numbers).

Year	Index	Year	Index
1975	114,137	1997	299,448
1976	346,702	1998	315,810
1977	202,997	1999	193,187
1978	144,698	2000	224,483
1979	255,753	2001	273,220
1980	376,276	2002	374,543
1981	377,124	2003	286,795
1982	294,834	2004	191,295
1983	528,185	2005	116,519
1984	496,879	2006	154,745
1985	481,668	2007	158,812
1986	352,122	2008	153,149
1987	271,974	2009	160,669
1988	294,157	2010	164,439
1989	353,819	2011	244,177
1990	363,825	2012	490,431
1991	523,153	2013	392,967
1992	721,764	2014	370,506
1993	340,431	2015	412,656
1994	180,807	2016	385,930
1995	190,295	2017	537,249
1996	276,289		

Table 54. Connecticut River Juvenile Beach Seine Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV	Year	n	Proportion Positive	Index	CV
1978	71	0.72	5.89	0.21	1998	108	0.53	3.65	0.22
1979	64	0.98	7.84	0.14	1999	96	0.59	5.47	0.25
1980	81	0.86	9.21	0.17	2000	98	0.59	4.42	0.22
1981	93	0.84	6.05	0.15	2001	90	0.47	2.73	0.27
1982	82	0.59	1.81	0.19	2002	97	0.58	5.55	0.24
1983	95	0.75	4.99	0.18	2003	87	0.67	6.88	0.22
1984	71	0.61	3.37	0.22	2004	97	0.73	5.62	0.19
1985	77	0.83	7.14	0.17	2005	93	0.77	10.08	0.20
1986	90	0.84	6.29	0.17	2006	96	0.49	1.82	0.23
1987	94	0.80	9.89	0.19	2007	97	0.75	8.15	0.21
1988	93	0.77	5.68	0.18	2008	86	0.62	5.06	0.23
1989	96	0.67	4.85	0.21	2009	97	0.59	3.40	0.21
1990	96	0.85	10.39	0.18	2010	103	0.73	10.23	0.22
1991	102	0.61	4.26	0.23	2011	83	0.64	3.08	0.21
1992	104	0.72	7.55	0.23	2012	88	0.49	3.03	0.24
1993	99	0.76	9.49	0.23	2013	91	0.64	3.16	0.19
1994	102	0.77	12.22	0.22	2014	90	0.76	8.09	0.20
1995	104	0.35	1.34	0.27	2015	91	0.75	8.53	0.21
1996	96	0.67	6.50	0.21	2016	96	0.66	16.70	0.29
1997	105	0.70	7.15	0.21	2017	100	0.72	5.00	0.20

Table 55. Mean length-at-age for the Connecticut River (scales).



Mean Length-at-age for Connecticut River (Scales)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Connecticut River	Connecticut River Commercial Fishery Monitoring	3					1996-2011	6	8	0.181
		4	1995-2012	15	14	0.519	1995-2011	13	-4	0.855
		5	1995-2012	15	5	0.843	1995-2011	13	-8	0.669
		6	1995-2012	15	5	0.843	1995-2011	12	-12	0.449
		7	1995-2012	6	-7	0.260				
	Holyoke Dam Fish Lift Counts	3	2011-2017	5	0	1.000	2000-2017	18	32	0.240
		4	2000-2017	17	12	0.650	2000-2017	18	-13	0.649
		5	2000-2017	18	-37	0.173	2000-2017	18	-33	0.225
		6	2000-2017	18	-71	0.008	2000-2017	16	-58	0.010
		7	2002-2017	7	-9	0.230	2007-2017	6	3	0.707

Table 56. Historic American shad landings (Hudson River only).

Year	NY Hudson Best	NJ Hudson Best	Hudson Total Best-lbs
1880			2,750,000
1881			
1882			
1883			
1884			
1885			3,500,000
1886			3,750,000
1887			4,750,000
1888			4,500,000
1889			4,250,000
1890			4,250,000
1891			2,750,000
1892			
1893			
1894			
1895	2,582,234	1,462,402	4,044,635
1896	1,470,028	590,800	2,060,828
1897			2,500,000
1898			3,000,000
1899			
1900			
1901			3,500,000
1902			
1903			
1904			500,000
1905			
1906			
1907			
1908			
1909			
1910			1,000,000
1911			
1912			
1913			
1914			
1915	48,564	20,104	68,668
1916	32,923	7,250	40,173
1917	38,344	5,040	43,384
1918	220,602	14,000	234,602
1919	301,306	73,668	374,974
1920	157,715	42,129	199,844
1921	104,883	25,920	130,803
1922	128,324	46,862	175,186
1923	97,863	23,865	121,728
1924	72,519	21,850	94,369
1925	110,359	13,975	124,334
1926	219,183	46,237	265,420
1927	299,693	58,362	358,055
1928	194,211	52,020	246,231
1929	157,895	38,850	196,745
1930	165,004	41,500	206,504
1931	342,611	72,000	414,611
1932	397,754	132,000	529,754
1933	347,656	171,024	518,680
1934	314,200	123,800	438,000
1935	453,300	394,100	847,400
1936	834,400	1,633,500	2,467,900
1937	976,000	1,756,200	2,732,200
1938	972,500	1,494,500	2,467,000
1939	1,516,400	1,754,300	3,270,700
1940	1,297,700	1,816,700	3,114,400
1941	1,341,000	1,792,500	3,133,500
1942	1,294,800	1,891,100	3,185,900
1943	1,640,000	1,585,350	3,225,350
1944	1,651,200	2,158,200	3,809,400
1945	2,091,300	1,385,900	3,477,200
1946	1,446,900	1,525,243	2,972,143
1947	957,400	1,024,392	1,981,792
1948	1,121,600	1,232,800	2,354,400
1949	748,800	978,570	1,727,370
1950	471,068	520,958	992,026
1951	423,476	331,523	754,999
1952	773,300	739,800	1,513,100
1953	491,200	572,600	1,063,800
1954	706,700	684,400	1,391,100
1955	615,000	1,017,100	1,632,100
1956	703,700	1,138,900	1,842,600
1957	626,000	1,082,200	1,708,200
1958	644,500	718,600	1,363,100
1959	672,200	732,400	1,404,600
1960	417,500	566,900	984,400
1961	302,700	501,000	803,700
1962	218,200	309,500	527,700
1963	132,500	212,500	345,000
1964	78,200	103,800	182,000
1965	120,100	117,600	237,700
1966	67,900	48,400	116,300
1967	79,000	99,900	178,900
1968	113,100	141,300	254,400
1969	122,700	120,400	243,100
1970	95,900	135,700	231,600
1971	70,100	100,800	170,900
1972	93,700	209,100	302,800
1973	153,500	98,200	251,700
1974	163,600	67,900	231,500
1975	196,200	37,100	233,300
1976	183,300	29,100	212,400
1977	120,400	63,800	184,200
1978	306,500	110,900	417,400
1979	430,300	59,800	490,100
1980	1,135,300	161,700	1,297,000
1981	482,800	100,600	583,400
1982	309,600	48,900	358,500
1983	415,400	27,200	442,600
1984	567,900	76,800	644,700
1985	680,064	53,400	733,464
1986	615,768	119,000	734,768
1987	607,482	31,900	639,382
1988	586,832	111,700	698,532
1989	351,500	63,700	415,200
1990	321,964	57,419	379,383
1991	272,519	29,060	301,579
1992	223,980	28,570	252,550
1993	112,368	8,600	120,968
1994	116,414	15,500	131,914
1995	433,784	0	433,784
1996	281,881	0	281,881
1997	229,554	0	229,554
1998	367,707	0	367,707
1999	245,117	0	245,117
2000	233,690	0	233,690
2001	165,311	0	165,311
2002	212,773	0	212,773
2003	179,485	0	179,485
2004	129,458	0	129,458
2005	114,718	0	114,718
2006	96,551	0	96,551
2007	89,953	0	89,953
2008	41,420	0	41,420
2009	12,635	0	12,635
2010	123	0	123
2011	20	0	20
2012	90	0	90
2013	40	0	40
2014	7	0	7
2015	15	0	15
2016	0	0	0
2017	52	0	52

Table 57. Survey results of two recreational creels targeting Hudson River shad fishing.

Creel period	Catch rate: fish per hour		Catch estimate	Retention rate	Mean size (Tl - mm)
	Boat	Shore			
March 16 - June 30, 2001	1.50	1.53	19,766	6.5%	511
March 16 - April 30, 2005	--	0.12	6,582	7.7%	541
May 1 - June 17, 2005	0.59	0.58			

Table 58. Maturity schedule for Hudson River American shad estimated by Deriso (1999).

Age	Male	Female
1	0%	0%
2	0%	0%
3	4%	0%
4	48%	15%
5	86%	63%
6	97%	91%
7	99%	98%
8	100%	100%
9	100%	100%
10	100%	100%
11	100%	100%
12	100%	100%
13	100%	100%
14	100%	100%

Table 59. Fecundity estimates of Hudson River American shad.

Fecundity of Hudson Shad		
Age	**1951 (Lehman 1955)**	**2001 (Piper 2003)**
3	95,491	299,469
4	157,637	394,727
5	219,783	489,985
6	281,929	585,243
7	344,075	680,501
8	406,221	775,759
9	468,367	871,017
10	530,513	966,275
11	592,659	1,061,533
12	654,805	1,156,791
13	716,951	1,252,049
14	779,097	1,347,307

Table 60. Entrainment estimates derived in CHG&E et al (1999).

Year	Conditional Entrainment Mortality Rates (CEMR)
1974	3.1%
1975	36.5%
1976	35.6%
1977	7.1%
1978	18.9%
1979	29.5%
1980	37.7%
1981	15.5%
1982	11.4%
1983	18.9%
1984	21.0%
1985	19.6%
1986	10.7%
1987	30.0%
1988	38.8%
1989	39.2%
1990	47.7%
1991	32.9%
1992	52.0%
1993	9.6%
1994	21.5%
1995	12.3%
1996	6.5%
1997	16.9%

Table 61. Observed discard of American shad in the commercial gill net fishery in the Hudson River Estuary, 1980-2009.

Year	Trips	Fishers	Catch				Discards				% Discards	% of Discards as Males
			Male	Female	Unknown	Total	Male	Female	Unknown	Total		
1980	36	19	720	2,716	5	3,441	242	61	2	305	8.9%	79.0%
1981	53	19	1,508	3,344	3	4,855	686	40	0	726	15.0%	94.0%
1982	66	24	1,935	3,735	1	5,671	547	48	0	595	10.5%	92.0%
1983	55	21	2,336	2,322	2	4,660	902	27	2	931	20.0%	97.0%
1984	63	21	1,425	2,721	266	4,412	852	1	100	953	21.6%	89.0%
1985	59	13	1,832	4,018	286	6,136	1,031	111	4	1,146	18.7%	90.0%
1986	60	11	2,705	5,745	158	8,608	1,579	55	152	1,786	20.7%	88.0%
1987	55	12	1,995	7,366	31	9,392	987	176	22	1,185	12.6%	83.0%
1988	53	11	2,887	7,263	9	10,159	1,994	27	9	2,030	20.0%	98.0%
1989	37	9	1,219	3,553	214	4,986	431	32	30	493	9.9%	87.0%
1990	23	3	526	2,232	15	2,773	262	1	5	268	9.7%	98.0%
1991	22	4	251	2,059	21	2,331	2	5	3	10	0.4%	20.0%
1992	41	8	358	3,316	12	3,686	67	1	2	70	1.9%	96.0%
1993	9	4	111	1,133	2	1,246	42	0	2	44	3.5%	95.0%
1994	9	3	64	1,230	0	1,294	0	0	0	0	0.0%	--
1995	14	3	230	1,596	0	1,826	94	0	0	94	5.1%	100.0%
1996	24	5	324	1,930	2	2,256	31	1	0	32	1.4%	97.0%
1997	26	9	315	1,392	3	1,710	136	3	3	142	8.3%	96.0%
1998	22	8	974	2,153	0	3,127	847	0	0	847	27.1%	100.0%
1999	40	8	551	3,128	36	3,715	229	13	36	278	7.5%	82.0%
2000	36	7	1,013	2,591	3	3,607	497	4	3	504	14.0%	99.0%
2001	36	8	1,275	2,923	8	4,206	918	4	0	922	21.9%	100.0%
2002	13	4	1,449	973	30	2,452	1,277	36	0	1,313	53.5%	97.0%
2003	8	5	414	440	0	854	251	0	0	251	29.4%	100.0%
2004	15	6	781	786	0	1,567	534	0	0	534	34.1%	100.0%
2005	21	4	1,427	1,266	1	2,694	961	3	0	964	35.8%	100.0%
2006	16	3	425	667	1	1,093	79	1	0	80	7.3%	99.0%
2007	7	4	98	125	0	223	1	2	0	3	1.3%	33.0%
2008	6	2	44	101	1	146	0	0	1	1	0.7%	0.0%
2009	6	2	35	173	0	208	0	0	0	0	0.0%	--

Table 62. Annual CPUE Estimates for American shad from observed commercial monitoring trips. Gray indicates poor sampling coverage.

		Annual weekly CPUE - FIXED GEAR-FEMALES										Annual weekly CPUE - FIXED GEAR- MALES									
		Week of Year									Sum of	Week of Year									Sum of
Year	Trips	13	14	15	16	17	18	19	20	21	weekly	13	14	15	16	17	18	19	20	21	weekly
1980	25			3.38	8.90	4.28	1.27	0.34	0.93	0.00	19.10			1.20	2.17	0.47	0.13	0.02	0.14	0.10	4.24
1981	24		0.62	3.58	2.09	5.45	0.99	1.03	0.71	0.00	14.46		0.64	3.62	0.67	0.56	0.07	0.08	0.47	0.06	6.16
1982	37			0.41	1.99	2.34	2.94		0.13		7.81			0.26	1.41	0.84	0.40		0.05		2.97
1983	38			1.18	0.81	2.64	2.00	2.57			9.20			1.79	0.48	2.21	0.69	0.48			5.66
1984	55		0.00	0.02	0.52	3.19	4.83	0.29	0.19		9.04		0.00	0.00	0.24	1.40	1.61	0.06	0.06		3.37
1985	54		2.28	6.91	4.82	6.39		1.22	4.97	0.06	26.65		2.14	5.35	1.44	0.77		0.17	0.79	0.00	10.66
1986	47	7.82	7.61	8.83	7.69	7.65	2.56	8.50	1.61		52.27	9.19	5.30	7.37	1.73	0.41	0.05	0.57	0.23		24.84
1987	49		11.81	6.90	15.13	5.91	3.92	3.83			47.49		4.62	3.98	3.28	0.56	0.27	0.33			13.04
1988	38		3.74	11.59	6.77	10.36	5.77	3.99			42.20		3.23	8.14	4.11	2.57	0.80	0.55			19.41
1989	30		0.83	1.39	7.51	11.84	12.22				33.79		1.05	1.25	3.39	2.51	1.10				9.30
1990	23		2.88	4.86	3.98	4.89					16.62		1.37	1.50	0.26	0.40					3.53
1991	22		6.86	4.14	4.61	1.53	1.17				18.31		0.90	0.77	0.50	0.06	0.09				2.33
1992	32		1.10	2.79	2.69	6.53	1.50				14.60		0.13	0.41	0.27	0.39	0.12				1.31
1993	8				8.55	4.47					13.02				0.73	0.18					0.92
1994	9				10.44	3.88	9.04	0.88			24.23				0.66	0.13	0.07	0.00			0.85
1995	12			12.37	10.47	5.88				0.00	28.72			1.52	1.64	0.33				0.00	3.49
1996	19			2.19	5.21	5.38	4.43	3.04			20.25			0.28	1.02	0.56	0.18	0.15			2.18
1997	23			3.13	2.43	1.91	0.78				8.24			0.32	0.31	0.30	0.10				1.02
1998	16			2.00	6.41	1.03					9.44			0.54	1.22	0.09					1.85
1999	27				2.29	3.76	4.76				10.81				0.26	0.36	0.18				0.80
2000	16		2.77	5.96	8.51	4.21	10.16				31.60		1.01	2.46	1.41	0.76	0.85				6.49
2001	22		0.12	14.63	5.90	7.18					27.83		0.00	2.63	0.78	0.28					3.69
2002	4			5.35		0.00					5.35			7.31		0.00					7.31
2003	1				6.13						6.13				1.04						1.04
2004	2				24.75	3.96					28.71				2.25	0.36					2.61
2005	1					0.99					0.99					0.00					0.00
2006	2					6.74					6.74					1.66					1.66
2007	3				12.86		0.74				13.59				1.61		0.00				1.61
2008	2			0.90	4.30						5.20			0.00	0.86						0.86

Table 63. Comparison of two methods for CPUE estimation for catches observed in the commercial fishery monitoring survey.

Year	Refined Trips*	GAM Predicted (5.5 mesh only) Catch rate	se	cv	Traditional AUC (all mesh)
1980	24	7.60	1.91	0.25	19.10
1981	24	3.43	0.80	0.23	14.46
1982	32	3.84	0.80	0.21	7.81
1983	38	2.80	0.70	0.25	9.20
1984	20	3.52	0.94	0.27	9.04
1985	28	7.25	1.80	0.25	26.65
1986	26	9.68	2.45	0.25	52.27
1987	17	10.77	2.79	0.26	47.49
1988	29	11.05	2.61	0.24	42.20
1989	25	8.79	2.30	0.26	33.79
1990	21	7.66	1.98	0.26	16.62
1991	22	5.68	1.48	0.26	18.31
1992	32	3.75	0.92	0.25	14.60
1993	8	5.07	1.72	0.34	13.02
1994	9	6.48	2.12	0.33	24.23
1995	11	13.27	4.11	0.31	28.72
1996	19	5.04	1.39	0.28	20.25
1997	23	2.53	0.65	0.26	8.24
1998	15	2.89	0.83	0.29	9.44
1999	27	2.89	0.66	0.23	10.81
2000	12	9.05	2.79	0.31	31.60
2001	22	12.33	2.90	0.24	27.83

*5.5" mesh trips only

Table 64. Observed lengths and weights of American shad in the commercial gill net fishery in the Hudson River Estuary, 1980-2001.

	Females						Males					
	TL (cm)			Weight (kg)			TL (cm)			Weight (kg)		
Year	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD
1980	272	55.0	2.6	272	2.10	0.34	110	51.7	2.8	110	1.57	0.27
1981	579	56.3	3.0	579	2.09	0.40	225	52.7	2.6	225	1.51	0.25
1982	426	57.0	3.3	420	2.31	0.45	173	53.4	3.2	172	1.78	0.30
1983	389	56.7	3.7	388	2.30	0.51	153	53.4	3.4	152	1.75	0.35
1984	399	57.9	3.6	411	2.51	0.51	138	53.3	3.7	139	1.83	0.41
1985	474	57.2	4.0	473	2.49	0.60	117	53.5	3.2	115	1.84	0.34
1986	480	58.7	3.8	476	2.64	0.57	154	54.2	3.5	153	1.92	0.41
1987	470	59.5	3.9	469	2.65	0.55	71	56.5	2.8	71	2.12	0.33
1988	254	58.2	4.0	253	2.57	0.57	118	53.9	2.7	118	1.91	0.37
1989	332	57.8	3.2	300	2.50	0.47	192	54.9	2.9	174	2.04	0.37
1990	223	58.5	4.0	223	2.53	0.55	40	54.4	4.0	40	1.91	0.49
1991	223	56.9	3.9	220	2.27	0.47	29	54.7	4.1	27	1.79	0.40
1992	364	54.6	3.2	361	1.96	0.40	143	51.3	3.9	138	1.46	0.39
1993	73	55.5	3.4	73	1.96	0.40	35	52.2	3.0	35	1.60	0.30
1994	114	54.3	2.5	104	1.80	0.31	15	51.4	1.9	8	1.57	0.21
1995	149	54.4	2.1	107	1.99	0.28	113	51.7	2.2	78	1.67	0.19
1996	355	54.0	2.9	355	1.96	0.35	63	52.1	2.3	63	1.63	0.27
1997	242	53.7	3.5	242	1.91	0.40	124	51.5	3.2	124	1.52	0.29
1998	275	53.1	3.7	275	1.90	0.44	84	50.5	2.9	84	1.53	0.28
1999	306	54.2	3.3	305	1.87	0.38	157	51.6	3.0	157	1.47	0.28
2000	305	54.3	2.8	293	2.03	0.39	202	51.1	3.1	192	1.53	0.30
2001	355	54.7	3.3	356	1.90	0.36	194	52.1	2.6	194	1.47	0.24

Table 65. Age structure and repeat spawn data of American shad from fishery-dependent sampling (commercial gill net) in the Hudson River Estuary, 1980-2001, by sex. The ages from 1996-2001 were estimated with a length-age key and are indicated with an asterisk (*). Table continues on next page.

Female American Shad - Commercial Fishery Sampling																
	Age												Mean	Mean	%	%
Year	3	4	5	6	7	8	9	10	11	12	13	Total	age	RS	Virgin	Repeat
								Female								
1980		6	100	101	36	11	3					257	5.8	0.72	50%	50%
1981		7	104	160	87	56	12	4				430	6.3	1.10	41%	59%
1982		11	101	105	79	48	17	8	1			370	6.4	1.23	39%	61%
1983	1	9	104	97	31	28	14	16	1			301	6.2	0.97	58%	42%
1984		6	57	99	48	20	23	9	2	2		266	6.5	1.30	48%	52%
1985		18	91	107	68	26	20	11	6	2		349	6.4	1.25	44%	56%
1986		8	87	91	49	27	16	6	1	2		287	6.3	1.33	41%	59%
1987		2	63	104	74	46	27	30	12	3	2	363	7.1	1.85	27%	73%
1988	1	7	52	74	60	32	13	4				243	6.5	1.52	28%	72%
1989		2	69	113	82	36	7	3				312	6.4	1.29	41%	59%
1990		3	42	61	48	28	9	4	1	1		197	6.6	1.61	33%	67%
1991		17	59	62	45	12	8	1	1			205	6.0	1.18	46%	54%
1992		11	148	115	51	13	6	2				346	5.8	0.71	55%	45%
1993		5	16	23	11	6	1					62	6.0	1.16	35%	65%
1994			28	46	24	5	2					105	6.1	0.96	42%	58%
1995		3	53	54	23	4	2	1				140	5.9	0.73	54%	46%
1996*	2.5	22.2	154.2	122.0	41.8	9.3	1.9	0.8	0.1			355	5.6			
1997*	0.5	18.6	111.7	69.7	29.6	8.6	2.2	0.8	0.2	0.0	0.0	242	5.6			
1998*	5.0	26.6	129.2	72.0	29.0	8.8	3.0	1.1	0.2	0.0	0.0	275	5.5			
1999*	1.5	19.2	135.1	97.4	36.2	10.8	3.7	1.7	0.3	0.1	0.0	306	5.7			
2000*	1.5	18.0	137.9	100.3	32.8	9.6	3.2	1.3	0.2	0.0	0.0	305	5.6			
2001*	1.5	19.9	137.5	124.2	52.7	13.8	3.5	1.6	0.3	0.1	0.0	355	5.8			

Table 65 Continued

Male American Shad - Commercial Fishery Sampling																
	Age												Mean	Mean	%	%
Year	3	4	5	6	7	8	9	10	11	12	13	Total	age	Rs	Virgin	Repeat
1980		9	26	29	28	10						102	6.0	1.42	23%	77%
1981		12	23	45	57	23	1					161	6.4	1.74	19%	81%
1982	1	11	24	29	33	20	17	3				138	6.6	2.03	22%	78%
1983		9	37	23	16	19	9	5	2			120	6.5	1.87	29%	71%
1984		1	28	24	11	16	6	3	1			90	6.5	1.99	23%	77%
1985		5	20	27	21	10	4	2				89	6.3	1.84	29%	71%
1986		7	28	25	18	10	4	1	2			95	6.2	1.87	17%	83%
1987			4	16	11	12	10	2	3			58	7.4	2.78	5%	95%
1988	1	3	19	44	25	12	7	3				114	6.5	1.96	15%	85%
1989		1	21	64	43	38	11	2				180	6.8	2.19	13%	87%
1990		1	8	8	6	5	1					29	6.3	1.69	31%	69%
1991	2	2	1	5	9	6						25	6.4	2.32	16%	84%
1992	2	20	28	39	30	9	1					129	5.8	1.20	33%	67%
1993		3	3	13	11	2	0					32	6.2	1.66	16%	84%
1994			2	6	5	0	1					14	6.4	1.79	7%	93%
1995		4	22	44	26	9	1					106	6.2	1.47	25%	75%
1996*	0.2	7.9	22.7	20.6	8.9	2.3	0.4	0.1	0.0			63	5.6			
1997*	1.2	15.6	32.6	37.6	24.7	9.5	2.3	0.4	0.0			124	5.9			
1998*	0.3	11.1	29.2	26.5	11.8	3.9	0.9	0.2	0.0			84	5.7			
1999*	0.8	17.0	47.9	48.5	28.3	11.0	2.9	0.6	0.1			157	5.9			
2000*	0.7	25.9	69.5	62.2	30.2	10.0	2.1	0.4	0.0			201	5.7			
2001*	0.5	14.6	51.1	67.5	41.1	14.4	3.8	0.7	0.2			194	6.0			

Table 66. Mean total length and weight of American shad collected during spawning stock sampling in the Hudson River Estuary. All seine and electrofishing data are combined.

	Males						Females						
	Total length (cm)			Weight (kg)			Total length (cm)			Weight (kg)			
Year	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD	Sex Ratio (% Females)
1983	31	51.9	3.7	31	1.43	0.31	55	55.7	4.1	54	1.86	0.37	64%
1984	86	51.4	4.5	85	1.43	0.40	61	58.7	4.2	61	2.36	0.54	43%
1985	203	49.1	5.0	148	1.17	0.42	126	57.5	4.6	80	2.01	0.63	38%
1986	416	49.2	4.7	393	1.30	0.39	287	56.8	4.4	277	2.04	0.54	41%
1987	316	50.1	4.8	313	1.27	0.40	314	57.0	4.5	308	1.91	0.51	50%
1988	228	50.6	3.9	219	1.37	0.37	315	57.3	3.9	309	2.01	0.52	58%
1989	169	50.1	4.9	169	1.24	0.41	213	56.7	4.0	211	1.88	0.52	58%
1990	56	47.5	4.4	55	1.02	0.34	62	55.3	4.7	63	1.68	0.45	53%
1991	121	46.1	3.6	119	0.89	0.22	104	53.6	3.5	103	1.48	0.33	47%
1992	965	46.0	2.9	817	0.88	0.21	479	52.6	3.3	474	1.44	0.37	33%
1993	332	45.9	2.7	330	0.80	0.19	160	51.4	3.1	154	1.18	0.27	33%
1994	93	46.2	2.7	86	0.88	0.17	89	51.5	2.3	83	1.25	0.24	49%
1995	299	47.2	3.5	292	0.99	0.24	589	53.1	2.7	577	1.49	0.31	67%
1996	295	46.0	3.8	292	0.87	0.27	131	53.3	4.4	126	1.55	0.51	32%
1997	78	45.5	3.9	76	0.90	0.26	77	52.2	4.6	76	1.43	0.42	50%
1998	164	45.7	3.2	160	0.95	0.22	145	53.0	3.7	143	1.53	0.40	48%
1999	196	47.1	3.5	193	0.92	0.21	209	51.9	3.4	207	1.33	0.34	53%
2000	216	47.6	3.5	207	1.06	0.26	219	53.5	3.0	215	1.51	0.30	51%
2001	574	47.8	3.6	538	0.97	0.24	486	54.2	3.5	462	1.50	0.35	46%
2002	12	49.9	3.8	12	1.33	0.34	16	55.2	3.7	15	2.02	0.53	57%
2003	274	49.5	3.5	271	1.20	0.30	342	56.0	3.9	338	1.83	0.45	56%
2004	282	50.2	4.3	283	1.25	0.34	543	56.9	4.4	540	1.92	0.53	66%
2005	224	49.1	4.9	223	1.17	0.35	382	56.4	4.2	380	1.84	0.48	63%
2006	133	47.4	4.6	129	1.11	0.34	294	55.9	5.1	293	1.89	0.56	69%
2007	72	47.0	4.4	72	1.12	0.35	121	54.9	4.9	121	1.79	0.54	64%
2008	110	46.3	4.8	110	0.98	0.32	258	53.8	5.3	256	1.73	0.56	72%
2009	150	44.3	3.2	148	0.82	0.22	33	52.2	4.5	32	1.45	0.39	21%
2010	282	45.9	2.5	279	0.92	0.17	137	50.6	3.3	136	1.26	0.31	34%
2011	36	45.8	2.9	36	0.99	0.24	69	52.2	3.2	68	1.45	0.28	66%
2012	195	46.3	4.0	192	1.02	0.29	149	52.9	3.5	148	1.53	0.36	44%
2013	160	46.4	3.0	160	0.91	0.20	149	52.4	3.2	147	1.43	0.31	49%
2014	78	47.9	3.0	78	1.02	0.20	118	52.9	3.0	116	1.43	0.33	61%
2015	82	47.0	3.2	82	0.93	0.19	43	52.2	3.0	43	1.36	0.29	35%
2016	305	46.0	2.8	303	0.89	0.17	154	50.8	3.0	154	1.26	0.22	34%
2017	422	47.5	3.0	422	0.99	0.20	321	52.1	2.7	320	1.37	0.25	45%
2018	399	47.1	3.1	396	0.96	0.20	539	52.2	2.8	537	1.43	0.26	58%

Table 67. Age structure of American shad from spawning stock sampling in the Hudson River Estuary, by sex. Seine and electrofishing gears combined. Bold and italic ages were estimated using an age-length key. Table continues on next page.

	Female														
	Aged	ALK est	Total	Age											Mean age
Year				3	4	5	6	7	8	9	10	11	12	13	
1983	53	2	55	0	7	17	13	8	5	3	1	0	0	0	6.0
1984	54	7	61	0	1	8	17	16	8	6	4	2	0	0	7.1
1985	94	32	126	1	13	21	36	23	15	7	6	5	0	0	6.6
1986	197	90	287	0	23	78	95	40	26	15	4	7	0	0	6.2
1987	211	103	314	0	19	108	77	39	30	24	13	2	2	1	6.3
1988	303	12	315	0	17	93	108	58	14	11	7	6	2	0	6.2
1989	197	16	213	0	9	60	56	50	21	7	7	3	0	0	6.4
1990	63	0	62	0	3	23	15	13	6	1	1	0	0	0	6.0
1991	98	6	104	1	10	35	37	15	3	1	1	0	0	0	5.7
1992	434	45	479	0	26	192	175	71	7	6	2	0	0	0	5.7
1993	148	12	160	0	9	63	58	20	10	0	0	0	0	0	5.7
1994	77	12	89	0	0	56	23	8	2	0	0	0	0	0	5.5
1995	451	137	588	4	80	284	172	43	4	1	0	0	0	0	5.3
1996	114	17	131	0	32	58	26	9	5	2	0	0	0	0	5.3
1997	75	2	77	0	14	33	13	6	5	6	0	0	0	0	5.7
1998	130	15	145	0	31	74	27	7	6	1	0	0	0	0	5.2
1999	185	24	209	0	39	120	33	16	0	2	0	0	0	0	5.2
2000	192	27	219	0	50	128	30	6	2	2	1	0	0	0	5.0
2001	430	57	487	8	82	197	140	48	7	4	1	0	0	0	5.4
2002	72	17	89	0	12	29	23	22	3		electrofish only				5.7
2003	***0***	***342***	***342***	***1***	***20***	***94***	***100***	***74***	***33***	***15***	***4***	***1***	***0***	***0***	***6.2***
2004	***0***	***542***	***542***	***1***	***28***	***133***	***136***	***118***	***62***	***42***	***16***	***5***	***0***	***0***	***6.5***
2005	***0***	***382***	***382***	***1***	***21***	***103***	***105***	***79***	***38***	***23***	***9***	***3***	***0***	***0***	***6.3***
2006	***0***	***294***	***294***	***1***	***24***	***83***	***71***	***55***	***29***	***18***	***10***	***2***	***0***	***0***	***6.3***
2007	***0***	***121***	***121***	***0***	***12***	***41***	***29***	***20***	***10***	***6***	***3***	***1***	***0***	***0***	***6.1***
2008	***0***	***257***	***257***	***1***	***33***	***96***	***57***	***35***	***17***	***12***	***6***	***2***	***0***	***0***	***5.9***
2009	***0***	***33***	***33***	***0***	***6***	***15***	***7***	***4***	***1***	***1***	***0***	***0***	***0***	***0***	***5.5***
2010	***0***	***137***	***137***	***1***	***29***	***71***	***26***	***7***	***2***	***1***	***0***	***0***	***0***	***0***	***5.2***
2011	***0***	***60***	***60***	***0***	***9***	***28***	***15***	***6***	***2***	***1***	***0***	***0***	***0***	***0***	***5.4***
2012	139	10	149	0	7	46	33	49	7	7	0	0	0	0	6.2
2013	144	5	149	1	16	45	56	10	18	2	0	0	0	0	***5.8***
2014	110	8	118	0	4	45	40	18	6	2	2	0	0	0	5.9
2015	***0***	***43***	***43***	***0***	***3***	***15***	***15***	***7***	***3***	***1***	***0***	***0***	***0***	***0***	***5.9***
2016	77	77	154	1	8	58	61	18	9	0	0	0	0	0	5.7
2017	70	251	321	0	19	56	152	82	12	0	0	0	0	0	6.0
2018	84	455	539	1	53	168	228	73	15	1	0	0	0	0	5.7

Table 67 Continued

Year	Male														
	Aged	**ALK est**	**Total**	**Age**											**Mean age**
				3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	
1983	29	2	31	1	5	8	6	5	3	2	1				6.0
1984	83	2	85	3	17	24	23	9	7	1	1				5.6
1985	166	37	203	16	62	63	31	15	12	3	2				5.1
1986	221	194	415	19	139	133	74	29	12	6		2			5.1
1987	205	110	315	11	83	91	60	36	13	15	2	4			5.5
1988	223	5	228	2	43	101	43	26	7	4	2				5.4
1989	163	6	169	3	34	47	38	24	17	5	1				5.7
1990	54	2	56		14	26	8	7	1						5.2
1991	114	7	121	12	51	35	17	4	1						4.6
1992	492	473	965	24	336	459	128	14	2	2					4.8
1993	318	14	332	5	95	162	49	18	2						5.0
1994	80	12	92	2	37	42	8	3							4.7
1995	241	58	299	25	117	105	40	12							4.7
1996	269	26	295	24	174	74	18	4	1						4.3
1997	70	8	78	4	27	33	11	1			1				4.8
1998	149	15	164	7	85	54	13	4							4.5
1999	168	28	196	3	74	90	24	3	3						4.8
2000	185	30	215	25	88	80	19	1	2						4.5
2001	495	79	574	46	237	169	86	30	5						4.7
2002	11	0	11		2	5	3	1		electrofish only					5.3
2003	***0***	***274***	***274***	***5***	***62***	***107***	***61***	***28***	***8***	***2***	***0***	***0***			***5.3***
2004	***0***	***282***	***282***	***6***	***56***	***95***	***66***	***37***	***15***	***4***	***1***	***0***			***5.5***
2005	***0***	***224***	***224***	***10***	***58***	***70***	***46***	***25***	***10***	***4***	***1***	***0***			***5.3***
2006	***0***	***133***	***133***	***8***	***48***	***43***	***19***	***10***	***4***	***1***	***0***	***0***			***4.9***
2007	***0***	***72***	***72***	***4***	***29***	***24***	***9***	***4***	***2***	***1***	***0***	***0***			***4.9***
2008	***0***	***110***	***110***	***10***	***44***	***34***	***12***	***6***	***3***	***1***	***0***	***0***			***4.8***
2009	***0***	***150***	***150***	***17***	***79***	***43***	***8***	***2***	***1***	***0***	***0***	***0***			***4.3***
2010	***0***	***282***	***282***	***15***	***127***	***112***	***23***	***4***	***1***	***0***	***0***				***4.6***
2011	***0***	***36***	***36***	***3***	***16***	***13***	***3***	***1***	***0***	***0***					***4.5***
2012	56	139	195	35	44	50	29	28	9						5.0
2013	***0***	***160***	***160***	***9***	***66***	***62***	***17***	***4***	***1***	***0***	***0***				***4.7***
2014	73	5	78	2	13	37	15	7		3					5.3
2015	***0***	***82***	***82***	***4***	***31***	***33***	***11***	***3***	***1***	***0***	***0***				***4.8***
2016	96	209	305	1	66	187	33	17		1					5.0
2017	80	342	422	4	51	164	132	60	12						5.5
2018	79	320	399	5	91	215	83	5							5.0

Table 68. Repeat spawning marks of American shad from spawning stock sampling in the Hudson River Estuary. Seine and electrofishing gears combined. Table continues on next page.

	Females												
	Repeat Marks												
Year	0	1	2	3	4	5	6	7	8	Total	Mean RS	% virgin	% repeat
1983	28	8	9	6	2					53	0.98	53%	47%
1984	17	10	8	6	9	4				54	1.85	31%	69%
1985	32	24	15	11	5	7				94	1.51	34%	66%
1986	104	42	18	11	14	6	1	1		197	1.07	53%	47%
1987	109	39	19	23	12	5	2	2		211	1.16	52%	48%
1988	126	86	45	26	11	5	4			303	1.15	42%	58%
1989	97	27	34	25	6	5	3			197	1.20	49%	51%
1990	37	8	11	5	1	1				63	0.86	59%	41%
1991	70	15	8	3	1	1				98	0.50	71%	29%
1992	268	118	35	6	5	2				434	0.54	62%	38%
1993	89	35	18	6						148	0.60	60%	40%
1994	46	19	8	3	1					77	0.62	60%	40%
1995	284	113	47	7						451	0.51	63%	37%
1996	54	30	20	7	3					114	0.90	47%	53%
1997	47	11	6	8	3					75	0.79	63%	37%
1998	53	36	31	7	3					130	1.01	41%	59%
1999	76	71	30	7		1				185	0.85	41%	59%
2000	91	63	29	7	2					192	0.78	47%	53%
2001	157	125	103	37	6	2				430	1.11	37%	63%
2002	Sample size too small (11 fish)- electrofish only												
	2003 - 2011 ageing in progress (previously reported 2004 data were draft and inconsistent)												
2012	55	34	24	14	9	4				140	1.29	39%	61%
2013	65	46	16	13	4					144	0.92	45%	55%
2014	47	37	14	10	1		1			110	0.95	43%	57%
2015													
2016	59	9	8	1						77	0.36	77%	23%
2017	33	28	8	1						70	0.67	47%	53%
2018	33	31	8	10	1	1				84	1.02	39%	61%

Table 68 Continued

	Males												
	Repeat Marks												
Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**	**Mean RS**	**% virgin**	**% repeat**
1983	10	6	3	7	2	1				29	1.59	34%	66%
1984	38	17	16	10	2	1				84	1.10	45%	55%
1985	99	33	17	11	4	3				167	0.78	59%	41%
1986	135	41	25	10	11					222	0.74	61%	39%
1987	109	38	29	14	9	4	2			205	1.00	53%	47%
1988	129	40	30	14	8	2				223	0.83	58%	42%
1989	78	31	18	19	15	2				163	1.19	48%	52%
1990	38	6	7	2	1					54	0.56	70%	30%
1991	91	17	4	1	1					114	0.28	80%	20%
1992	387	84	22		2					495	0.27	78%	22%
1993	217	72	23	7						319	0.44	68%	32%
1994	55	12	10	2	1					80	0.53	69%	31%
1995	164	48	25	4						241	0.46	68%	32%
1996	168	76	19	5	1					269	0.49	62%	38%
1997	48	16	3	2		1				70	0.47	69%	31%
1998	78	44	22	5						149	0.69	52%	48%
1999	73	53	37	4	2					169	0.87	43%	57%
2000	103	52	27	2	1					185	0.63	56%	44%
2001	216	172	71	32	4					495	0.86	44%	56%
2002													
2012	16	18	14	4	2	2				56	1.36	29%	71%
2013													
2014	25	28	14	2	4					73	1.07	34%	66%
2015													
2016	72	17	7							96	0.32	75%	25%
2017	47	15	12	5	1					80	0.73	59%	41%
2018	38	26	9	4	2					79	0.81	48%	52%

Table 69. Estimates of total instantaneous mortality (*Z*) and annual survival (S) of American shad collected in the spawning stock survey in the Hudson River Estuary. Seines and electrofishing data are collected.

	Females														Males													
		Catch curve-Age			C-R Bias Corrected				Catch Curve			C-R Bias Corrected				Catch curve-Age			C-R Bias Corrected				Catch Curve			C-R Bias Corrected		
	Ages	Z	SE	S	Z	SE	S	**Spawning Marks**	Z	SE	S	Z	SE	S	**Ages**	Z	SE	S	Z	SE	S	**Spawning Marks**	Z	SE	S	Z	SE	S
1983	5-10	0.54	0.06	0.58	0.56	0.05	0.57	0-4	0.56	0.13	0.57	0.68	0.11	0.51	5-10	0.41	0.04	0.66	0.48	0.05	0.62	0-5	0.40	0.12	0.67	0.47	0.11	0.63
1984	6-11	0.43	0.04	0.65	0.52	0.06	0.59	0-5	0.22	0.07	0.80	0.42	0.09	0.66	5-10	0.73	0.12	0.48	0.64	0.09	0.53	0-5	0.72	0.11	0.49	0.64	0.08	0.53
1985	6-11	0.42	0.05	0.66	0.55	0.05	0.58	0-5	0.36	0.06	0.70	0.50	0.06	0.61	5-10	0.70	0.06	0.50	0.71	0.05	0.49	0-5	0.69	0.05	0.50	0.81	0.06	0.44
1986	6-11	0.59	0.10	0.55	0.69	0.07	0.50	0-7	0.65	0.07	0.52	0.66	0.07	0.52	4-9	0.68	0.07	0.51	0.63	0.08	0.53	0-4	0.64	0.12	0.53	0.85	0.11	0.43
1987	5-13	0.61	0.06	0.54	0.51	0.04	0.60	0-7	0.57	0.05	0.57	0.62	0.06	0.54	5-11	0.61	0.10	0.54	0.60	0.05	0.55	0-6	0.63	0.03	0.53	0.69	0.05	0.50
1988	6-12	0.61	0.07	0.54	0.73	0.07	0.48	0-6	0.62	0.03	0.54	0.62	0.03	0.54	5-10	0.80	0.05	0.45	0.82	0.04	0.44	0-5	0.75	0.07	0.47	0.79	0.07	0.45
1989	5-11	0.54	0.07	0.58	0.52	0.07	0.59	0-6	0.55	0.07	0.58	0.60	0.08	0.55	5-10	0.73	0.14	0.48	0.59	0.08	0.55	0-5	0.58	0.14	0.56	0.60	0.09	0.55
1990	5-10	0.70	0.12	0.50	0.61	0.09	0.54	0-5	0.72	0.12	0.49	0.76	0.12	0.47	5-8	0.99	0.24	0.37	0.95	0.16	0.39	0-4	0.84	0.15	0.43	1.00	0.17	0.37
1991	6-10	0.99	0.15	0.37	1.08	0.10	0.34	0-5	0.87	0.10	0.42	1.08	0.11	0.34	4-8	1.00	0.14	0.37	0.81	0.11	0.44	0-4	1.19	0.18	0.30	1.49	0.14	0.23
1992	5-10	1.01	0.14	0.36	0.79	0.14	0.45	0-5	1.02	0.10	0.36	1.04	0.07	0.35	5-9	1.50	0.22	0.22	1.51	0.12	0.22	0-2	1.43	0.05	0.24	1.57	0.08	0.21
1993	5-8	0.66	0.14	0.52	0.77	0.15	0.46	0-3	0.88	0.06	0.41	0.97	0.07	0.38	5-8	1.42	0.19	0.24	1.25	0.08	0.29	0-3	1.14	0.01	0.32	1.19	0.04	0.30
1994	5-8	1.11	0.08	0.33	1.07	0.07	0.34	0-4	0.95	0.03	0.39	0.94	0.03	0.39	5-7	1.32	0.20	0.27	1.50	0.14	0.22	0-4	0.98	0.12	0.38	1.04	0.13	0.35
1995	5-9	1.51	0.18	0.22	1.04	0.16	0.35	0-3	1.20	0.17	0.30	1.09	0.09	0.34	4-7	0.78	0.18	0.46	0.80	0.16	0.45	0-3	1.18	0.16	0.31	1.15	0.10	0.32
1996	5-9	0.84	0.04	0.43	0.90	0.04	0.41	0-4	0.72	0.07	0.49	0.74	0.07	0.48	4-8	1.32	0.07	0.27	1.14	0.09	0.32	0-4	1.30	0.08	0.27	1.10	0.09	0.33
1997	5-9	0.44	0.14	0.64	0.67	0.13	0.51	0-4	0.58	0.16	0.56	0.80	0.16	0.45	5-7	1.75	0.38	0.17	1.43	0.22	0.24	0-3	1.12	0.17	0.33	1.21	0.09	0.30
1998	5-9	1.01	0.12	0.36	1.02	0.08	0.36	0-4	0.74	0.14	0.48	0.68	0.12	0.51	4-7	1.06	0.14	0.35	0.98	0.15	0.38	0-3	0.89	0.15	0.41	0.89	0.11	0.41
1999	5-7	1.01	0.16	0.36	1.27	0.16	0.28	0-3	0.80	0.22	0.45	0.79	0.17	0.45	5-8	1.23	0.29	0.29	1.38	0.14	0.25	0-4	0.98	0.19	0.38	0.76	0.15	0.47
2000	5-10	0.96	0.15	0.38	1.31	0.14	0.27	0-4	0.98	0.13	0.38	0.82	0.11	0.44	4-8	1.20	0.31	0.30	0.90	0.21	0.41	0-4	1.25	0.19	0.29	0.95	0.13	0.39
2001	5-10	1.11	0.10	0.33	0.88	0.12	0.41	0-5	0.91	0.16	0.40	0.64	0.11	0.53	4-8	0.94	0.16	0.39	0.77	0.10	0.46	0-4	0.97	0.19	0.38	0.77	0.11	0.46
2002		Did not estimate; low sample size							Did not estimate; low sample size						Did not estimate; low sample size								Did not estimate; low sample size					
2003	***6-11***	***0.93***	***0.10***	***0.39***	***0.74***	***0.08***	***0.48***								***5-9***	***1.00***	***0.11***	***0.37***	***0.86***	***0.08***								
2004	***6-11***	***0.65***	***0.09***	***0.52***	***0.60***	***0.07***	***0.55***								***5-10***	***0.92***	***0.11***	***0.40***	***0.72***	***0.08***								
2005	***6-11***	***0.71***	***0.07***	***0.49***	***0.66***	***0.06***	***0.52***								***5-10***	***0.84***	***0.08***	***0.43***	***0.72***	***0.06***								
2006	***5-11***	***0.58***	***0.09***	***0.56***	***0.51***	***0.05***	***0.60***								***4-9***	***0.77***	***0.09***	***0.46***	***0.66***	***0.08***								
2007	***5-11***	***0.60***	***0.05***	***0.55***	***0.56***	***0.04***	***0.57***		***No repeat data from 2002 to 2012***						***4-9***	***0.72***	***0.05***	***0.49***	***0.69***	***0.07***			***No repeat data from 2002 to 2012***					
2008	***5-11***	***0.61***	***0.04***	***0.54***	***0.61***	***0.03***	***0.54***								***4-9***	***0.77***	***0.05***	***0.46***	***0.72***	***0.07***								
2009	***5-9***	***0.74***	***0.10***	***0.48***	***0.78***	***0.06***	***0.46***								***4-8***	***1.18***	***0.10***	***0.31***	***1.06***	***0.14***								
2010	***5-9***	***1.11***	***0.06***	***0.33***	***1.12***	***0.04***	***0.33***								***4-8***	***1.30***	***0.17***	***0.27***	***0.92***	***0.21***								
2011	***5-9***	***0.87***	***0.04***	***0.42***	***0.85***	***0.05***	***0.43***								***4-7***	***0.98***	***0.18***	***0.38***	***0.87***	***0.19***								
2012	7-9	0.97	0.56	0.38	1.34	0.36	0.26	0-5	0.50	0.03	0.61	0.57	0.04	0.57	5-8	0.52	0.15	0.59	0.70	0.15	0.50	1-5	0.63	0.12	0.53	0.72	0.10	0.49
2013	6-9	0.94	0.37	0.39	0.96	0.28	0.38	0-4	0.68	0.09	0.51	0.73	0.08	0.48	***4-8***	***1.11***	***0.16***	***0.33***	***0.84***	***0.18***								
2014	5-10	0.73	0.09	0.48	0.69	0.09	0.50	0-4	0.90	0.20	0.41	0.73	0.11	0.48	5-7	0.83	0.04	0.44	1.08	0.15	0.34	1-4	0.78	0.35	0.46	0.92	0.18	0.40
2015	***5-9***	***0.70***	***0.12***	***0.50***	***0.66***	***0.11***	***0.52***								***5-8***	***1.18***	***0.03***	***0.31***	***1.18***	***0.04***								
2016	6-8	0.96	0.15	0.38	1.21	0.16	0.30	0-3	1.24	0.27	0.29	1.29	0.24	0.28	5-7	1.20	0.31	0.30	1.50	0.22	0.22	0-2	1.17	0.16	0.31	1.38	0.14	0.25
2017	6-8	1.27	0.38	0.28	1.19	0.26	0.30	0-3	1.17	0.30	0.31	0.89	0.21	0.41	5-8	0.86	0.22	0.42	0.82	0.16	0.44	0-4	0.88	0.13	0.41	0.85	0.09	0.43
2018	6-9	1.79	0.25	0.17	1.37	0.11	0.25	0-5	0.79	0.15	0.45	0.67	0.12	0.51	5-7	1.88	0.54	0.15	1.44	0.29	0.24	0-4	0.78	0.06	0.46	0.79	0.08	0.45

Table 70. GAM predicted catch rates of American shad from the fishery-independent seine survey.

	Sexes Combined					Females					Males				
Year	Mean	SE	CV	LCI	UCI	Mean	SE	CV	LCI	UCI	Mean	SE	CV	LCI	UCI
1988	2.84	1.11	0.39	0.66	5.01	3.13	1.17	0.37	0.84	5.43	0.82	0.35	0.43	0.13	1.51
1989	7.78	3.35	0.43	1.22	14.33	6.99	2.86	0.41	1.39	12.59	2.29	1.06	0.46	0.21	4.37
1990	2.61	1.09	0.42	0.47	4.75	1.90	0.75	0.39	0.43	3.37	0.84	0.40	0.47	0.06	1.61
1991	2.28	0.90	0.40	0.51	4.04	1.78	0.69	0.39	0.43	3.13	0.93	0.40	0.42	0.16	1.71
1992	24.43	9.55	0.39	5.72	43.14	15.54	5.91	0.38	3.95	27.13	11.86	4.87	0.41	2.31	21.41
1993	13.14	5.23	0.40	2.89	23.40	10.67	3.87	0.36	3.09	18.24	5.87	2.47	0.42	1.03	10.71
1994	3.02	1.22	0.40	0.64	5.41	1.75	0.71	0.41	0.36	3.15	1.14	0.50	0.44	0.16	2.13
1995	1.11	0.44	0.40	0.24	1.98	2.00	0.63	0.31	0.77	3.24	0.38	0.16	0.43	0.06	0.70
1996	2.57	0.97	0.38	0.66	4.48	1.36	0.50	0.36	0.39	2.33	1.27	0.52	0.41	0.26	2.29
1997	0.59	0.25	0.43	0.09	1.08	0.52	0.23	0.44	0.07	0.96	0.27	0.13	0.47	0.02	0.52
1998	1.05	0.38	0.36	0.30	1.79	0.99	0.34	0.35	0.32	1.66	0.44	0.17	0.39	0.10	0.78
1999	1.21	0.52	0.43	0.19	2.22	1.50	0.60	0.40	0.33	2.67	0.44	0.20	0.46	0.04	0.83
2000	2.05	0.77	0.38	0.53	3.56	1.48	0.49	0.33	0.53	2.44	0.89	0.37	0.41	0.17	1.62
2001	7.38	2.71	0.37	2.06	12.69	6.14	2.16	0.35	1.90	10.37	3.43	1.34	0.39	0.80	6.06
2002	No seining in 2002														
2003	2.00	0.69	0.35	0.64	3.36	1.60	0.54	0.34	0.54	2.66	0.82	0.31	0.37	0.22	1.42
2004	4.49	1.54	0.34	1.48	7.50	4.78	1.53	0.32	1.79	7.77	1.16	0.43	0.37	0.32	2.00
2005	3.44	1.20	0.35	1.10	5.78	3.79	1.23	0.33	1.37	6.20	0.87	0.33	0.38	0.22	1.51
2006	0.89	0.30	0.34	0.29	1.48	1.13	0.35	0.31	0.44	1.82	0.24	0.09	0.39	0.06	0.42
2007	0.78	0.25	0.32	0.30	1.27	0.63	0.20	0.32	0.23	1.03	0.24	0.09	0.35	0.07	0.41
2008	0.29	0.11	0.37	0.08	0.51	0.36	0.13	0.36	0.11	0.61	0.10	0.04	0.41	0.02	0.18
2009	0.40	0.13	0.32	0.15	0.65	0.14	0.05	0.35	0.04	0.24	0.11	0.04	0.37	0.03	0.20
2010	0.70	0.25	0.35	0.21	1.19	0.76	0.24	0.32	0.28	1.24	0.27	0.10	0.38	0.07	0.47
2011	0.41	0.18	0.44	0.06	0.77	0.37	0.15	0.41	0.07	0.66	0.16	0.08	0.50	0.00	0.32
2012	1.31	0.43	0.33	0.47	2.16	0.92	0.29	0.32	0.35	1.50	0.40	0.15	0.36	0.12	0.69
2013	1.04	0.37	0.36	0.31	1.76	0.92	0.30	0.33	0.32	1.51	0.40	0.15	0.38	0.10	0.70
2014	0.95	0.39	0.42	0.17	1.72	0.90	0.38	0.42	0.16	1.64	0.33	0.15	0.46	0.03	0.62
2015	0.32	0.13	0.40	0.07	0.57	0.27	0.10	0.38	0.07	0.47	0.13	0.06	0.43	0.02	0.24
2016	0.53	0.19	0.35	0.16	0.89	0.35	0.12	0.35	0.11	0.59	0.22	0.09	0.38	0.05	0.39
2017	1.68	0.60	0.35	0.51	2.85	0.79	0.27	0.34	0.26	1.32	0.55	0.21	0.39	0.13	0.96

Table 71. Comparison of two annual CPUE estimates for catches in the NYSDEC YOY seine survey.

Year	Number of Hauls	Number of Zero	Total Shad	Geometric Mean					GLM Standardized Mean				
				Mean	UCI	LCI	SE	CV	Mean	UCI	LCI	SE	CV
1980	21	1	1,167	21.68	42.44	10.84	7.62	0.35					
1981	23	3	1,127	18.48	36.88	9.02	6.73	0.36					
1982	23	2	674	14.87	27.11	7.96	4.73	0.32					
1983	132	3	5,406	20.68	25.86	16.49	2.38	0.12	37.59	45.85	29.33	4.21	0.11
1984	130	13	2,241	8.38	10.59	6.59	1.01	0.12	18.39	22.50	14.28	2.10	0.11
1985	185	10	10,920	26.64	32.59	21.74	2.76	0.10	46.29	54.83	37.74	4.36	0.09
1986	193	4	15,318	47.95	56.65	40.57	4.09	0.09	79.28	93.70	64.85	7.36	0.09
1987	103	7	3,921	20.67	26.46	16.11	2.63	0.13	30.90	38.64	23.16	3.95	0.13
1988	197	8	14,837	29.96	37.11	24.16	3.29	0.11	54.85	64.69	45.01	5.02	0.09
1989	212	3	19,649	47.30	56.00	39.93	4.08	0.09	79.79	93.54	66.04	7.02	0.09
1990	202	7	16,501	41.24	49.20	34.55	3.73	0.09	66.56	78.24	54.88	5.96	0.09
1991	240	17	15,051	24.05	29.55	19.54	2.54	0.11	44.45	51.60	37.30	3.65	0.08
1992	245	14	18,408	35.17	42.22	29.27	3.29	0.09	58.45	68.24	48.65	5.00	0.09
1993	205	21	5,107	11.64	14.18	9.52	1.18	0.10	24.98	29.48	20.49	2.29	0.09
1994	217	2	9,335	25.68	29.92	22.02	2.01	0.08	37.01	43.43	30.58	3.28	0.09
1995	238	57	3,851	5.64	6.94	4.55	0.61	0.11	13.69	16.13	11.25	1.24	0.09
1996	187	8	14,589	42.00	50.80	34.70	4.10	0.10	60.09	71.13	49.04	5.64	0.09
1997	210	8	6,717	13.68	16.57	11.27	1.35	0.10	25.35	29.76	20.95	2.25	0.09
1998	219	51	1,954	3.66	4.47	2.97	0.38	0.10	6.76	7.94	5.58	0.60	0.09
1999	239	16	15,926	20.88	25.77	16.89	2.25	0.11	31.48	36.77	26.18	2.70	0.09
2000	241	39	7,580	12.28	15.04	9.98	1.28	0.10	34.67	40.67	28.66	3.06	0.09
2001	227	5	15,692	37.97	44.72	32.22	3.18	0.08	53.81	62.89	44.73	4.63	0.09
2002	219	95	2,591	2.91	3.76	2.22	0.39	0.13	9.97	11.76	8.19	0.91	0.09
2003	244	49	4,004	6.71	8.16	5.50	0.68	0.10	15.61	18.18	13.05	1.31	0.08
2004	229	41	3,223	5.33	6.53	4.32	0.56	0.11	13.82	16.43	11.21	1.33	0.10
2005	234	37	4,783	8.27	10.11	6.73	0.86	0.10	13.11	15.39	10.83	1.16	0.09
2006	211	94	831	1.61	2.01	1.27	0.19	0.12	3.40	4.07	2.72	0.34	0.10
2007	221	47	3,046	4.86	6.03	3.89	0.54	0.11	9.73	11.42	8.03	0.87	0.09
2008	203	79	762	1.70	2.09	1.35	0.19	0.11	3.23	3.86	2.60	0.32	0.10
2009	232	70	1,385	2.45	2.99	1.99	0.25	0.10	5.52	6.52	4.51	0.51	0.09
2010	237	70	2,074	3.34	4.07	2.71	0.34	0.10	6.36	7.47	5.25	0.57	0.09
2011	203	51	1,853	3.70	4.59	2.96	0.41	0.11	7.60	9.06	6.13	0.75	0.10
2012	236	119	1,830	1.45	1.84	1.11	0.19	0.13	3.32	3.94	2.70	0.32	0.10
2013	226	102	639	1.17	1.43	0.93	0.13	0.11	2.40	2.86	1.94	0.24	0.10
2014	236	5	6,837	14.15	16.57	12.07	1.14	0.08	26.28	30.61	21.95	2.21	0.08
2015	240	37	3,639	6.16	7.46	5.06	0.61	0.10	11.64	13.59	9.69	1.00	0.09
2016	239	106	952	1.54	1.90	1.23	0.17	0.11	3.06	3.63	2.49	0.29	0.10
2017	240	64	1,642	3.02	3.64	2.49	0.29	0.10	6.57	7.73	5.41	0.59	0.09

Table 72. Ichthyoplankton density (number /1000 cubic meters) and catch per seine (BSS) of various life stages of American shad collected in the Long River Survey for the Hudson River Generating companies (ASA 2016). Indices expressed as density: number per 1000^3, CEMR expressed as percent.

Year	EGG Index	SE(eggs)	YSL Index	SE(YSL)	PYSL Index	SE(PYSL)	BSS Index	SE(BSS)
1974	0.10	0.03	0.00	0.00	0.17	0.07	11.50	0.83
1975	0.06	0.02	0.03	0.00	0.28	0.18	10.63	1.43
1976	0.04	0.01	0.02	0.00	0.16	0.05	13.33	0.87
1977	0.04	0.00	0.02	0.00	0.17	0.03	13.70	1.39
1978	0.04	0.01	0.03	0.00	0.09	0.03	23.67	2.66
1979	0.05	0.01	0.05	0.01	0.49	0.07	11.65	1.74
1980	0.05	0.01	0.11	0.01	0.48	0.22	10.75	2.46
1981	0.16	0.08	0.11	0.01	0.78	0.31	17.62	2.17
1982	0.12	0.04	0.15	0.02	0.59	0.12	16.31	1.92
1983	0.36	0.11	0.13	0.02	0.57	0.09	19.68	3.89
1984	0.47	0.11	0.24	0.02	0.38	0.17	8.69	1.84
1985	0.26	0.04	0.25	0.04	0.67	0.17	8.08	1.30
1986	0.77	0.33	0.12	0.02	1.05	0.15	19.06	3.74
1987	0.35	0.08	0.06	0.01	0.18	0.08	13.47	2.28
1988	0.26	0.05	0.09	0.03	0.73	0.34	7.72	1.01
1989	0.33	0.06	0.08	0.01	1.04	0.79	22.05	2.41
1990	0.27	0.06	0.40	0.05	1.17	0.73	18.67	1.74
1991	0.09	0.02	0.04	0.01	0.32	0.12	11.97	3.16
1992	0.08	0.02	0.08	0.01	0.62	0.21	13.92	1.05
1993	0.12	0.03	0.01	0.00	0.23	0.12	7.07	0.87
1994	0.23	0.04	0.04	0.01	0.37	0.13	17.56	3.28
1995	0.12	0.03	0.02	0.00	0.19	0.06	3.79	0.43
1996	0.26	0.04	0.01	0.00	0.26	0.06	11.77	1.93
1997	0.04	0.01	0.01	0.00	0.15	0.03	12.54	2.04
1998	0.09	0.01	0.01	0.00	0.09	0.03	2.36	0.42
1999	0.09	0.02	0.00	0.00	0.18	0.07	8.81	2.44
2000	0.12	0.02	0.01	0.00	0.09	0.03	5.93	0.93
2001	0.04	0.01	0.01	0.00	0.46	0.18	24.40	1.83
2002	0.03	0.00	0.02	0.00	0.10	0.04	4.79	0.47
2003	0.07	0.02	0.01	0.00	0.09	0.03	8.69	1.20
2004	0.03	0.01	0.01	0.00	0.14	0.06	3.40	0.61
2005	0.04	0.01	0.00	0.00	0.03	0.02	3.21	0.60
2006	0.01	0.00	0.00	<0.001	0.01	0.00	0.63	0.12
2007	0.01	0.01	0.00	0.00	0.02	0.02	1.52	0.37
2008	0.01	0.00	0.00	<0.001	0.01	0.00	0.77	0.14
2009	0.01	0.00	0.00	<0.001	0.02	0.01	1.88	0.39
2010	0.01	0.00	0.00	<0.001	0.01	0.01	1.83	0.40
2011	0.00	0.01	0.00	0.00	0.02	0.01	1.06	0.23
2012	0.01	0.01	0.00	<0.001	0.00	0.00	0.69	0.18
2013	0.02	0.01	0.00	0.00	0.02	0.01	0.78	0.28
2014	0.01	0.00	0.00	0.00	0.14	0.10	6.84	1.03
2015	0.00	0.00	0.00	0.00	0.06	0.05	5.11	0.73
2016	0.02	0.01	0.03	<0.001	0.05	0.02	0.74	0.19

Table 73. Correlation matrix (R) among the various juvenile indices for all juvenile shad surveys.

	EGG	YSL	PYSL	BSS_YOY	DEC_YOY_GeoMean
YSL	0.60				
PYSL	0.73	0.75			
BSS_YOY	0.61	0.46	0.77		
DEC_YOY_GeoMean	0.65	0.49	0.87	0.87	
DEC_YOY_GLM	0.67	0.52	0.89	0.85	0.99

Table 74. Correlation matrix (R) among the various spawning stock estimates.

	Eggs	GAM SSA	GAM SSB	AUC ESA
GAM ESSA	0.25			
GAM ESSB	0.44	0.95		
AUC ESSA	0.77	0.57	0.73	
AUC ESSB	0.82	0.53	0.73	0.98

Table 75. Correlation matrix (R values) for comparisons of the adult vs juvenile abundance estimates: 1988-2017 spawning stock years (1984-2013 year classes).

	PYSL	BSS YOY	DEC YOY GM	DEC YOY GLM
GAM FI 4yo	0.46	0.26	0.40	0.45
GAM FI 5yo	0.12	0.18	0.22	0.21
GAM FI 6yo	0.35	0.31	0.35	0.34
GAM FI 7yo	0.29	0.24	0.15	0.21
GAM FI 4-5yo	0.29	0.24	0.33	0.35
GAM FI 4-6yo	0.34	0.28	0.37	0.39
GAM FI 4-7yo	0.35	0.28	0.38	0.39
GAM FI 5-6yo	0.23	0.24	0.28	0.27
GAM FI 5-7yo	0.24	0.25	0.30	0.29

Table 76. Mean length-at-age for Hudson River (scales).

Mean Length-at-age for Hudson River (Scales)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Hudson River	Hudson River Commercial Gill Net Fishery Monitoring	3					1982-1992	3	1	1.000
		4	1980-1995	15	15	0.488	1980-1995	12	18	0.244
		5	1980-1995	16	-26	0.260	1980-1995	13	18	0.300
		6	1980-1995	16	-30	0.192	1980-1995	13	0	1.000
		7	1980-1995	16	-20	0.392	1980-1995	13	-4	0.855
		8	1980-1995	16	-26	0.260	1980-1995	13	-2	0.951
		9	1980-1995	16	18	0.444	1981-1995	11	9	0.533
		10	1981-1995	13	26	0.127	1982-1989	8	20	0.019
		11	1982-1991	8	22	0.009	1983-1987	4	0	1.000
		12	1984-1990	5	2	0.806				
	Hudson River Spawning Stock Haul Seine and Electrofishing Surveys	3	1985-2016	6	-3	0.707	1985-2017	19	28	0.345
		4	1985-2017	21	-110	0.001	1985-2017	21	-54	0.110
		5	1985-2017	22	-115	0.001	1985-2017	21	-60	0.075
		6	1985-2017	22	-103	0.004	1985-2017	21	-66	0.050
		7	1985-2017	22	-125	0.000	1985-2017	21	-94	0.005
		8	1985-2017	21	-114	0.001	1985-2017	15	-59	0.004
		9	1985-2014	17	-64	0.009	1985-2014	7	-11	0.133
		10	1985-2014	10	-11	0.371	1985-1997	5	-8	0.086
		11	1985-1989	5	-2	0.806				

Table 77. Lewis Haul Seine Fishery index (numbers).

Year	Index	Year	Index	Year	Index
1925	1.62	1956	0.00	1987	16.49
1926	3.18	1957	0.83	1988	35.62
1927	2.43	1958	3.00	1989	52.20
1928	4.00	1959	1.13	1990	25.35
1929	4.39	1960	0.32	1991	30.42
1930	1.30	1961	3.46	1992	50.96
1931	1.77	1962	13.89	1993	10.52
1932	3.20	1963	56.90	1994	7.90
1933	5.54	1964	18.29	1995	19.05
1934	3.45	1965	6.65	1996	3.67
1935	13.47	1966	1.75	1997	11.96
1936	2.43	1967	3.74	1998	13.20
1937	9.29	1968	1.22	1999	4.60
1938	4.68	1969	3.10	2000	4.07
1939	8.77	1970	4.88	2001	6.84
1940	3.59	1971	12.30	2002	3.85
1941	0.80	1972	5.44	2003	8.46
1942	5.68	1973	7.19	2004	4.07
1943	14.07	1974	8.51	2005	2.89
1944	5.02	1975	14.85	2006	1.66
1945	2.05	1976	11.95	2007	3.38
1946	2.15	1977	10.18	2008	2.24
1947	3.79	1978	10.13	2009	2.57
1948	0.73	1979	18.72	2010	12.31
1949	0.09	1980	12.97	2011	1.93
1950	0.18	1981	54.17	2012	5.30
1951	0.66	1982	29.83	2013	26.63
1952	0.63	1983	14.44	2014	10.67
1953	0.00	1984	15.68	2015	7.17
1954	0.35	1985	29.30	2016	7.81
1955	0.84	1986	30.67	2017	29.35

Table 78. Smithfield Beach Gill Net Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
1990	9	1.00	2.53	0.11
1991	12	1.00	2.00	0.17
1992	9	1.00	2.67	0.15
1993	16	0.94	1.34	0.16
1994	17	0.94	1.37	0.16
1995	15	1.00	1.33	0.11
1996	13	1.00	1.17	0.12
1997	19	1.00	1.52	0.12
1998	15	1.00	1.41	0.14
1999	15	1.00	0.53	0.10
2000	12	1.00	0.64	0.13
2001	20	1.00	0.60	0.12
2002	9	1.00	1.06	0.19
2003	13	1.00	1.02	0.12
2004	15	1.00	0.51	0.13
2005	15	1.00	0.98	0.10
2006	15	1.00	0.49	0.12
2007	14	1.00	0.61	0.11
2008	18	1.00	0.67	0.15
2009	19	1.00	0.36	0.15
2010	15	1.00	0.88	0.15
2011	13	1.00	3.04	0.19
2012	13	1.00	1.43	0.16
2013	14	1.00	1.06	0.16
2014	12	0.92	1.10	0.13
2015	12	1.00	0.80	0.17
2016	19	1.00	0.63	0.15
2017	14	1.00	1.27	0.11

Table 79. Fish counts at the Easton Dam on the Lehigh River.

Year	Index
1994	87
1995	873
1996	1,141
1997	1,428
1998	3,293
1999	2,346
2000	2,094
2001	4,740
2002	3,314
2003	422
2004	754
2005	675
2006	2,023
2007	1,397
2008	408
2009	425
2010	1,910
2011	558
2012	2,096

Table 80. Fish counts at the Fairmount Fish Ladder on the Schuylkill River.

Year	Index
2004	91
2005	41
2006	345
2007	56
2008	NA
2009	1,485
2010	2,521
2011	3,366
2012	2,227
2013	166
2014	NA
2015	771
2016	1,759
2017	1,297

Table 81. Delaware River Tidal Seine Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
1987	60	0.55	9.08	0.30
1988	60	0.20	10.27	0.22
1989	60	0.88	31.37	0.21
1990	60	0.77	17.32	0.22
1991	193	0.63	10.60	0.17
1992	194	0.87	23.37	0.15
1993	153	0.87	19.10	0.16
1994	153	0.86	19.63	0.16
1995	153	0.76	21.74	0.17
1996	153	0.93	43.85	0.16
1997	154	0.68	20.12	0.17
1998	124	0.89	15.76	0.17
1999	144	0.84	21.59	0.16
2000	144	0.93	22.29	0.15
2001	144	0.78	16.78	0.15
2002	144	0.40	2.99	0.17
2003	144	0.90	30.86	0.16
2004	144	0.88	19.07	0.15
2005	142	0.85	30.24	0.17
2006	144	0.31	2.01	0.19
2007	144	0.92	47.10	0.15
2008	120	0.44	3.39	0.17
2009	144	0.81	9.95	0.16
2010	144	0.73	15.65	0.17
2011	125	0.90	23.06	0.17
2012	144	0.78	11.82	0.15
2013	142	0.98	57.86	0.15
2014	141	0.87	27.52	0.15
2015	144	0.84	21.58	0.17
2016	142	0.51	3.25	0.17
2017	146	0.93	36.63	0.15

Table 82. Total catch (N) of YOY American shad collected during the 2015 synoptic exploratory surveys in the upper Delaware River.

		Fyke		Beach seine			
Site	Visual	Upper	Lower	Haul 1	Haul 2	Haul 3	Haul 4
	July						
Skinners Falls	0	N/A	N/A	47	95	9	4
Buckingham	N/A	N/A	N/A	0	0	0	0
Balls Eddy	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fireman's Launch	0	N/A	N/A	0	0	0	0
	August						
Skinners Falls	100+	0	0	2	9	29	21
Buckingham	0	0	0	N/A	N/A	N/A	N/A
Balls Eddy	0	0	0	0	0	0	0
Fireman's Launch	0	0	0	0	0	0	0
	September						
Skinners Falls	100+	N/A	N/A	0	1	13	14
Buckingham	N/A	N/A	N/A	0	1	0	0
Balls Eddy	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fireman's Launch	0	N/A	N/A	0	8	0	3
	October						
Skinners Falls	N/A	N/A	N/A	6	4	1	1

Table 83. Delaware River Non-Tidal Seine Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
1988	36	0.94	167.48	0.23
1989	36	0.94	201.97	0.23
1990	34	0.97	307.94	0.23
1991	36	0.92	180.93	0.23
1992	35	0.89	114.72	0.23
1993	34	0.91	305.69	0.23
1994	36	0.89	224.35	0.23
1995	36	0.86	166.89	0.23
1996	36	0.97	414.85	0.23
1997	36	0.94	282.97	0.23
1998	36	0.81	53.74	0.23
1999	36	0.94	153.00	0.23
2000	35	0.91	186.69	0.23
2001	35	1.00	171.79	0.23
2002	36	0.92	80.86	0.23
2003	36	0.81	277.12	0.23
2004	36	0.92	251.67	0.23
2005	32	0.97	202.10	0.24
2006	36	0.86	55.52	0.23
2007	36	0.97	333.90	0.23
2008	NA	NA	NA	NA
2009	NA	NA	NA	NA
2010	NA	NA	NA	NA
2011	NA	NA	NA	NA
2012	36	0.97	368.01	0.23
2013	36	1.00	52.63	0.23
2014	36	0.97	163.33	0.23
2015	72	0.94	111.04	0.17
2016	36	0.97	157.94	0.23
2017	36	1.00	485.03	0.23

Table 84. Mann-Kendall analysis on mean length-at-age by sex for the Delaware and Lehigh Rivers using both scales and otoliths.

Mean Length-at-age for Delaware River (Scales)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Delaware River	Smithfield Beach Gill Net Survey	3	1998-2006	3	-1	1.000	1997-2015	10	1	1.000
		4	1996-2017	21	-38	0.264	1996-2016	20	-84	0.007
		5	1996-2017	21	-100	0.003	1996-2016	20	-50	0.112
		6	1996-2017	21	-116	0.001	1996-2016	20	-74	0.018
		7	1997-2017	20	-86	0.006	2000-2016	11	-28	0.035
		8	2005-2017	9	2	0.917				
		9	2009-2017	4	6	0.089				
Lehigh River	Lehigh River Electrofishing Survey	3					1999-2017	10	-17	0.152
		4					1999-2017	13	-34	0.044
		5					1999-2017	13	-18	0.300
		6					2000-2017	10	-5	0.721
		7					2012-2014	3	3	1.000

Mean Length-at-age for Delaware River (Otoliths)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Delaware River	Smithfield Beach Gill Net Survey	3	1996-2016	8	2	0.902	1997-2016	11	-11	0.436
		4	1996-2017	22	-15	0.693	**1996-2017**	**22**	**-103**	**0.004**
		5	**1996-2017**	**22**	**-83**	**0.021**	1996-2017	22	-43	0.236
		6	**1996-2017**	**22**	**-91**	**0.011**	1996-2017	22	-45	0.215
		7	**1996-2017**	**22**	**-93**	**0.009**	1996-2017	18	-1	1.000
		8	1996-2017	19	-19	0.529	2000-2015	8	-14	0.108
		9	2002-2016	6	1	1.000				
Lehigh River	Lehigh River Electrofishing Survey	3					1999-2017	8	12	0.174
		4					1999-2017	13	-8	0.669
		5					1999-2017	13	-8	0.669
		6					1999-2017	12	-16	0.304
		7					2004-2015	5	-2	0.806

Table 85. MD DNR American shad stockings by life stage in the Nanticoke River, 1995-2006.

Year	Larvae	Early Juveniles	Late Juveniles
1995	34,000		8,400
1996	0		0
1997	152,000		0
1998	0		0
1999	0		0
2000	0		0
2001	40,000		0
2002	90,000	20,000	13,347
2003	324,000	73,500	0
2004	100,000	60,000	0
2005	275,000	60,000	0
2006	0	40,500	0
Total	**1,015,000**	**254,000**	**21,747**

Table 86. MD DNR American shad stockings by life stage in Marshyhope Creek, 2002-2009.

Year	Larvae	Early Juveniles	Late Juveniles
2002	100,000	39,000	9,074
2003	243,000	50,000	0
2004	238,000	33,000	0
2005	205,000	40,000	0
2006	500,000	100,000	0
2007	0	137,000	0
2008	335,000	119,500	0
2009	330,000	78,000	0
Total	**1,951,000**	**596,500**	**9,074**

Table 87. Juvenile American shad captures and origin in Marshyhope Creek from the MD DNR Fish Health and Hatcheries Program summer seine survey, 2002-2009.

Sample year	n	Larval stocked origin	Early Juvenile stocked origin	Late Juvenile stocked origin	Wild fish
2002	164	24%	21%	13%	41%
2003	230	16%	29%	NA	56%
2004	130	27%	35%	NA	38%
2005	86	29%	24%	NA	47%
2006	380	78%	16%	NA	7%
2007	241	0%	84%	NA	16%
2008	182	32%	60%	NA	8%
2009	90	61%	31%	NA	8%

Table 88. Maryland commercial landings of American shad from the Nanticoke River, 1930-1980.

Year	Landings (lbs)	Source	Year	Landings (lbs)	Source
1930	14,000	Sadzinski - unpublished	1957	168,850	Sadzinski - unpublished
1931	40,000	Sadzinski - unpublished	1958	132,194	Sadzinski - unpublished
1932	24,000	Sadzinski - unpublished	1959	99,795	Sadzinski - unpublished
1933	63,000	Sadzinski - unpublished	1960	85,302	Sadzinski - unpublished
1934	58,000	Sadzinski - unpublished	1961	82,166	Sadzinski - unpublished
1935	48,000	Sadzinski - unpublished	1962	66,652	Weinrich - unpublished
1936	28,000	Sadzinski - unpublished	1963	47,205	Weinrich - unpublished
1937	16,000	Sadzinski - unpublished	1964	47,562	Weinrich - unpublished
1938	14,000	Sadzinski - unpublished	1965	39,978	Weinrich - unpublished
1939	20,000	Sadzinski - unpublished	1966	36,324	Weinrich - unpublished
1940	6,000	Sadzinski - unpublished	1967	22,983	Weinrich - unpublished
1941	16,000	Sadzinski - unpublished	1968	23,253	Weinrich - unpublished
1944	33,123	Hammer et al. - 1948	1969	38,282	Weinrich - unpublished
1945	16,606	Hammer et al. - 1948	1970	45,198	Weinrich - unpublished
1946	17,912	Hensel et al. - 1952	1971	37,888	Weinrich - unpublished
1947	26598	Hensel et al. - 1952	1972	15,756	Weinrich - unpublished
1948	20,711	Hensel et al. - 1952	1973	21,648	Weinrich - unpublished
1949	29,154	Hensel et al. - 1952	1974	17,102	Weinrich - unpublished
1950	28,517	Hensel et al. - 1952	1975	8,181	Weinrich - unpublished
1951	29,110	Hensel et al. - 1954	1976	4,654	Weinrich - unpublished
1952	56,370	Hensel et al. - 1954	1977	3,071	Weinrich - unpublished
1953	58,856	Sadzinski - unpublished	1978	7,317	Weinrich - unpublished
1954	51,130	Sadzinski - unpublished	1979	6,000	Weinrich - unpublished
1955	161,632	Sadzinski - unpublished	1980	5,201	Weinrich - unpublished
1956	131,867	Sadzinski - unpublished			

Table 89. Catch-at-age of male American shad captured in the Nanticoke River fishery-dependent pound and fyke net survey, 1989-2017. No fishing occurred in 2015.

Year	Age								Mean Age
	2	3	4	5	6	7	8	9	
1989		45	161	27	6		1		4.0
1990		5	64	73	4	4	1		4.6
1991		20	73	81	22	2	1		4.6
1992	1	3	18	21	18	4			5.0
1993	1	2	22	50	22	12	4	1	5.3
1994	1	24	41	23	5	1			4.1
1995	1	8	33	27	4				4.3
1996		7	28	23	7				4.5
1997		6	27	13	4				4.3
1998		3	14	14	3	2			4.6
1999		1	6	7	1				4.5
2000		7	58	43	6				4.4
2001		11	16	25	11				4.6
2002		10	26	28	18	2			4.7
2003		2	21	34	17				4.9
2004		3	8	14	1	1			4.6
2005		2	8	5	2	1	1		4.7
2006		2		3			1		4.8
2007		7	22	12	1	2	1		4.4
2008		9	12	3	1				3.8
2009		7	30	21	2				4.3
2010		2	6	7	4				4.7
2011		6	25	12	2				4.2
2012		5	38	44	23	1			4.8
2013				3	9	2	2		6.2
2014			8	12	14	4			5.4
2016		1	7	14	8	3	1		5.2
2017		2	8	5	3				4.5

Table 90. Catch-at-age of female American shad captured in the Nanticoke River fishery-dependent pound and fyke net survey, 1989-2017. No fishing occurred in 2015.

Year	Age										Mean
	1	2	3	4	5	6	7	8	9	10	Age
1989				20	49	12	8	6			5.3
1990				18	81	30	9	2			5.3
1991			1	24	75	49	22	2			5.4
1992			1	4	22	24	19				5.8
1993				5	28	22	17	9	2	2	6.1
1994			1	16	22	8	3	1			5.0
1995			1	8	22	20	2				5.3
1996			2	10	14	11	10				5.4
1997			1	10	12	5	5	1			5.2
1998				8	13	7	1				5.0
1999					5	2	1				5.5
2000				21	27	19	1	3			5.1
2001				11	10	13	3				5.2
2002				12	5	23	9	1			5.6
2003				10	15	15	10	1			5.5
2004				7	13	7	2				5.1
2005				2	7	7	3	1	1		5.9
2006					2						5.0
2007			1	6	9	2		1	1		5.1
2008			1	6	5	2			1		4.9
2009				6	10	2	2				5.0
2010				2	8	4					5.1
2011				4	9	3	1				5.1
2012	2			4	26	21	6				5.4
2013					2	5	2	2	1		6.6
2014				1	6	14	4	1	1		6.0
2016					5	4	5	1			6.1
2017			1	4	7	4					4.9

Table 91. Catch-at-age of American shad, sexes combined, captured in the Nanticoke River fishery-dependent pound and fyke net survey, 1989-2017. No fishing occurred in 2015.

Year	Age										Mean
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Age**
1989			45	181	76	18	8	7			4.4
1990			5	82	154	34	13	3			4.9
1991			21	97	156	71	24	3			5.0
1992		1	4	22	43	42	23				5.4
1993		1	2	27	78	44	29	13	3	2	5.6
1994		1	25	57	45	13	4	1			4.4
1995		1	9	41	49	24	2				4.7
1996			9	38	37	18	10				4.8
1997			7	37	25	9	5	1			4.7
1998			3	22	27	10	3				4.8
1999			1	6	12	3	1				4.9
2000			7	79	70	25	1	3			4.7
2001			12	27	35	25	3				4.8
2002			11	41	33	41	11	1			5.0
2003			2	31	49	33	10	1			5.2
2004			3	15	27	8	3				4.9
2005			2	10	12	9	4	2	1		5.3
2006			2		5			1			4.9
2007			8	28	21	3	2	2	1		4.6
2008			10	18	8	3			1		4.2
2009			7	36	31	4	2				4.5
2010			2	8	15	8					4.9
2011			6	29	21	5	1				4.5
2012	3		5	42	72	45	7				5.0
2013					5	16	5	4	1		6.4
2014				9	19	30	9	1	1		5.7
2016			1	7	19	12	9	2			5.5
2017			3	13	13	7					4.7

Table 92. Proportion of repeat spawning-at-age and by year of American shad, sexes combined, captured in the Nanticoke River fishery-dependent pound and fyke net survey, 1989-2017. No fishing occurred in 2015. Repeat spawning data was not available for 1994.

Year	Age										Yearly proportion
	1	2	3	4	5	6	7	8	9	10	
1989	-	-	0.02	0.03	0.03	0.83	1.00	1.00	-	-	0.11
1990	-	-	0.00	0.01	0.05	0.41	0.85	1.00	-	-	0.13
1991	-	-	0.00	0.00	0.11	0.45	0.79	1.00	-	-	0.19
1992	-	0.00	0.00	0.00	0.02	0.31	0.65	-	-	-	0.21
1993	-	0.00	0.00	0.00	0.12	0.61	0.86	1.00	1.00	1.00	0.40
1994	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1995	-	0.00	0.00	0.02	0.24	0.50	1.00	-	-	-	0.21
1996	-	-	0.00	0.00	0.22	0.83	0.80	-	-	-	0.28
1997	-	-	0.00	0.03	0.32	0.67	1.00	1.00	-	-	0.25
1998	-	-	0.00	0.00	0.19	0.50	1.00	-	-	-	0.20
1999	-	-	0.00	0.17	0.17	0.33	1.00	-	-	-	0.22
2000	-	-	0.00	0.01	0.17	0.48	1.00	1.00	-	-	0.16
2001	-	-	0.00	0.00	0.37	0.68	0.67	-	-	-	0.31
2002	-	-	0.00	0.05	0.33	0.61	0.55	1.00	-	-	0.33
2003	-	-	0.00	0.06	0.24	0.55	0.60	1.00	-	-	0.31
2004	-	-	0.00	0.00	0.30	0.38	0.67	-	-	-	0.23
2005	-	-	0.00	0.00	0.25	0.89	1.00	1.00	1.00	-	0.45
2006	-	-	0.00	-	0.40	-	-	1.00	-	-	0.38
2007	-	-	0.00	0.00	0.14	0.33	1.00	1.00	1.00	-	0.14
2008	-	-	0.00	0.00	0.50	0.67	-	-	1.00	-	0.18
2009	-	-	0.00	0.11	0.71	1.00	1.00	-	-	-	0.40
2010	-	-	0.00	0.00	0.53	1.00	-	-	-	-	0.48
2011	-	-	0.00	0.00	0.33	0.40	1.00	-	-	-	0.16
2012	0.00	-	0.00	0.07	0.46	0.78	1.00	-	-	-	0.45
2013	-	-	-	-	0.00	0.69	1.00	1.00	1.00	-	0.68
2014	-	-	-	0.22	0.89	0.90	1.00	1.00	1.00	-	0.83
2016	-	-	0.00	0.14	0.63	0.83	1.00	1.00	-	-	0.68
2017	-	-	0.00	0.31	0.46	0.57	-	-	-	-	0.39

Table 93. Mean fork length-at-age (mm) of male American shad captured in the Nanticoke River fishery-dependent pound and fyke net survey, 1989-2017. No fishing occurred in 2015.

Year	Age							
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1989		340	368	410	419		470	
1990		344	376	401	456	441	457	
1991		342	373	405	426	457	477	
1992	208	357	360	393	424	437		
1993	247	344	366	381	407	429	457	497
1994	295	341	363	390	420	440		
1995	243	334	373	399	427			
1996		346	369	398	415			
1997		345	377	407	449			
1998		341	373	401	442	430		
1999		306	364	387	437			
2000		350	379	407	424			
2001		360	391	423	450			
2002		345	377	427	453	497		
2003		355	379	402	456			
2004		351	394	412	463	448		
2005		333	362	397	430	438	482	
2006		330		387			453	
2007		350	372	408	385	466	443	
2008		331	374	380	445			
2009		339	367	388	433			
2010		331	382	397	410			
2011		336	374	406	440			
2012		345	369	387	402	416		
2013				387	384	436	412	
2014			362	404	411	425		
2016		303	359	378	401	406	449	
2017		361	369	392	387			
Mean Length	248	342	372	400	424	436	452	497

Table 94. Mean fork length-at-age (mm) of female American shad captured in the Nanticoke River fishery-dependent pound and fyke net survey, 1989-2017. No fishing occurred in 2015.

Year	Age									
	1	2	3	4	5	6	7	8	9	10
1989				427	452	472	504	520		
1990				397	429	471	489	518		
1991			360	412	438	459	489	507		
1992			343	413	422	445	470			
1993				398	413	443	459	483	498	499
1994			330	401	422	446	484	480		
1995			373	408	421	451	487			
1996			364	401	424	460	472			
1997			334	414	422	447	472	525		
1998				406	431	451	473			
1999					431	453	484			
2000				411	448	458	470	488		
2001				425	442	471	503			
2002				417	444	473	502	495		
2003				415	445	474	502	515		
2004				420	448	486	526			
2005				389	431	462	496	462	540	
2006					425					
2007			378	409	438	464		515	571	
2008			375	409	444	480			504	
2009				405	438	443	474			
2010				415	420	452				
2011				410	435	461	462			
2012	132			374	425	447	410			
2013					374	422	452	484	410	
2014				378	418	447	453	477	495	
2016					395	432	456	409		
2017			390	430	434	434				
Mean Length	132		361	410	433	458	478	494	502	499

Table 95. Mean fork length-at-age (mm) of American shad, sexes combined, captured in the Nanticoke River fishery-dependent pound and fyke net survey, 1989-2017. No fishing occurred in 2015.

Year	Age									
	1	2	3	4	5	6	7	8	9	10
1989			340	374	437	454	504	513		
1990			344	381	416	469	474	498		
1991			343	382	421	449	486	497		
1992		208	353	369	408	436	464			
1993		247	344	372	392	424	447	475	498	499
1994		295	340	374	406	436	473	480		
1995		243	339	380	409	447	487			
1996			350	377	407	442	472			
1997			343	387	414	447	472	525		
1998			341	385	416	448	444			
1999			306	364	406	447	484			
2000			350	388	423	450	470	488		
2001			359	405	428	463	503			
2002			346	389	429	464	501	495		
2003			355	391	415	465	502	515		
2004			351	406	429	483	500			
2005			333	367	416	455	481	472	540	
2006			330		402			453		
2007			353	380	421	438	466	479	571	
2008			335	385	420	468			504	
2009			339	373	404	438	474			
2010			331	390	409	431				
2011			336	379	419	452	462			
2012	137		345	370	401	423	411			
2013					381	389	444	448	410	
2014				364	409	432	432	477	495	
2016			303	359	383	411	433	429		
2017			371	393	417	414				
Mean Length	137	248	343	380	414	444	468	482	502	499

Table 96. Nanticoke River Commercial CPUE number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
1996	8	1.00	4.94	0.28
1997	8	0.88	2.67	0.31
1998	5	1.00	3.30	0.36
1999	3	0.67	0.76	0.76
2000	14	0.86	3.96	0.20
2001	7	1.00	6.63	0.26
2002	14	0.93	4.68	0.22
2003	10	0.90	7.43	0.20
2004	NA	NA	NA	NA
2005	9	1.00	4.22	0.26
2006	5	0.60	0.75	0.62
2007	2	1.00	6.47	0.46
2008	12	1.00	1.45	0.32
2009	5	1.00	4.48	0.33
2010	8	0.88	4.00	0.30
2011	15	0.93	4.59	0.22
2012	16	0.94	7.13	0.18
2013	7	0.86	2.03	0.38
2014	5	1.00	2.30	0.39
2015	NA	NA	NA	NA
2016	9	1.00	2.50	0.26
2017	6	1.00	1.81	0.38

Table 97. Nanticoke River Spawning Stock Electrofishing Survey index (numbers).

Year	Index
2002	21.20
2003	48.80
2004	36.90
2005	26.00
2006	11.80
2007	24.00
2008	25.50
2009	30.60
2010	50.40
2011	52.60
2012	55.20
2013	39.58
2014	34.26
2015	7.60
2016	27.02
2017	37.32

Table 98. Nanticoke River Juvenile Haul Seine Survey index (numbers).

Year	Index
1999	0.50
2000	0.30
2001	0.80
2002	1.60
2003	1.30
2004	3.50
2005	2.60
2006	3.20
2007	3.20
2008	2.00
2009	5.00
2010	3.90
2011	3.00
2012	2.40
2013	0.70
2014	1.20
2015	1.30
2016	0.60
2017	0.50

Table 99. Mann-Kendall results for mean length-at-age over time for male and female American shad in the Nanticoke River.

Mean Length-at-age for Nanticoke River (Scales)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Nanticoke River	Nanticoke River Electrofishing Survey	3	2004-2013	4	-2	0.734	2003-2017	15	-1	1.000
		4	2004-2017	9	-12	0.251	2003-2017	15	-1	1.000
		5	2004-2017	11	-17	0.213	2003-2017	15	5	0.843
		6	2004-2017	11	-5	0.755	2003-2017	15	15	0.488
		7	2005-2017	10	9	0.474	2003-2017	14	5	0.827
		8	2005-2017	7	1	1.000	2005-2014	5	0	1.000
		9	2007-2013	3	-3	1.000				
	Nanticoke River Commercial Pound Net Fishery Monitoring	2					1992-1995	4	2	0.734
		3	1988-1997	7	-7	0.368	1988-2016	19	11	0.726
		4	1988-2012	14	-7	0.743	1988-2016	20	-25	0.436
		5	1988-2012	14	-7	0.743	1988-2016	20	-26	0.417
		6	1988-2012	14	-5	0.827	1988-2016	20	-38	0.230
		7	1988-2012	14	-27	0.155	1988-2016	12	-26	0.086
		8	1988-2003	10	-8	0.530	1989-2016	6	-8	0.181

Table 100. American shad eggs (millions) used in the Susquehanna River shad restoration program, by egg source.

	Location (collection source)													
Year	**Hudson**	**Delaware**	**Susq. Conowingo**	**Susq. Lapidum**	**Susq. Muddy Run**	**Susq. Lamar**	**Connecticut**	**Pamunkey**	**Mattaponi**	**James**	**Savannah**	**Columbia**	**Potomac**	**Total**
1971				8.42										**8.4**
1972				7.10										**7.1**
1973				4.74			4.30	8.45	6.48				34.64	**58.6**
1974							0.53	9.75	6.80	19.20		8.18	5.56	**50.0**
1975								1.88		7.15		18.42	5.70	**33.2**
1976		4.10										54.80		**58.9**
1977							0.35	4.40	0.57	3.42		8.90		**17.6**
1978								6.90		10.11		0.00		**17.0**
1979								3.17		4.99		0.00		**8.2**
1980								6.73		6.83		0.00		**13.6**
1981								4.58		1.26		5.78		**11.6**
1982								2.03		1.25		22.57		**25.9**
1983	1.17	2.40						5.49		5.91		19.51		**34.5**
1984		2.64						9.83		0.74		27.88		**41.1**
1985		6.16						5.28		2.05		12.06		**25.6**
1986		5.86						5.62		1.07		39.97		**52.5**
1987		5.01						4.35		0.11		23.53		**33.0**
1988		2.91						1.92		0.05		26.92		**31.8**
1989	11.18	5.96						1.91		0.53		23.10		**42.7**
1990	14.53	13.15				0.33		0.48			0.12			**28.6**
1991	17.66	10.75				0.30	1.10							**29.8**
1992	3.00	9.60					5.71			0.17				**18.5**
1993	2.97	9.30					7.45	1.78						**21.5**
1994	6.29	10.27					4.09	0.53	0.03					**21.2**
1995	11.85	10.75												**22.6**
1996	5.69	8.31				0.41								**14.4**
1997	11.08	11.76												**22.8**
1998	15.68	10.38				1.66								**27.7**
1999	21.10	5.49												**26.6**
2000	14.88													**14.9**
2001	3.92		5.81			5.05								**14.8**
2002	18.51		7.08			7.99								**33.6**
2003	17.12		11.72	0.56	0.02									**29.4**
2004	9.39		4.74	0.75										**14.9**
2005	2.92		8.00											**10.9**
2006	1.86		10.28										4.51	**16.7**
2007			6.77										7.49	**14.3**
2008			5.75										8.50	**14.3**
2009			5.89										6.38	**12.3**
2010			7.34										17.84	**25.2**
2011			7.36										6.22	**13.6**
2012			3.83										11.18	**15.0**
2013			7.19										7.51	**14.7**
2014			1.13										14.41	**15.5**
2015			3.45										8.85	**12.3**
2016			2.10										8.39	**10.5**
2017			3.22										14.44	**17.7**
Total	**190.8**	**134.8**	**101.6**	**21.6**	**0.0**	**15.7**	**23.5**	**85.1**	**13.9**	**64.8**	**0.1**	**291.6**	**161.6**	**1,105.3**

Table 101. Summary of American shad collection and stocking activities in the Susquehanna River Basin above dams. Fish passage was documented with visual counts.

				Live Pre-Spawn Adults					
	Hatchery Stocking				Conowingo Fish Lifts (rkm 16.1)		Adult Shad Passage		
Year	Eggs Planted (millions)	Fry (thousands)	Fingerlings (thousands)	Out-of-Basin Transfers	Catch*	Transfers /Passage**	Holtwood (rkm 39.6)	Safe Harbor (rkm 51.8)	York Haven (rkm 90.3)
1971	8.4	-	-	-	-	-	-	-	-
1972	7.1	-	-	-	182	-	-	-	-
1973	58.6	-	-	-	65	-	-	-	-
1974	50.0	-	-	-	121	-	-	-	-
1975	33.2	-	-	-	87	-	-	-	-
1976	54.0	518	266	-	82	-	-	-	-
1977	11.0	969	35	-	165	-	-	-	-
1978	-	2,124	6	-	54	-	-	-	-
1979	-	629	34	-	50	-	-	-	-
1980	-	3,526	5	114	139	-	-	-	-
1981	-	2,030	24	1,165	328	-	-	-	-
1982	-	5,019	41	2,565	2,039	800	-	-	-
1983	-	4,048	98	4,310	413	64	-	-	-
1984	-	11,996	31	3,777	167	0	-	-	-
1985	-	6,228	115	2,834	1,546	967	-	-	-
1986	-	9,899	73	4,965	5,195	4,172	-	-	-
1987	-	5,180	81	6,051	7,667	7,202	-	-	-
1988	-	6,451	74	-	5,146	4,736	-	-	-
1989	-	13,465	65	-	8,218	6,469	-	-	-
1990	-	5,619	90	-	15,719	15,075	-	-	-
1991	-	7,218	54	-	27,227	24,662	-	-	-
1992	-	3,039	22	-	25,721	15,674	-	-	-
1993	-	6,542	79	-	13,546	11,717	-	-	-
1994	-	6,420	140	-	32,330	28,681	-	-	-
1995	-	10,001	-	-	61,650	56,370	-	-	-
1996	-	7,466	-	-	37,512	33,825	-	-	-
1997	-	8,019	25	-	103,945	101,684	28,063	20,828	-
1998	-	11,757	2.2	-	46,481	44,497	8,235	6,054	-
1999	-	13,501	-	-	79,370	75,220	34,702	34,210	-
2000	-	9,461	-	-	163,331	158,249	29,421	21,079	4,687
2001	-	6,524	6.5	-	203,776	193,574	109,976	89,816	16,200
2002	-	2,589	-	-	117,348	108,001	17,522	11,705	1,555
2003	-	12,742	-	-	134,937	125,135	25,254	16,646	2,536
2004	-	4,730	-	-	112,786	109,360	3,428	2,109	219
2005	-	3,571	-	-	72,822	68,926	34,189	25,425	1,771
2006	-	4,346	-	-	60,869	56,899	35,968	24,929	1,913
2007	-	1,380	-	-	27,765	25,464	10,338	7,215	192
2008	-	2,490	-	-	22,541	19,914	2,795	1,252	21
2009	-	2,701	-	-	35,806	29,272	10,896	7,994	402
2010	-	4,743	2.5	-	43,362	37,757	16,472	12,706	907
2011	-	3,053	9.1	-	23,645	20,571	21	8	0
2012	-	3,437	1.5	-	23,629	22,143	4,238	3,089	224
2013	-	2,362	-	-	14,763	12,733	2,503	1,927	202
2014	-	3,840	-	-	10,938	10,425	2,625	1,336	8
2015	-	1,994	-	-	9,184	8,309	5,280	3,884	43
2016	-	1,747	-	-	15,137	14,276	6,747	4,242	178
2017	-	3,787	-	-	17,001	16,265	3,208	2,011	62
Totals	**222**	**227,160**	**1,380**	**25,781**	**1,584,805**	**1,469,088**	**391,881**	**298,465**	**31,120**

Table 102. Commercial American shad landings (pounds) and market value by gear type harvested from the northern Chesapeake Bay (line from Howell Point to Romney Creek, north to Conowingo Dam, inclusive of all tributaries), 1944-1952.

Year	Haul Seine	Gill Net			Pound Net	Fyke Net	Total		Source
		Anchor	Drift	Stake			Pounds	Value	
1944	9,344	32,711	43,591	17,144	50,807		153,597	$14,429	*Hammer et al.-1948*
1945	5,996	58,785	33,520	2,867	56,203		157,371	$29,613	*Hammer et al.-1948*
1946	4,014	148,813	42,165	17,994	37,598		250,584	$40,807	*Hensel & Tiller-1952*
1947	12,095	101,178	64,967	40,910	45,189		264,339	$39,965	*Hensel & Tiller-1952*
1948	3,942	136,427	77,409	37,853	57,018		312,649	$39,948	*Hensel & Tiller-1952*
1949	4,740	106,248	78,010	17,783	95,492		302,273	$42,907	*Hensel & Tiller-1952*
1950	1,175	111,328	63,945	19,823	151,849	4,750	352,870	$48,486	*Hensel & Tiller-1952*
1951	7,498	140,096	296,525	18,614	146,411		609,144	$98,710	*Hensel & Tiller-1954*
1952	1,880	180,451	186,298	64,122	156,654		589,405	$74,226	*Hensel & Tiller-1954*

Table 103. Catch-at-age of American shad, sexes combined, from the MD DNR Upper Chesapeake Bay pound net survey, 1988-2001. For 1996 to 2001, age-length keys were applied to random subsamples that were selected for ageing. Prior to 1996, biologists attempted to age all scale samples.

Year	Age									Mean Age
	2	3	4	5	6	7	8	9	10	
1988	1	16	57	69	18					4.5
1989		27	119	140	53	4				4.7
1990		18	91	182	66	26				5.0
1991	2	14	111	280	255	52	7			5.3
1992		1	24	61	46	29	1			5.5
1993		7	39	71	66	22	9			5.4
1994		22	84	134	49	13	1			4.8
1995		28	94	104	55	16	1			4.8
1996	2	128	266	561	411	131				5.1
1997		3	226	353	205	17	12			5.1
1998		7	102	122	70	5				4.9
1999		25	105	149	75	14	4			4.9
2000		21	622	491	91	14	2		2	4.6
2001		32	204	335	137	13	1			4.9

Table 104. Upper Chesapeake Bay Commercial Pound Net number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
1980	30	0.73	3.04	0.39
1981	16	0.50	1.67	0.52
1982	19	0.95	3.19	0.39
1983	3	0.33	0.20	0.90
1985	5	1.00	4.17	0.46
1987	1	1.00	0.75	0.20
1988	46	0.83	2.12	0.21
1989	35	0.94	4.68	0.25
1990	38	0.95	4.97	0.23
1991	48	1.00	10.97	0.22
1992	28	1.00	3.15	0.24
1993	28	1.00	6.97	0.27
1994	32	0.91	7.71	0.21
1995	44	1.00	9.19	0.20
1996	51	1.00	6.32	0.20
1997	26	1.00	15.59	0.24
1998	14	1.00	4.04	0.30
1999	30	0.97	7.18	0.22
2000	27	1.00	29.60	0.28
2001	27	0.93	20.51	0.26

Table 105. **MD DNR Susquehanna River Creel Survey number of observations (n), proportion positive observations, index values (units), and CVs.**

Year	n	Proportion Positive	Index	CV
2001	4	1.00	2.95	0.49
2002	5	1.00	1.96	0.37
2003	3	1.00	3.78	0.41
2004	6	1.00	1.17	0.27
2005	3	0.67	0.52	0.70
2006	4	0.75	1.30	0.48
2007	NA	NA	NA	NA
2008	NA	NA	NA	NA
2009	3	1.00	1.49	0.24
2010	4	1.00	1.59	0.31
2012	6	0.67	0.60	0.59
2013	3	1.00	0.67	0.09
2014	7	0.86	1.02	0.30
2015	5	1.00	1.80	0.12
2016	13	0.85	1.02	0.29
2017	9	0.89	1.15	0.38

Table 106. Catch-at-age of male American shad, from the MD DNR Susquehanna hook-and-line survey, 1982-2017. For 1995 to 1997 and 1999 to 2003, age-length keys were applied to random subsamples that were selected for ageing. In all other years, biologists attempted to age all scale samples.

Year	Age								Mean Age
	2	3	4	5	6	7	8	9	
1982		18	38	4					3.8
1983				3					5.0
1984		30	34	8	4				3.8
1985		22	70	21					4.0
1986		100	198	59					3.9
1987	1	61	149	62	1				4.0
1988	3	59	86	26	1				3.8
1989		46	94	49	7				4.1
1990		15	102	59	6				4.3
1991		8	49	93	30	2			4.8
1992	1	18	52	90	16	2			4.6
1993		8	67	56	18	2			4.6
1994		15	120	122	13				4.5
1995		15	105	164	27				4.7
1996		25	89	84	21				4.5
1997		59	200	80	22	4			4.2
1998	1	8	60	54	5	1			4.4
1999	2	67	286	157	6	1			4.2
2000		9	264	178	6				4.4
2001		33	134	220	26	2			4.6
2002		13	101	142	85	20			5.0
2003		10	170	200	54	6		6	4.8
2004		7	39	87	17				4.8
2005		8	64	37	32	7	1		4.8
2006		17	62	43	6	2			4.3
2007		17	98	59	9	1	1		4.4
2008		6	28	21	4				4.4
2009		20	244	94	11				4.3
2010		14	97	106	17	2			4.6
2011			18	25	7				4.8
2012		4	31	46	22				4.8
2013			11	66	48	32	4	1	5.7
2014		3	50	97	45	4			5.0
2015		19	59	60	14				4.5
2016		5	43	140	37	2			4.9
2017		11	53	44	3				4.4

Table 107. Catch-at-age of female American shad, from the MD DNR Susquehanna hook-and-line survey, 1982-2017. For 1995 to 1997 and 1999 to 2003, age-length keys were applied to random subsamples that were selected for ageing. In all other years, biologists attempted to age all scale samples.

Year	Age								Mean Age
	3	4	5	6	7	8	9	10	
1982		8	5						4.4
1983		1	5						4.8
1984		11	24	10	3				5.1
1985		13	28	18	2				5.1
1986	2	28	35	3					4.6
1987	4	41	64	3					4.6
1988	5	37	28	7					4.5
1989	1	23	37	12					4.8
1990	1	36	60	22	4				4.9
1991		18	76	65	6				5.4
1992		9	88	66	28	1			5.6
1993		16	27	31	8				5.4
1994		22	94	41	8				5.2
1995		49	161	93	6				5.2
1996	1	63	76	78	9				5.1
1997	4	57	117	52	10	1			5.0
1998		77	64	30	6	1	1		4.8
1999	3	78	165	52	3		1	1	4.9
2000		118	126	31	4	1			4.7
2001	1	132	242	164	15				5.1
2002		57	150	150	77	5			5.6
2003	2	60	97	116	57		3		5.5
2004		41	114	67	12	1	1		5.2
2005		35	81	92	27	1			5.5
2006	1	95	74	19	12	6	1		4.8
2007		64	113	79	5	2	1		5.1
2008		49	37	13	2		1		4.7
2009		120	91	36	5	1			4.7
2010		89	82	27	2	1			4.7
2011		14	64	40	4				5.3
2012	1	1	14	34	23	1			6.1
2013		4	23	51	38	14	5	1	6.4
2014		5	89	104	30		1		5.7
2015	2	22	66	29	7	1			5.2
2016		11	77	47	4				5.3
2017	3	34	92	24					4.9

Table 108. Catch-at-age of American shad, sexes combined, from the MD DNR Susquehanna hook-and-line survey, 1982-2017. For 1995 to 1997 and 1999 to 2003, age-length keys were applied to random subsamples that were selected for ageing. In all other years, biologists attempted to age all scale samples.

Year	Age									Mean Age
	2	3	4	5	6	7	8	9	10	
1982		18	46	9						3.9
1983			1	8						4.9
1984		30	45	32	14	3				4.3
1985		22	83	49	18	2				4.4
1986		102	226	94	3					4.0
1987	1	65	190	126	4					4.2
1988	3	64	123	54	8					4.0
1989		47	117	86	19					4.3
1990		16	138	119	28	4				4.6
1991		8	67	169	95	8				5.1
1992	1	18	61	178	82	30	1			5.1
1993		8	83	83	49	10				4.9
1994		15	142	216	54	8				4.8
1995		15	154	325	120	6				4.9
1996		26	152	160	99	9				4.8
1997		63	257	197	74	14	1			4.5
1998	1	8	137	118	35	7	1	1		4.7
1999	2	70	364	322	58	4		1	1	4.5
2000		9	382	304	37	4	1			4.5
2001		34	266	462	190	17				4.9
2002		13	158	292	235	97	5			5.3
2003		12	230	297	170	63		9		5.1
2004		7	80	201	84	12	1	1		5.1
2005		8	99	118	124	34	2			5.2
2006		18	157	117	25	14	6	1		4.7
2007		17	162	172	88	6	3	1		4.8
2008		6	77	58	17	2		1		4.6
2009		20	364	185	47	5	1			4.4
2010		14	186	188	44	4	1			4.6
2011			32	89	47	4				5.1
2012		5	32	60	56	23	1			5.4
2013			15	89	99	70	18	6	1	6.0
2014		3	55	186	149	34		1		5.4
2015		21	81	126	43	7	1			4.8
2016		5	54	217	84	6				5.1
2017		14	87	136	27					4.7

Table 109. Mean fork length-at-age (mm) of male American shad from the MD DNR Susquehanna hook-and-line survey, 1982-2017.

Year	Age							
	2	3	4	5	6	7	8	9
1982		380	407	460				
1983				410				
1984		332	376	442	478			
1985		362	381	436				
1986		324	393	426				
1987	238	340	379	431	430			
1988	296	333	394	432	505			
1989		345	368	421	453			
1990		346	387	413	448			
1991		339	377	408	447	453		
1992	275	317	375	405	428	475		
1993		318	371	416	436	471		
1994		354	381	405	454			
1995		342	383	411	453			
1996		343	379	425	454			
1997		336	389	433	460	479		
1998	280	349	387	410	444	455		
1999	287	338	371	405	427			460
2000		351	383	419	453			
2001		351	393	418	449	477		
2002		346	379	419	454	455		
2003		361	389	415	450	447		480
2004		350	392	424	440			
2005		355	383	416	447	467	485	
2006		348	388	416	461	468		
2007		358	387	418	448	465	503	
2008		355	383	414	434			
2009		351	380	400	429			
2010		361	392	413	436	445		
2011			384	417	445			
2012		351	366	382	405			
2013			377	391	399	415	411	414
2014		329	367	395	409	416		
2015		365	377	397	418			
2016		348	386	391	399	419		
2017		370	399	417	416			
Mean Length	282	342	383	410	432	439	439	451

Table 110. Mean fork length-at-age (mm) of female American shad from the MD DNR Susquehanna hook-and-line survey, 1982-2017.

Year	Age							
	3	4	5	6	7	8	9	10
1982		427	469					
1983		478	452					
1984		397	465	501	558			
1985		420	451	497	515			
1986	390	430	468	528				
1987	389	412	464	527				
1988	385	422	456	508				
1989	335	419	457	508				
1990	360	414	443	477	513			
1991		409	434	467	503			
1992		408	435	454	497	535		
1993		397	430	459	483			
1994		412	429	471	475			
1995		414	441	471	503			
1996	355	420	448	483	495			
1997	360	393	457	485	502	508		
1998		419	439	464	486	525	562	
1999	420	406	440	463	473		540	505
2000		418	446	482	499	505		
2001	378	422	450	479	501			
2002		423	455	482	504	509		
2003		420	442	473	500		510	
2004		429	454	473	515	518	520	
2005		427	452	474	498	546		
2006	354	419	446	467	483	494	519	
2007		422	447	471	502	514	526	
2008		419	442	469	484		506	
2009		415	442	467	483	503		
2010		418	444	463	502	515		
2011		417	442	462	485			
2012	376	452	419	450	464	445		
2013		417	433	438	454	458	461	432
2014		437	437	445	447		435	
2015	397	414	435	452	454	461		
2016		410	424	437	469			
2017	408	426	445	445				
Mean Length	383	418	444	466	484	485	494	469

Table 111. Mean fork length-at-age (mm) of American shad, sexes combined, from the MD DNR Susquehanna hook-and-line survey, 1982-2017.

Year	Age								
	2	3	4	5	6	7	8	9	10
1982		380	410	465					
1983			478	437					
1984		332	381	459	494	558			
1985		362	387	445	497	515			
1986		325	398	442	528				
1987	238	343	387	448	503				
1988	296	337	403	444	508				
1989		345	378	437	488				
1990		347	394	428	471	513			
1991		339	385	420	461	491			
1992	275	317	380	420	449	495	535		
1993		318	376	420	450	480			
1994		354	385	415	467	475			
1995		342	396	424	466	503			
1996		343	395	434	475	495			
1997		339	393	441	474	492	508		
1998	280	349	405	426	461	481	525	562	
1999	287	341	381	423	457	473		500	505
2000		351	395	431	477	499	505		
2001		352	405	433	475	499			
2002		346	393	435	470	491	509		
2003		361	396	421	463	491		495	
2004		350	411	441	467	515	518	520	
2005		355	399	441	467	492	516		
2006		348	407	435	466	481	494	519	
2007		358	401	437	469	496	510	526	
2008		355	406	432	461	484		506	
2009		351	392	420	458	483	503		
2010		361	405	426	453	473	515		
2011			398	435	460	485			
2012		356	369	390	433	464	445		
2013			388	402	419	436	447	453	432
2014		329	374	415	434	443		435	
2015		368	387	417	441	454	461		
2016		348	391	403	420	453			
2017		378	409	436	442				
Mean Length	282	344	394	427	456	475	479	486	469

Table 112. Susquehanna River Hook-and-Line Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV	Year	n	Proportion Positive	Index	CV
1982	5	1.00	9.90	0.22	2000	14	1.00	25.27	0.19
1983	NA	NA	NA	NA	2001	20	1.00	17.68	0.12
1984	13	0.92	5.21	0.25	2002	18	1.00	22.68	0.14
1985	18	1.00	2.03	0.12	2003	23	1.00	16.99	0.13
1986	30	0.73	4.41	0.18	2004	13	1.00	19.80	0.23
1987	17	1.00	8.37	0.12	2005	16	1.00	9.87	0.16
1988	11	1.00	9.40	0.12	2006	12	1.00	9.52	0.17
1989	11	1.00	12.16	0.13	2007	15	0.93	12.42	0.13
1990	17	0.88	6.25	0.18	2008	13	1.00	5.97	0.17
1991	19	1.00	7.92	0.14	2009	20	1.00	12.36	0.12
1992	15	1.00	9.14	0.17	2010	19	1.00	7.74	0.14
1993	13	1.00	8.97	0.23	2011	NA	NA	NA	NA
1994	23	1.00	9.11	0.16	2012	16	0.88	4.70	0.26
1995	19	1.00	10.12	0.13	2013	16	1.00	7.49	0.25
1996	10	1.00	21.47	0.21	2014	11	1.00	14.27	0.18
1997	14	1.00	13.41	0.11	2015	11	1.00	12.49	0.17
1998	6	1.00	33.94	0.24	2016	17	0.94	10.32	0.19
1999	15	1.00	19.67	0.12	2017	14	1.00	10.97	0.20

Table 113. Upper Chesapeake Bay Juvenile Seine Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV	Year	n	Proportion Positive	Index	CV
1959	4	1.00	NA	NA	1989	15	0.00	0.00	NA
1960	4	1.00	NA	NA	1990	15	0.07	0.00	NA
1961	4	1.00	NA	NA	1991	15	0.00	0.00	NA
1962	10	0.90	4.66	0.67	1992	15	0.00	0.00	NA
1963	10	0.40	0.75	0.65	1993	15	0.07	0.13	0.78
1964	10	0.40	0.59	0.67	1994	15	0.07	0.04	1.15
1965	10	0.30	0.28	0.81	1995	15	0.27	0.32	0.73
1966	15	0.67	7.51	0.56	1996	15	0.67	0.93	0.60
1967	15	0.27	0.54	0.56	1997	15	0.00	0.00	NA
1968	15	0.53	2.60	0.44	1998	15	0.80	2.76	0.44
1969	15	0.60	5.59	0.56	1999	15	0.13	0.18	0.80
1970	15	0.20	0.86	0.62	2000	15	0.73	4.23	0.45
1971	15	0.27	0.43	0.64	2001	15	0.20	0.14	0.65
1972	15	0.07	0.08	1.07	2002	15	0.20	0.79	0.56
1973	15	0.00	0.00	NA	2003	15	0.80	1.01	0.53
1974	14	0.00	0.00	NA	2004	15	0.53	0.90	0.50
1975	15	0.07	0.00	NA	2005	15	0.67	1.40	0.51
1976	15	0.00	0.00	NA	2006	15	0.07	0.07	0.72
1977	15	0.00	0.00	NA	2007	15	0.93	14.04	0.47
1978	15	0.00	0.00	NA	2008	15	0.13	0.04	0.87
1979	15	0.00	0.00	NA	2009	15	0.00	0.00	NA
1980	15	0.00	0.00	NA	2010	15	0.27	0.62	0.53
1981	15	0.00	0.00	NA	2011	15	0.53	0.96	0.58
1982	15	0.00	0.00	NA	2012	15	0.07	0.18	0.71
1983	15	0.00	0.00	NA	2013	15	0.27	2.46	0.45
1984	15	0.00	0.00	NA	2014	15	0.47	0.53	0.52
1985	15	0.00	0.00	NA	2015	15	0.73	3.35	0.47
1986	15	0.00	0.00	NA	2016	15	0.13	0.21	0.63
1987	15	0.00	0.00	NA	2017	15	0.60	1.21	0.49
1988	15	0.00	0.00	NA					

Table 114. Summary of annual American shad passage at four successive Susquehanna River Hydroelectric dams; passage efficiency expressed as a percentage of shad that passed the next lowest dam, 1997-2017.

Year	Fish Passage (number)				Fish Passage Efficiency			
	Conowingo (rkm 16.1)	Holtwood (rkm 39.6)	Safe Harbor (rkm 51.7)	York Haven (rkm 90.3)	Holtwood %	Safe Harbor %	York Haven %	Combined %
1997	90,971	28,063	20,828	-	31%	74%	-	-
1998	39,904	8,235	6,054	-	21%	74%	-	-
1999	69,712	34,702	34,210	-	50%	99%	-	-
2000	153,546	29,421	21,079	4,687	19%	72%	22%	3%
2001	193,574	109,976	89,816	16,200	57%	82%	18%	8%
2002	108,001	17,522	11,705	1,555	16%	67%	13%	1%
2003	125,135	25,254	16,646	2,536	20%	66%	15%	2%
2004	109,360	3,428	2,109	219	3%	62%	10%	0%
2005	68,926	34,189	25,425	1,772	50%	74%	7%	3%
2006	56,899	35,968	24,929	1,913	63%	69%	8%	3%
2007	25,464	10,338	7,215	192	41%	70%	3%	1%
2008	19,914	2,795	1,252	21	14%	45%	2%	0%
2009	29,272	10,896	7,994	402	37%	73%	5%	1%
2010	37,757	16,472	12,706	907	44%	77%	7%	2%
2011	20,571	21	8	0	0%	38%	0%	0%
2012	23,629	4,238	3,089	224	18%	73%	7%	1%
2013	12,733	2,503	1,927	202	20%	77%	10%	2%
2014	10,425	2,625	1,336	8	25%	51%	1%	0%
2015	8,309	5,280	3,884	43	64%	74%	1%	1%
2016	14,276	6,747	4,242	178	47%	63%	4%	1%
2017	16,265	3,208	2,011	62	20%	63%	3%	0%
Total	**1,234,643**	**391,881**	**298,465**	**31,121**	**32%**	**76%**	**10%**	**3%**

Table 115. Catch-at-age (otolith age) of male American shad from PFBC Conowingo Dam Fish Lift survey, 1995-2017 (? Notes no otolith or undetermined age).

Year	Otolith Age (Males)											
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**?**	**Mean Age**
1995		11	75	82	14	2					7	**4.6**
1996	4	79	70	47	1	2					10	**3.8**
1997		61	82	17	5						2	**3.8**
1998		4	36	27								**4.3**
1999		19	62	16	2		1				1	**4.1**
2000		19	85	25	5							**4.1**
2001		4	29	42	7							**4.6**
2002		16	15	31	9	2		1			1	**4.6**
2003		4	49	17	17	2	1				2	**4.6**
2004		13	12	33	8	5	1					**4.8**
2005		7	62	28	22	3	1				1	**4.6**
2006	1	5	32	27	7							**4.5**
2007		1	25	16	9							**4.6**
2008		17	35	23	10	1						**4.3**
2009			74	26	6							**4.4**
2010		6	21	50	1						4	**4.6**
2011		1	15	38	17							**5.0**
2012		17	12	21	4	3						**4.4**
2013		2	50	37	4	1					1	**4.5**
2014		2	25	21	4							**4.5**
2015		13	33	28	4							**4.3**
2016		13	149	165	23	1					3	**4.6**
2017		5	83	179	22						39	**4.8**

Table 116. Catch-at-age (otolith age) of female American shad from PFBC Conowingo Dam Fish Lift survey, 1995-2017 (? Notes no otolith or undetermined age).

Year	Otolith Age (Females)											
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**?**	**Mean Age**
1995			14	86	28	7					5	**5.2**
1996		3	44	74	16	5					12	**4.8**
1997	1	2	28	27	21	2					1	**4.9**
1998			12	34	14	1					0	**5.1**
1999			24	46	13	2					4	**4.9**
2000		1	13	27	14	2					0	**5.1**
2001			18	56	34	4					0	**5.2**
2002			13	43	42	9	3				2	**5.5**
2003		1	12	30	44	13	1				0	**5.6**
2004			5	43	16	18	2				0	**5.6**
2005		2	18	33	71	16	4	1		1	2	**5.7**
2006			14	66	14	8	1	1			0	**5.2**
2007			10	29	57	2	2				0	**5.6**
2008			10	31	40	8	1				0	**5.5**
2009			15	34	11	4					0	**5.1**
2010			7	57	10	1	1				4	**5.1**
2011				20	42	3					2	**5.7**
2012			5	21	35	15					0	**5.8**
2013			6	27	31	8					0	**5.6**
2014		1	9	22	15	4					0	**5.2**
2015			2	45	32	7	1				2	**5.5**
2016		1	34	106	61	5	3				2	**5.2**
2017			23	107	68	4					30	**5.3**

Table 117. Catch-at-age (otolith age) of American shad, sexes combined, from PFBC Conowingo Dam Fish Lift survey, 1995-2017 (? Notes no otolith or undetermined age).

Year	Otolith Age (Sexes Combined)											
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**?**	**Mean Age**
1995		11	89	168	42	9					12	**4.8**
1996	4	82	114	121	17	7					22	**4.2**
1997	1	63	110	44	26	2					3	**4.2**
1998		4	48	61	14	1						**4.7**
1999		19	86	62	15	2	1				5	**4.4**
2000		20	98	52	19	2						**4.4**
2001		4	47	98	41	4						**5.0**
2002		16	28	74	51	11	3	1			3	**5.1**
2003		5	61	47	61	15	2				2	**5.1**
2004		13	17	76	24	23	3					**5.2**
2005		9	80	61	93	19	5	1		1	3	**5.2**
2006	1	5	46	93	21	8	1	1				**4.9**
2007		1	35	45	66	2	2					**5.3**
2008		17	45	54	50	9	1					**5.0**
2009		0	89	60	17	4						**4.6**
2010		6	28	107	11	1	1				8	**4.8**
2011		1	15	58	59	3					2	**5.4**
2012		17	17	42	39	18						**5.2**
2013		2	56	64	35	9					1	**5.0**
2014		3	34	43	19	4						**4.9**
2015		13	35	73	36	7	1				2	**5.0**
2016		14	183	271	84	6	3				5	**4.8**
2017		5	106	286	90	4					69	**5.0**

Table 118. Mean fork length (mm) at age (otolith) of male American shad from PFBC Conowingo Dam Fish Lifts survey, 1995-2017.

Year	Otolith Age (Males)									
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1995		362	393	413	421	468				
1996	345	374	408	427	465	435				
1997		366	394	431	424					
1998		380	401	417						
1999		370	390	419	426		450			
2000		394	406	430	455					
2001		420	411	429	434	415				
2002		371	416	438	465	450		482		
2003		382	405	433	453	452	452			
2004		366	387	430	444	477	410			
2005		365	390	419	440	438	455			
2006	389	346	393	410	430					
2007		385	388	393	429					
2008		349	385	407	416	400				
2009			377	394	415					
2010		363	395	412	411					
2011			392	411	437					
2012		355	376	406	428	430				
2013		355	389	410	454	455				
2014		347	386	406	428					
2015		360	372	417	444					
2016		355	386	401	413	460				
2017		352	379	417	429					
Mean Length	**354**	**368**	**393**	**415**	**435**	**448**	**442**	**482**		

Table 119. Mean fork length (mm) at age (otolith) of female American shad from PFBC Conowingo Dam Fish Lifts survey, 1995-2017.

Year	Otolith Age (Females)									
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1995			433	451	457	501				
1996		403	445	465	470	471				
1997	375	390	429	455	476	495				
1998			434	460	476	437				
1999			441	449	460	478				
2000		405	441	465	479	485				
2001			448	458	476	476				
2002			470	483	488	509	510			
2003		405	434	480	494	509	510			
2004			445	461	486	495	498			
2005		357	435	462	471	487	507	550		510
2006			437	443	462	479	480	494		
2007			444	454	462	468	389			
2008			417	435	455	462	524			
2009			423	436	451	465				
2010			426	440	452	519	610			
2011				444	448	460				
2012			402	443	456	462				
2013			422	432	465	472				
2014		305	434	458	468	518				
2015			416	443	464	472	471			
2016		420	418	437	449	450	466			
2017			423	448	450	465				
Mean Length	**375**	**381**	**435**	**453**	**466**	**482**	**491**	**522**		**510**

Table 120. Mean fork length (mm) at age (otolith) of American shad, sexes combined from PFBC Conowingo Dam Fish Lifts survey, 1995-2017.

Year	Otolith Age (Sexes Combined)									
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1995		362	399	432	444	496				
1996	345	374	422	450	469	460				
1997	375	367	403	445	466	495				
1998		380	409	442	476	437				
1999		370	404	441	456	478	450			
2000		395	410	448	472	485				
2001		420	425	445	469	464				
2002		371	441	465	484	498	510	482		
2003		386	411	463	482	502	481			
2004		366	403	447	472	492	468			
2005		363	401	442	464	479	497	550		510
2006	389	346	406	434	451	479	480	494		
2007		385	404	432	457	468	389			
2008		349	392	423	447	455	524			
2009			385	417	439	465				
2010		363	402	427	443	519	610			
2011			392	432	443	460				
2012		354	383	424	452	459				
2013		355	393	419	464	470				
2014		333	399	433	460	518				
2015		360	375	433	462	472	471			
2016		360	392	415	439	452	466			
2017		352	389	429	445	465				
Mean Length	**357**	**369**	**403**	**435**	**460**	**478**	**482**	**509**		**510**

Table 121. Mean weight (g) at age (otolith) of male American shad from PFBC Conowingo Dam Fish Lifts survey, 1995-2017.

Year	Otolith Age (Males)									
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1995		623	851	960	1022	1293				
1996	546	662	869	967	1220	970				
1997		667	834	1022	1018					
1998		614	750	861						
1999		642	717	855	885		1130			
2000		784	828	983	1195					
2001		949	831	956	1009	795				
2002		669	986	1126	1413	1280		1380		
2003		740	919	1090	1336	1335	1180			
2004		590	834	1025	1094	1402	1020			
2005		608	797	982	1160	1237	1270			
2006	630	557	811	921	1047					
2007		780	777	885	1072					
2008		529	725	896	947	940				
2009			724	816	930					
2010		653	833	964	905					
2011			750	874	1006					
2012		593	676	863	932	965				
2013		585	761	867	1220	1450				
2014		543	777	957	1070					
2015		568	660	883	1085					
2016		597	712	805	858	1140				
2017		583	666	874	978					
Mean Wt	**563**	**646**	**783**	**912**	**1060**	**1230**	**1150**	**1380**		

Table 122. Mean weight (g) at age (otolith) of female American shad from PFBC Conowingo Dam Fish Lifts survey, 1995-2017.

Year	Otolith Age (Females)									
	2	3	4	5	6	7	8	9	10	11
1995			1153	1347	1440	1826				
1996			1344	1440	1513	1321				
1997	1400	950	1233	1524	1647	1695				
1998			1012	1311	1474	1210				
1999			1154	1234	1382	1500				
2000			1227	1425	1495	1885				
2001			1247	1340	1496	1460				
2002			1383	1619	1657	1841	1675			
2003		1000	1216	1726	1817	1989	2080			
2004			1250	1345	1572	1739	1715			
2005		673	1242	1437	1555	1740	1613	2470		1900
2006			1253	1248	1468	1589	1605	2050		
2007			1212	1380	1494	1517	1195			
2008			996	1125	1367	1310	1770			
2009			1088	1198	1311	1473				
2010			1143	1307	1306	2000	2820			
2011				1169	1307	1487				
2012			976	1254	1357	1437				
2013			983	1136	1401	1486				
2014		310	1143	1396	1478	1665				
2015			855	1171	1348	1323	1300			
2016		1120	1011	1150	1195	1201	1330			
2017			1043	1171	1238	1335				
Mean Wt	**1400**	**833**	**1172**	**1308**	**1442**	**1620**	**1624**	**2260**		**1900**

Table 123. Mean weight (g) at age (otolith) of American shad, sexes combined, from PFBC Conowingo Dam Fish Lifts survey, 1995-2017.

Year	Otolith Age (Sexes Combined)									
	2	3	4	5	6	7	8	9	10	11
1995		623	890	1150	1297	1742				
1996	546	666	1041	1253	1491	1263				
1997	1400	676	934	1323	1526	1695				
1998		614	816	1111	1474	1210				
1999		642	839	1139	1316	1500	1130			
2000		789	882	1212	1416	1885				
2001		949	986	1174	1416	1327				
2002		669	1170	1413	1614	1739	1675	1380		
2003		792	974	1496	1680	1902	1630			
2004		590	950	1204	1419	1669	1483			
2005		622	899	1228	1462	1661	1544	2470		1900
2006	630	557	946	1153	1328	1589	1605	2050		
2007		780	901	1204	1437	1517	1195			
2008		529	785	1037	1284	1269	1770			
2009			784	1023	1188	1473				
2010		653	901	1148	1210	2000	2820			
2011			750	980	1221	1487				
2012		585	759	1054	1304	1367				
2013		585	785	980	1380	1482				
2014		465	874	1181	1392	1665				
2015		568	671	1060	1319	1327	1300			
2016		635	768	940	1101	1191	1330			
2017		583	748	985	1174	1335				
Mean Wt	**703**	**650**	**869**	**1115**	**1357**	**1569**	**1542**	**1967**		**1900**

Table 124. Otolith age and repeat spawning for pre-spawn male American shad collected at the Conowingo Dam Fish Lift, 2000-2017.

	Repeat	**Age**									
Year	**Spawn**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total**	**%**
2000	0		18	77	17	2				114	89%
	1			3	4	3				10	8%
	2				4					4	3%
	Total		**18**	**80**	**25**	**5**				**128**	
2001	0		3	30	38	7	1			79	99%
	1				1					1	1%
	Total		**3**	**30**	**39**	**7**	**1**			**80**	
2002	0		16	9	12	4				41	58%
	1			5	13	3				21	30%
	2				4	2	2		1	9	13%
	Total		**16**	**14**	**29**	**9**	**2**		**1**	**71**	
2003	0		4	44	17	17	2			84	95%
	1			3				1		4	5%
	Total		**4**	**47**	**17**	**17**	**2**	**1**		**88**	
2004	0		13	13	27	7	3	1		64	86%
	1				7	1	1			9	12%
	2						1			1	1%
	Total		**13**	**13**	**34**	**8**	**5**	**1**		**74**	
2005	0		7	44	21	6	1			79	64%
	1			18	4	9	1	1		33	27%
	2			2	2	5				9	7%
	3					2	1			3	2%
	Total		**7**	**64**	**27**	**22**	**3**	**1**		**124**	
2006	0	1	5	30	20	6				62	86%
	1			2	6					8	11%
	2				1	1				2	3%
	Total	**1**	**5**	**32**	**27**	**7**				**72**	
2007	0		1	17	13	2				33	65%
	1			7	2	4				13	25%
	2			1	1	2				4	8%
	3					1				1	2%
	Total		**1**	**25**	**16**	**9**				**51**	
2008	0		17	29	13	4				63	73%
	1			6	7	5				18	21%
	2				3	1				4	5%
	3				1					1	1%
	Total		**17**	**35**	**24**	**10**				**86**	
2009	0			73	22	2				97	92%
	1			3	3	2				8	8%
	2					1				1	1%
	Total			**76**	**25**	**5**				**106**	
2010	0		6	25	49	1				81	89%
	1			4	5	1				10	11%
	Total		**6**	**29**	**54**	**2**				**91**	
2011	0		1	15	29	14				59	86%
	1					7	2			9	13%
	2									0	0%
	3						1			1	1%
	Total		**1**	**15**	**36**	**17**				**69**	
2012	0		17	12	21	4	3			57	88%
	1				5	2	1			8	12%
	Total		**17**	**12**	**26**	**6**	**4**			**65**	
2013	0		2	46	35	3	1			87	93%
	1				4	2	1			7	7%
	Total		**2**	**50**	**37**	**4**	**1**			**94**	
2014	0		2	21	8	3				34	65%
	1			4	13	1				18	35%
	Total		**2**	**25**	**21**	**4**				**52**	
2015	0		13	32	20					65	83%
	1			1	8	3				12	15%
	2					1				1	1%
	Total		**13**	**33**	**28**	**4**				**78**	
2016	0		12	121	115	15	1			264	75%
	1		1	26	48	5				80	23%
	2			2	2	3				7	2%
	Total		**13**	**149**	**165**	**23**	**1**			**351**	
2017	0		5	69	126	13				213	74%
	1			12	31	6				49	17%
	2			2	20	2				24	8%
	Total		**5**	**83**	**177**	**21**				**286**	
2016	0			28	83	37	3	2			
	1		1	6	21	21	2	1			
	2				2	3					
	Total		**1**	**34**	**106**	**61**	**5**	**3**			
2017	0			20	74	32	2				
	1			2	18	21	1				
	2				15	10					
	3			0		2	1				
	Total			**22**	**107**	**65**	**4**				

Table 125. Otolith age and repeat spawning for pre-spawn female American shad collected at the Conowingo Dam Fish Lift, 2000-2017.

	Repeat	Age											
Year	Spawn	2	3	4	5	6	7	8	9	10	11	Total	%
2000	0		1	13	19	11	1					45	79%
	1				4							4	7%
	2				3	3						6	11%
	3						1					1	2%
	4				1							1	2%
	Total		**1**	**13**	**27**	**14**	**2**					**57**	
2001	0			16	51	30	4					101	100%
	Total			**16**	**51**	**30**	**4**					**101**	
2002	0			11	19	21	5	1				57	53%
	1			2	19	15	4	2				42	39%
	2				4	5						9	8%
	Total			**13**	**42**	**41**	**9**	**3**				**108**	
2003	0		1	12	24	40	9	1				87	86%
	1				3	2	2					7	7%
	2				3	2	2					7	7%
	Total		**1**	**12**	**30**	**44**	**13**	**1**				**101**	
2004	0			5	37	14	12					68	83%
	1				5	2	4					11	13%
	2				1	1		1				3	4%
	3						3					3	4%
	4							1				1	1%
	Total			**5**	**43**	**17**	**19**	**2**				**82**	
2005	0		2	11	19	37	4	1				74	51%
	1			7	7	21	4	2				41	28%
	2				7	5	3	1	1		1	18	12%
	3					7	3					10	7%
	4						2					2	1%
	Total		**2**	**18**	**33**	**70**	**16**	**4**	**1**		**1**	**145**	
2006	0			14	50	10	5					79	76%
	1				12	4	2	1				19	18%
	2				3		1					4	4%
	3				1							1	1%
	4								1			1	1%
	Total			**14**	**66**	**14**	**8**	**1**	**1**			**104**	
2007	0			10	16	33	2	2				63	62%
	1				7	8						15	15%
	2				5	12	1					18	18%
	3				1	4						5	5%
	Total			**10**	**29**	**57**	**3**	**2**				**101**	
2008	0			9	22	22	2					55	60%
	1			1	6	9	2					18	20%
	2				3	5	1					9	10%
	3					4	2	1				7	8%
	4					1	1					2	2%
	Total			**10**	**31**	**41**	**8**	**1**				**91**	
2009	0			15	24	10	2					51	80%
	1			3	6	2	1					12	19%
	2						1					1	2%
	Total			**18**	**30**	**12**	**4**					**64**	
2010	0			8	58	8		1				75	86%
	1				6	3						9	10%
	2			1		1	1					3	3%
	Total			**9**	**64**	**12**	**1**	**1**				**87**	
2011	0				19	37	3					59	92%
	1					5						5	8%
	Total				**19**	**42**	**3**					**64**	
2012	0			5	21	35	15					76	92%
	1				2	3	2					7	8%
	Total			**5**	**23**	**38**	**17**					**83**	
2013	0			6	26	27	6					65	90%
	1					2	2					4	6%
	2				1	2						3	4%
	Total			**6**	**27**	**31**	**8**					**72**	
2014	0		1	8	17	8	1					35	70%
	1			1	4	7	3					15	30%
	Total		**1**	**9**	**21**	**15**	**4**					**50**	
2015	0			2	41	23	3					69	81%
	1				4	9	1	1				15	18%
	2						1					1	1%
	Total			**2**	**45**	**32**	**5**	**1**				**85**	
2016	0			28	83	37	3	2				153	73%
	1		1	6	21	21	2	1				52	25%
	2				2	3						5	2%
	Total		**1**	**34**	**106**	**61**	**5**	**3**				**210**	
2017	0			20	74	32	2					128	65%
	1			2	18	21	1					42	21%
	2				15	10						25	13%
	3			0		2	1					3	2%
	Total			**22**	**107**	**65**	**4**					**198**	

Table 126. Otolith age and repeat spawning for pre-spawn American shad collected at the Conowingo Dam Fish Lift, 2000-2017.

	Repeat	Age											
Year	**Spawn**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Total**	**%**
2000	0		19	90	36	13	1					159	86%
	1			3	8	3						14	8%
	2				7	3						10	5%
	3						1					1	1%
	4				1							1	1%
	Total		**19**	**93**	**52**	**19**	**2**					**185**	
2001	0		3	46	89	37	5					180	99%
	1				1							1	1%
	Total		**3**	**46**	**90**	**37**	**5**					**181**	
2002	0		16	20	31	25	5	1				98	55%
	1			7	32	18	4	2				63	35%
	2				8	7	2		1			18	10%
	Total		**16**	**27**	**71**	**50**	**11**	**3**	**1**			**179**	
2003	0		5	56	41	57	11	1				171	90%
	1			3	3	2	2	1				11	6%
	2				3	2	2					7	4%
	Total		**5**	**59**	**47**	**61**	**15**	**2**				**189**	
2004	0		13	18	64	21	15	1				132	83%
	1				12	3	5					20	13%
	2				1	1	1	1				4	3%
	3						3					3	2%
	4							1				1	1%
	Total		**13**	**18**	**77**	**25**	**24**	**3**				**160**	
2005	0		9	55	40	43	5	1				153	57%
	1			25	11	30	5	3				74	28%
	2			2	9	10	3	1	1		1	27	10%
	3					9	4					13	5%
	4						2					2	1%
	Total		**9**	**82**	**60**	**92**	**19**	**5**	**1**		**1**	**269**	
2006	0	1	5	44	70	16	5					141	80%
	1			2	18	4	2	1				27	15%
	2				4	1	1					6	3%
	3				1							1	1%
	4								1			1	1%
	Total	**1**	**5**	**46**	**93**	**21**	**8**	**1**	**1**			**176**	
2007	0	0	1	27	29	35	2	2				96	63%
	1			7	9	12						28	18%
	2			1	6	14	1					22	14%
	3				1	5						6	4%
	Total	**0**	**1**	**35**	**45**	**66**	**3**	**2**				**152**	
2008	0	0	17	38	35	26	2					118	67%
	1			7	13	14	2					36	20%
	2				6	6	1					13	7%
	3				1	4	2	1				8	5%
	4					1	1					2	1%
	Total	**0**	**17**	**45**	**55**	**51**	**8**	**1**				**177**	
2009	0			88	46	12	2					148	87%
	1			6	9	4	1					20	12%
	2					1	1					2	1%
	Total	**0**	**0**	**94**	**55**	**17**	**4**	**0**				**170**	
2010	0		6	33	107	9		1				156	88%
	1			4	11	4						19	11%
	2			1		1	1					3	2%
	Total	**0**	**6**	**38**	**118**	**14**	**1**	**1**				**178**	
2011	0		1	15	48	51	3					118	89%
	1				7	7						14	11%
	2											0	0%
	3					1						1	1%
	Total	**0**	**1**	**15**	**55**	**59**	**3**	**0**				**133**	
2012	0		17	17	42	39	18					133	90%
	1				7	5	3					15	10%
	Total		**17**	**17**	**49**	**44**	**21**					**148**	
2013	0		2	52	61	30	7					152	92%
	1			4	2	3	2					11	7%
	2				1	2						3	2%
	Total		**2**	**56**	**64**	**35**	**9**					**166**	
2014	0		3	29	25	11	1					69	68%
	1			5	17	8	3					33	32%
	Total		**3**	**34**	**42**	**19**	**4**					**102**	
2015	0		13	34	61	23	3					134	82%
	1			1	12	12	1	1				27	17%
	2					1	1					2	1%
	Total		**13**	**35**	**73**	**36**	**5**	**1**				**163**	
2106	0		143	98	38	3	2					284	71%
	1		54	26	21	2	1					104	26%
	2		2	5	3							10	3%
	Total		**199**	**129**	**62**	**5**	**3**					**398**	
2017	0		146	87	32	2						267	67%
	1		33	24	21	1						79	20%
	2		20	17	10							47	12%
	3				2	1						3	1%
	Total		**199**	**128**	**65**	**4**						**396**	

Table 127. Origin of adult American shad collected at Conowingo Dam Fish Lifts, based on otolith analysis.

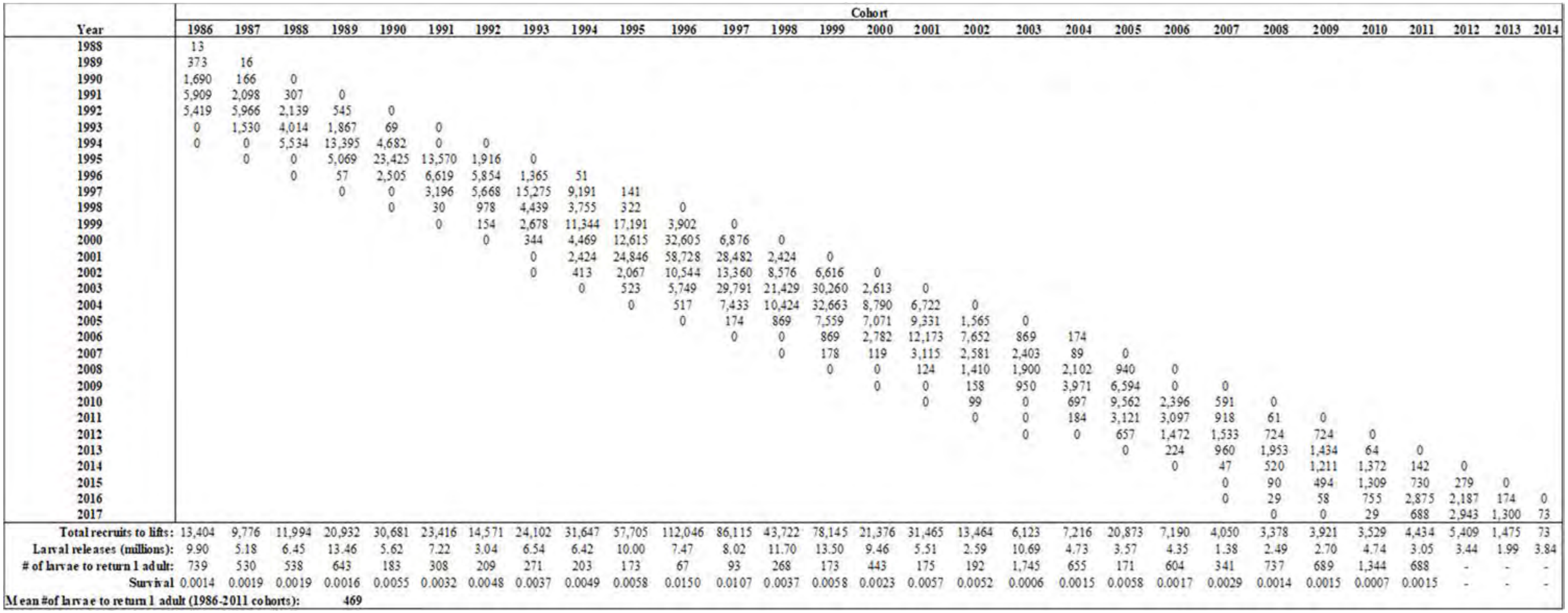
Year	Sample: 1 in every x	Hatchery Larvae Susquehanna		Hatchery Larvae Below Conowingo		Hatchery Fingerling		Hatchery Unmarked**		Naturally Reproduced		Total Sample Size
		N	%*	N	%*	N	%*	N	%**	N	%	
1989	50	36	22.6%	0	0.0%	0	0.0%	94	59.1%	29	18.2%	159
1990	100	49	39.5%	1	0.8%	0	0.0%	42	33.9%	32	25.8%	124
1991	100	111	43.9%	8	3.2%	3	1.2%	63	24.9%	68	26.9%	253
1992	100	154	65.0%	8	3.4%	2	0.8%	19	8.0%	54	22.8%	237
1993	100	76	61.3%	21	16.9%	2	1.6%	4	3.2%	21	16.9%	124
1994	100	217	75.6%	22	7.7%	3	1.0%	17	5.9%	28	9.8%	287
1995	100	255	77.0%	19	5.7%	4	1.2%	1	0.3%	52	15.7%	331
1996	100	180	47.5%	22	5.8%	4	1.1%	1	0.3%	172	45.4%	379
1997	50	84	33.6%	12	4.8%	4	1.6%	0	0.0%	150	60.0%	250
1998	50	29	22.3%	7	5.4%	2	1.5%	0	0.0%	92	70.8%	130
1999	50	90	47.9%	9	4.8%	1	0.5%	0	0.0%	88	46.8%	188
2000	50	78	40.4%	11	5.7%	0	0.0%	0	0.0%	104	53.9%	193
2001	50	120	57.7%	9	4.3%	0	0.0%	0	0.0%	79	38.0%	208
2002	50	118	64.8%	2	1.1%	0	0.0%	0	0.0%	62	34.1%	182
2003	50	146	74.5%	0	0.0%	0	0.0%	0	0.0%	50	25.5%	196
2004	50	113	71.5%	0	0.0%	0	0.0%	0	0.0%	45	28.5%	158
2005	50	176	64.2%	2	0.7%	0	0.0%	0	0.0%	96	35.0%	274
2006	50	89	50.3%	0	0.0%	0	0.0%	0	0.0%	88	49.7%	177
2007	50	71	45.5%	1	0.6%	0	0.0%	3	1.9%	81	51.9%	156
2008	50	73	41.5%	0	0.0%	0	0.0%	3	1.7%	100	56.8%	176
2009	50	63	36.4%	0	0.0%	0	0.0%	2	1.2%	108	62.4%	173
2010	50	58	32.4%	0	0.0%	0	0.0%	5	2.8%	116	64.8%	179
2011	50	49	36.6%	0	0.0%	0	0.0%	0	0.0%	85	63.4%	134
2012	50	37	27.6%	0	0.0%	0	0.0%	5	3.7%	92	68.7%	134
2013	50	56	36.6%	0	0.0%	0	0.0%	0	0.0%	97	63.4%	153
2014	50	45	44.6%	0	0.0%	0	0.0%	0	0.0%	56	55.4%	101
2015	25***	64	38.6%	0	0.0%	0	0.0%	0	0.0%	102	61.4%	166
2016	25***	284	54.0%	0	0.0%	0	0.0%	0	0.0%	242	46.0%	526
2017	25***	210	42.1%	0	0.0%	0	0.0%	0	0.0%	289	57.9%	500
	Totals	**3,131**	**50%**	**154**	**2%**	**25**	**0%**	**259**	**4%**	**2,678**	**43%**	**6,247**

*Unmarked hatchery fish distributed among groups based on annual percentage.

**Distinguished from naturally-reproduced fish by otolith microstructure.

*** Random sampling supplemented with brood fish from tank spawning due to low catch and limited lift operations.

Table 128. Recruitment of virgin hatchery larvae stocked above dams, to the Conowingo Fish Lifts, Susquehanna River (for fully recruited cohorts, 1986-2011).



	Cohort																												
Year	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
1988	13																												
1989	373	16																											
1990	1,690	166	0																										
1991	5,909	2,098	307	0																									
1992	5,419	5,966	2,139	545	0																								
1993	0	1,530	4,014	1,867	69	0																							
1994	0	0	5,534	13,395	4,682	0	0																						
1995		0	0	5,069	23,425	13,570	1,916	0																					
1996			0	57	2,505	6,619	5,854	1,365	51																				
1997				0	0	3,196	5,668	15,275	9,191	141																			
1998					0	30	978	4,439	3,755	322	0																		
1999						0	154	2,678	11,344	17,191	3,902	0																	
2000							0	344	4,469	12,615	32,605	6,876	0																
2001								0	2,424	24,846	58,728	28,482	2,424	0															
2002								0	413	2,067	10,544	13,360	8,576	6,616	0														
2003									0	523	5,749	29,791	21,429	30,260	2,613	0													
2004										0	517	7,433	10,424	32,663	8,790	6,722	0												
2005											0	174	869	7,559	7,071	9,331	1,565	0											
2006												0	0	869	2,782	12,173	7,652	869	174										
2007													0	178	119	3,115	2,581	2,403	89	0									
2008														0	0	124	1,410	1,900	2,102	940	0								
2009															0	0	158	950	3,971	6,594	0	0							
2010																0	99	0	697	9,562	2,396	591	0						
2011																	0	0	184	3,121	3,097	918	61	0					
2012																		0	0	657	1,472	1,533	724	724	0				
2013																				0	224	960	1,953	1,434	64	0			
2014																					0	47	520	1,211	1,372	142	0		
2015																						0	90	494	1,309	730	279	0	
2016																						0	29	58	755	2,875	2,187	174	0
2017																							0	0	29	688	2,943	1,300	73
Total recruits to lifts:	13,404	9,776	11,994	20,932	30,681	23,416	14,571	24,102	31,647	57,705	112,046	86,115	43,722	78,145	21,376	31,465	13,464	6,123	7,216	20,873	7,190	4,050	3,378	3,921	3,529	4,434	5,409	1,475	73
Larval releases (millions):	9.90	5.18	6.45	13.46	5.62	7.22	3.04	6.54	6.42	10.00	7.47	8.02	11.70	13.50	9.46	5.51	2.59	10.69	4.73	3.57	4.35	1.38	2.49	2.70	4.74	3.05	3.44	1.99	3.84
# of larvae to return 1 adult:	739	530	538	643	183	308	209	271	203	173	67	93	268	173	443	175	192	1,745	655	171	604	341	737	689	1,344	688	-	-	-
Survival	0.0014	0.0019	0.0019	0.0016	0.0055	0.0032	0.0048	0.0037	0.0049	0.0058	0.0150	0.0107	0.0037	0.0058	0.0023	0.0057	0.0052	0.0006	0.0015	0.0058	0.0017	0.0029	0.0014	0.0015	0.0007	0.0015	-	-	-
Mean #of larvae to return 1 adult (1986-2011 cohorts):				**469**																									

Table 129. Juvenile abundance index for American shad collected by lift net in the forebay of Holtwood Hydroelectric Station, Susquehanna River, 1985-2009.

		Total					Wild				Hatchery			
Year	# Lifts	# Fish	Mean Combined Daily CPUE	GM Combined Daily CPUE	GM Individual Lift CPUE*	Area Under the Curve CPUE	# Fish	Mean Combined Daily CPUE	GM Combined Daily CPUE	Area Under the Curve CPUE	# Fish	Mean Combined Daily CPUE	GM Combined Daily CPUE	Area Under the Curve CPUE
1985	378	3626	20.31	7.55		1422	**	**						
1986	404	2926	10.30	5.71		888	**	**						
1987	428	832	3.17	1.90		178	**	**						
1988	230	929	3.87	1.28		254	**	**						
1989	286	556	0.86	0.43		53	**	**						
1990	290	3988	13.75	3.67		1059	70	0.24	0.18	16	3984	13.74	3.66	1042
1991	370	208	0.56	0.39		72	19	0.05	0.05	7	189	0.51	0.36	65
1992	250	39	0.16	0.12		13	14	0.06	0.05	5	25	0.10	0.08	9
1993	250	1095	4.38	1.20		383	669	2.79	0.86	233	426	1.70	0.72	149
1994	250	206	0.82	0.48		71	35	0.15	0.13	12	171	0.68	0.42	59
1995	115	1048	9.11	1.26	1.07	801	83	0.72	0.32	53	965	8.39	1.01	742
1997	300	1372	4.57	0.88	0.61	411	100	0.33	0.23	30	1272	4.24	0.85	381
1998	300	180	0.60	0.37	0.22	53	9	0.03	0.03	2	171	0.57	0.35	49
1999	300	490	1.63	0.78	0.50	145	19	0.06	0.07	5	471	1.57	0.76	140
2000	300	406	1.35	0.61	0.18	121	4	0.01	0.01	1	402	1.34	0.60	120
2001	299	1245	4.18	1.37	0.43	273	538	1.81	0.45	112	707	2.38	0.99	161
2002	220	68	0.31	0.15	0.09	20	15	0.07	0.05	3	53	0.24	0.13	16
2003	300	61	0.20	0.13	0.07	17	3	0.01	0.01	1	58	0.23	0.15	17
2004	240	0	0.00	0.00	0.00	0	0	0.00	0.00	0	0	0.00	0.00	0
2005	300	200	0.67	0.15	0.10	59	47	0.16	0.11	13	153	0.00	0.00	46
2006	230	0	0.00	0.00	0.00	0	0	0.00	0.00	0	0	0.00	0.00	0
2007	300	0	0.00	0.00	0.00	0	0	0.00	0.00	0	0	0.00	0.00	0
2008	300	1	0.00	0.004	0.002	0.23	0	0.00	0.00	0	1	0.003	0.003	0.23
2009	300	0	0.00	0.00	0.00	0	0	0.00	0.00	0	0	0.00	0.00	0

No lift net collections beyond 2009 due to loss of sampling location as a result of redevelopment of the Holtwood Hydroelectric Station

* Required by ASMFC

**Most of the Holtwood samples processed were from cast net collections.

Table 130. Juvenile abundance index for American shad collected by haul seine in the Susquehanna River at Marietta, Columbia, and Wrightsville, 1990-2017.

		Total				Wild			Hatchery		
Year	# Hauls	# Fish	Mean Combined Daily CPUE	GM Combined Daily CPUE	GM Individual Haul CPUE*	# Fish	Mean Combined Daily CPUE	GM Combined Daily CPUE	# Fish	Mean Combined Daily CPUE	GM Combined Daily CPUE
1990	87	285	4.40	1.23		0	0.15	0.11	272	4.251	1.181
1991	144	170	1.01	0.54		80	0.48	0.35	90	0.526	0.211
1992	92	269	4.24	1.45		146	2.49	0.78	172	2.630	0.913
1993	111	218	1.90	1.22		174	1.61	1.01	44	0.291	0.194
1994	110	390	4.74	2.29		254	3.19	1.38	322	3.639	2.039
1995	48	409	8.92	7.89		58	1.29	1.06	351	7.630	6.848
1996	105	283	2.89	2.05		157	1.61	1.20	126	1.280	0.994
1997	90	879	9.77	6.77	3.36	136	1.51	1.24	743	8.259	5.648
1998	94	230	2.51	1.03	0.50	5	0.05	0.05	225	2.457	0.972
1999	90	322	3.58	1.16	0.67	13	0.15	0.13	309	3.431	1.058
2000	90	31	0.34	0.26	0.14	0	0.00	0.00	31	0.344	0.264
2001	90	377	4.19	3.04	1.52	119	1.32	1.25	258	2.870	2.139
2002	84	0	0.00	0.00	0.00	0	0.00	0.00	0	0.000	0.000
2003	48	17	0.35	0.28	0.20	2	0.04	0.04	15	0.313	0.254
2004	66	25	0.38	0.25	0.17	0	0.00	0.00	25	0.379	0.246
2005	90	23	0.26	0.24	0.16	21	0.23	0.24	2	0.022	0.019
2006	66	1	0.02	0.01	0.01	0	0.00	0.00	1	0.015	0.014
2007	66	2	0.02	0.02	0.02	2	0.02	0.02	0	0.000	0.000
2008	90	0	0.00	0.00	0.00	0	0.00	0.00	0	0.000	0.000
2009	84	0	0.00	0.00	0.00	0	0.00	0.00	0	0.000	0.000
2010	84	3	0.04	0.03	0.03	2	0.02	0.02	1	0.012	0.014
2011	50	3	0.06	0.06	0.04	0	0.00	0.00	3	0.060	0.060
2012	90	1	0.01	0.01	0.01	**	0.00	0.00	**	0.000	0.000
2013	90	1	0.01	0.01	0.01	0	0.00	0.00	1	0.011	0.010
2014	90	7	0.08	0.07	0.05	0	0.00	0.00	7	1.167	0.069
2015	90	0	0.00	0.00	0.00	0	0.00	0.00	0	0.000	0.000
2016	90	4	0.04	0.04	0.03	2	0.02	0.02	2	0.333	0.019
2017	60	0	0.00	0.00	0.00	0	0.00	0.00	0	0.000	0.000

* Required by ASMFC
** Otolith analysis for OTC marks undetermined (specimens over processed)

Table 131. Origin of juvenile American shad collected by lift net at Holtwood Dam and haul seine at Columbia, based on otolith analysis. All values are numbers of fish.

Year	Lift net					Haul seine - Columbia				
	Lifts	Total Fish	Wild Fish	Hatchery Fish	% Hatchery	Hauls	Total Fish	Wild Fish	Hatchery Fish	% Hatchery
1990	290	3988	70	3984	99.9%	87	285	0	272	95.5%
1991	370	208	19	189	90.6%	144	170	80	90	53.0%
1992	250	39	14	25	64.1%	92	269	146	172	63.8%
1993	250	1095	669	426	38.9%	111	218	174	44	20.0%
1994	250	206	35	171	82.8%	110	390	254	322	82.5%
1995	115	1048	83	965	92.1%	48	409	58	351	85.7%
1996	No lift net collections					105	283	157	126	44.4%
1997	300	1372	100	1272	92.7%	90	879	136	743	84.6%
1998	300	180	9	171	95.1%	94	230	5	225	97.8%
1999	300	490	19	471	96.1%	90	322	13	309	95.9%
2000	300	406	4	402	99.0%	90	31	0	31	100.0%
2001	299	1245	538	707	56.8%	90	377	119	258	68.5%
2002	220	68	15	53	77.5%	84	0	0	0	0.0%
2003	300	61	3	58	95.1%	48	17	2	15	88.2%
2004	240	0	0	0	0.0%	66	25	0	25	100.0%
2005	300	200	47	153	76.5%	90	23	21	2	8.7%
2006	230	8	0	8	100.0%	66	1	0	1	100.0%
2007	300	0	0	0	0.0%	66	2	2	0	0.0%
2008	300	1	0	1	100.0%	90	0	0	0	0.0%
2009	300	0	0	0	0.0%	84	0	0	0	0.0%
2010	No lift net surveys conducted after 2009. Sampling location lost due to redevelopment of the Holtwood Hydroelectric Station.					84	3	2	1	33.3%
2011						50	3	0	3	100.0%
2012						90	1	Otoliths ground out		
2013						90	1	0	0	0.0%
2014						90	7	0	7	100.0%
2015						90	0	0	0	0.0%
2016						90	4	2	2	50.0%
2017						60	0	0	0	0.0%

Table 132. Mean length-at-age for the Upper Chesapeake Bay (scales and otoliths).

Mean Length-at-age for Upper Chesapeake Bay (Scales)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Susquehanna River	Conowingo Dam Fish Lift Count	3	2000-2014	5	-6	0.221	2000-2017	17	-62	0.012
		4	2000-2017	17	-82	0.001	2000-2017	18	-91	0.001
		5	2000-2017	18	-77	0.004	2000-2017	18	-83	0.002
		6	2000-2017	18	-71	0.008	2000-2017	17	-58	0.019
		7	2000-2017	18	-67	0.012	2002-2016	7	-8	0.288
		8	2002-2016	7	-5	0.548				
		9	2003-2010	3	3	1.000				
	Susquehanna Hook-and-Line Survey	2					1987-1999	5	4	0.462
		3	1986-2017	13	7	0.714	1982-2017	33	178	0.006
		4	1984-2017	34	95	0.163	1982-2017	35	-3	0.977
		5	1984-2017	34	-187	0.006	1982-2017	35	-269	0.000
		6	1984-2017	34	-322	0.000	1984-2017	32	-214	0.001
		7	1984-2016	29	-180	0.001	1991-2016	15	-49	0.018
		8	1992-2015	14	-39	0.037	2005-2013	3	-1	1.000
		9	1998-2014	9	-26	0.009	1999-2013	3	-1	1.000
Upper Chesapeake Bay	Upper Chesapeake Onboard Fishery Monitoring	2					1981-1991	4	-5	0.149
		3	1985-2001	6	-3	0.697	1980-2001	19	-66	0.023
		4	1980-2001	20	-78	0.012	1980-2001	21	-86	0.010
		5	1980-2001	20	-72	0.021	1980-2001	21	-110	0.001
		6	1980-2001	20	-90	0.004	1980-2001	20	-42	0.183
		7	1980-2001	16	-48	0.034	1990-2001	10	-8	0.530
		8	1991-2001	8	-8	0.386				

Mean Length-at-age for Upper Chesapeake Bay (Otoliths)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Susquehanna River	Conowingo Dam Fish Lift Count	3	2000-2016	5	-1	1.000	**2000-2017**	**16**	**-66**	**0.003**
		4	**2000-2017**	**17**	**-70**	**0.004**	**2000-2017**	**18**	**-85**	**0.001**
		5	**2000-2017**	**18**	**-65**	**0.015**	**2000-2017**	**18**	**-53**	**0.049**
		6	**2000-2017**	**18**	**-75**	**0.005**	**2000-2017**	**18**	**-63**	**0.019**
		7	**2000-2017**	**18**	**-57**	**0.034**	2001-2016	9	8	0.466
		8	2002-2016	10	-11	0.371	2003-2005	3	1	1.000

Table 133. American shad stockings by life stage in the Patuxent River, MD, 1994-2009.

Year	Larvae	Early Juveniles	Late Juveniles
1994	14,000		89,760
1995	346,000		121,124
1996	655,000		173,994
1997	1,345,000		60,040
1998	61,000		16,726
1999	526,000		60,377
2000	349,000	37,250	26,765
2001	364,000	77,500	21,903
2002	472,000	124,750	24,968
2003	717,000	108,000	31,061
2004	537,000	93,000	36,571
2005	708,000	93,000	40,873
2006	720,000	222,300	93,808
2007	431,000	170,500	34,382
2008	490,000	150,000	0
2009	758,000	130,000	25,954
Total	**8,493,000**	**1,206,300**	**832,352**

Table 134. Juvenile American shad captures and origin in the Patuxent River from a MD DNR trawl survey (1994) and the MD DNR Fish Health and Hatcheries Program summer seine survey (1995-2009).

Sample year	n	Larval stocked origin	Early Juvenile stocked origin	Late Juvenile stocked origin	Wild fish
1994	NA	0%	NA	100%	0%
1995	330	54%	NA	46%	0%
1996	285	60%	NA	40%	0%
1997	362	79%	NA	21%	0%
1998	90	0%	NA	83%	17%
1999	260	25%	NA	74%	1%
2000	347	1%	50%	39%	8%
2001	401	10%	56%	20%	13%
2002	163	51%	37%	2%	10%
2003	268	47%	28%	11%	17%
2004	256	19%	41%	33%	7%
2005	314	43%	35%	4%	18%
2006	241	20%	54%	23%	4%
2007	309	14%	77%	2%	6%
2008	185	24%	72%	NA	4%
2009	235	27%	64%	9%	<1%

Table 135. Patuxent River American shad commercial landings, 1944-1978.

Year	Landings (lbs)	Source	Year	Landings (lbs)	Source
1944	1,312	Hammer et al - 1948	1963	498	Weinrich - unpublished
1945	849	Hammer et al - 1948	1964	595	Weinrich - unpublished
1946	70	Hensel and Tiller - 1952	1965	272	Weinrich - unpublished
1947	1,668	Hensel and Tiller - 1952	1966	726	Weinrich - unpublished
1948	806	Hensel and Tiller - 1952	1967	484	Weinrich - unpublished
1949	409	Hensel and Tiller - 1952	1968	22	Weinrich - unpublished
1950	2,700	Hensel and Tiller - 1952	1969	113	Weinrich - unpublished
1951	1,441	Hensel and Tiller - 1954	1970	511	Weinrich - unpublished
1952	3,427	Hensel and Tiller - 1954	1971	1,262	Weinrich - unpublished
1955	8,035	Sadzinski - unpublished	1972	2,156	Weinrich - unpublished
1956	3,840	Sadzinski - unpublished	1973	7,701	Weinrich - unpublished
1957	16,230	Sadzinski - unpublished	1974	887	Weinrich - unpublished
1958	9,594	Sadzinski - unpublished	1975	4,091	Weinrich - unpublished
1959	425	Sadzinski - unpublished	1976	426	Weinrich - unpublished
1960	297	Sadzinski - unpublished	1977	702	Weinrich - unpublished
1961	1,097	Sadzinski - unpublished	1978	340	Weinrich - unpublished
1962	609	Weinrich - unpublished			

Table 136. Catch-at-age of male American shad captured in the Patuxent River electrofishing survey, 2001-2014.

Year	Age								Mean
	3	4	5	6	7	8	9	10	Age
2001	5	25	29	6	2				4.6
2002	1	8	24	11	5				5.2
2003	1	3	5	6	3	1			5.5
2004		2	3	2	1	4	1	1	6.6
2005	7	15	18	10	4	3			5.0
2006		8	20	17	5	3			5.5
2007		3	8	1	4				5.4
2008		5	13	5	1				5.1
2009			1	3	2				6.2
2010		5	12	5	2				5.2
2011	15	26	11	1					4.0
2012	4	47	46	12	1				4.6
2013		19	42	20	3				5.1
2014			4	7	3				5.9

Table 137. Catch-at-age of female American shad captured in the Patuxent River electrofishing survey, 2001-2014.

Year	Age							Mean
	3	4	5	6	7	8	9	Age
2001	2	9	19	6				4.8
2002	1	7	28	15	3			5.2
2003		4	3	9				5.3
2004			3	4	3	4		6.6
2005		4	6	8	6	1		5.8
2006		2	6	16	7	1	2	6.1
2007			2	4	1			5.9
2008			8	4	3			5.7
2009			5	6	2			5.8
2010		2	1	2	2	1		5.9
2011	2	7	6		1			4.4
2012	1	7	22	11	1			5.1
2013		3	14	12	3	1		5.5
2014			1	3	2			6.2

Table 138. Catch-at-age of American shad, sexes combined, captured in the Patuxent River electrofishing survey, 2001-2014.

Year	Age								Mean
	3	4	5	6	7	8	9	10	Age
2001	7	34	49	12	2				4.7
2002	2	15	52	26	8				5.2
2003	1	7	8	15	3	1			5.4
2004		2	6	6	4	8	1	1	6.6
2005	7	19	24	18	10	4			5.2
2006		10	26	33	12	4	2		5.8
2007		3	10	5	5				5.5
2008		5	21	9	4				5.3
2009			6	9	4				5.9
2010		7	13	7	4	1			5.3
2011	17	33	17	1	1				4.1
2012	5	54	68	23	2				4.8
2013		22	56	32	6	1			5.2
2014			5	10	5				6.0

Table 139. Proportion of repeat spawning-at-age and by year of American shad, sexes combined, captured in the Patuxent River electrofishing survey, 2002-2014.

Year	Age								Yearly proportion
	3	4	5	6	7	8	9	10	
2002	0.00	0.73	0.90	0.96	1.00			0.00	0.88
2003	0.00	1.00	1.00	1.00	1.00	1.00		0.00	0.97
2004		0.00	0.83	1.00	0.75	1.00	1.00		0.86
2005	0.00	0.32	0.63	0.83	0.90	1.00		0.00	0.60
2006		0.30	0.58	0.76	0.92	1.00	1.00		0.69
2007		0.67	1.00	1.00	1.00				0.96
2008		0.40	0.90	1.00	1.00				0.87
2009			0.83	1.00	1.00				0.95
2010		0.14	0.92	1.00	1.00	1.00			0.78
2011	0.06	0.67	0.76	1.00	1.00			0.06	0.55
2012	0.00	0.61	0.90	1.00	1.00			0.00	0.78
2013		0.45	0.86	1.00	1.00	1.00			0.83
2014			1.00	1.00	1.00				1.00

Table 140. Mean fork length-at-age (mm) of male American shad captured in the Patuxent River electrofishing survey, 2001-2014.

Year	Age							
	3	4	5	6	7	8	9	10
2001	340	350	352	366	357			
2002	385	368	361	368	388			
2003	306	346	353	371	391	404		
2004		291	342	320	418	385	377	371
2005	328	352	391	394	441	442		
2006		336	355	374	383	423		
2007		365	381	376	396			
2008		357	374	390	476			
2009			360	392	398			
2010		385	384	377	391			
2011	358	387	401	407				
2012	350	376	373	393	404			
2013		379	391	402	414			
2014			403	398	421			
Mean Length	347	368	374	384	402	413	377	371

Table 141. Mean fork length-at-age (mm) of female American shad captured in the Patuxent River electrofishing survey, 2001-2014.

Year	Age						
	3	4	5	6	7	8	9
2001	365	387	392	391			
2002	335	382	394	408	405		
2003		404	412	413			
2004			368	405	431	439	
2005		370	436	449	466	529	
2006		407	400	429	434	420	470
2007			400	433	417		
2008			426	420	450		
2009			408	419	422		
2010		412	435	411	417	460	
2011	400	420	434		447		
2012	345	415	419	427	425		
2013		412	433	443	453	423	
2014			335	446	453		
Mean Length	368	399	409	423	439	448	470

Table 142. Mean fork length-at-age (mm) of American shad, sexes combined, captured in the Patuxent River electrofishing survey, 2001-2014.

Year	Age							
	3	4	5	6	7	8	9	10
2001	347	360	368	379	357			
2002	360	375	379	391	394			
2003	306	379	375	396	391	404		
2004		291	355	377	428	412	377	371
2005	328	356	402	419	456	464		
2006		350	365	401	413	422	470	
2007		365	385	421	400			
2008		357	394	403	457			
2009			400	410	410			
2010		389	388	387	404	460		
2011	363	394	413	407	447			
2012	349	381	388	409	415			
2013		383	402	417	434	423		
2014			389	413	434			
Mean Length	351	374	386	403	420	428	439	371

Table 143. MD DNR Patuxent River Restoration Electrofishing Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Index	CV
2001	15	16.94	0.19
2002	10	14.19	0.24
2003	9	5.21	0.26
2004	8	5.95	0.39
2005	6	0.86	0.64
2006	12	5.20	0.26
2007	9	2.10	0.38
2008	10	3.73	0.42
2009	9	2.32	0.30
2010	9	2.95	0.26
2011	11	5.82	0.22
2012	12	12.66	0.32
2013	10	8.80	0.20
2014	10	1.77	0.19

Table 144. American shad stocking data for the Potomac River.

Year	River	Stocking site	# Fry	# Viable Eggs	Cultured By:	Stocked For:
1995	Potomac	Mather Gorge	1,175,000		Harrison Lake	* Task Force
1996	Potomac	Mather Gorge	1,989,000		Harrison Lake	* Task Force
1997	Potomac	Mather Gorge	1,535,000		Harrison Lake	* Task Force
1998	Potomac	Mather Gorge	1,589,000		Harrison Lake	* Task Force
1999	Potomac	Mather Gorge	1,304,000		Harrison Lake	* Task Force
2000	Potomac	**Mather Gorge	3,176,000		Harrison Lake	* Task Force
2001	Potomac	Mather Gorge	3,336,000		Harrison Lake	* Task Force
2002	Potomac	Mather Gorge	1,531,000		Harrison Lake	* Task Force
2003	Potomac	Occoquan	200,000		Harrison Lake	ICPRB/VDGIF/USFWS
2004	Potomac	Occoquan	400,000		Harrison Lake	ICPRB/VDGIF/USFWS
2005	Potomac	Occoquan	919,000		Harrison Lake	ICPRB/VDGIF/USFWS
2006	Potomac	Occoquan	1,158,000		Harrison Lake	ICPRB/VDGIF/USFWS
2006	Potomac	Anacostia	114,920		DC Fisheries	DC Fisheries mitigation
2007	Potomac	Occoquan	728,000		Harrison Lake	ICPRB/VDGIF/USFWS
2007	Potomac	Anacostia	200,000		DC Fisheries	MD DNR mitigation
2007	Potomac	Anacostia	763,600		DC Fisheries	DC Fisheries mitigation
2007	Potomac	Marshall Hall	259,119		PA - Van Dyke	USFWS mitigation
2007	Potomac	Marshall Hall		287,545		USFWS mitigation
2008	Potomac	Occoquan	884,000		Harrison Lake	ICPRB/VDGIF/USFWS
2008	Potomac	Anacostia	200,000		DC Fisheries	MD DNR mitigation
2008	Potomac	Anacostia	261,710		DC Fisheries	DC Fisheries mitigation
2008	Potomac	Marshall Hall	188,739		PA - Van Dyke	USFWS mitigation
2009	Potomac	Occoquan	528,000		Harrison Lake	ICPRB/VDGIF/USFWS
2009	Potomac	Anacostia	200,000		DC Fisheries	MD DNR mitigation
2009	Potomac	Anacostia	922,650		DC Fisheries	DC Fisheries mitigation
2009	Potomac		528,200		Harrison Lake	VDGIF mitigation
2010	Potomac	Occoquan	510,000		Harrison Lake	ICPRB/VDGIF/USFWS
2010	Potomac	Marshall Hall	365,000		PA - Van Dyke	USFWS mitigation
2010	Potomac	Anacostia	400,000		DC Fisheries	MD DNR mitigation
2010	Potomac	Anacostia	1,672,411		DC Fisheries	DC Fisheries mitigation
2011	Potomac	Occoquan	488,000		Harrison Lake	ICPRB/VDGIF/USFWS
2011	Potomac	Marshall Hall	90,000		PA - Van Dyke	USFWS mitigation
2011	Potomac	Marshall Hall	263,000		MD DNR	MD DNR mitigation
2012	Potomac	Occoquan	537,000		Harrison Lake	ICPRB/VDGIF/USFWS
2012	Potomac	Marshall Hall	165,000		MD DNR	MD DNR mitigation
2012	Potomac	Anacostia	200,000		DC Fisheries	MD DNR mitigation
2012	Potomac	Anacostia	1,712,947		DC Fisheries	DC Fisheries mitigation
2012	Potomac	Marshall Hall		670,292		USFWS mitigation
2013	Potomac	Pohick Bay	406,000		Harrison Lake	ICPRB/VDGIF/USFWS
2013	Potomac	Anacostia	200,000		DC Fisheries	MD DNR mitigation
2013	Potomac	Anacostia	1,016,443		DC Fisheries	DC Fisheries mitigation
2013	Potomac	Marshall Hall	280,400		MD DNR	MD DNR mitigation
2013	Potomac	Marshall Hall		277,864		USFWS mitigation

Table 144 Continued

Year	River	Stocking site	# Fry	# Viable Eggs	Cultured By:	Stocked For:
2014	Potomac	Pohick Bay	350,000		Harrison Lake	ICPRB/VDGIF/USFWS
2014	Potomac	Marshall Hall	93,000		MD DNR	MD DNR mitigation
2014	Potomac	Anacostia	166,000		DC Fisheries	MD DNR mitigation
2014	Potomac	Anacostia	796,787		DC Fisheries	DC Fisheries mitigation
2014	Potomac	Marshall Hall		555,650		USFWS mitigation
2015	Potomac	Marshall Hall	183,500		MD DNR	MD DNR mitigation
2015	Potomac	Marshall Hall		298,476		USFWS mitigation
2016	Potomac	Marshall Hall	61,600		MD DNR	MD DNR mitigation
2016	Potomac	Marshall Hall		155,125		USFWS mitigation
2017	Potomac	Marshall Hall	343,900		MD DNR	MD DNR mitigation
2017	Potomac	Marshall Hall		576,839		USFWS mitigation
			650,900		*****Schools-in-Schools Program (1996–2017)**	
			34,191,926	2,821,791		

* Little Falls Fish Passage Task Force members: Virginia, Maryland, District of Columbia, Interstate Commission on the Potomac River Basin, Potomac River Fisheries Commission, U.S. Fish & Wildlife Service, U.S. Army Corps of Engineers, National Biological Survey, U.S. Environmental Protection Agency, National Park Service, National Marine Fisheries Service, Montgomery County, MD, Chesapeake Bay Foundation, and Potomac Conservancy.

** New fish-passage installed in the Brookmont Dam at Little Falls by USACE

*** Schools-in-Schools Program began in 1996 with three schools and grew to involve more than 50 schools in the D.C. area. It is a partnership with ICPRB, USFWS, CBF and Living Classrooms of D.C., where each class received American shad eggs and the students hatched the shad fry and then released them in the Potomac River. This program has greatly increased public awareness.

Table 145. Annual American shad removals (# of fish) from the Potomac River for restoration activities.

Year	ICPRB	AWC	USFWS	VDGIF	MD DNR	DC FISH	Total
1995	294*		*	*		*	294
1996	375*		*	*		*	375
1997	544*		*	*		*	544
1998	316*		*	*		*	316
1999	289*		*	*		*	289
2000	757*		*	*		*	757
2001	735*		*	*	441	*	1,176
2002	658*		*	*	1,651	*	2,309
2003	615**			**	948		1,563
2004	976			**	517		1,493
2005	506			**	946		1,452
2006	682		382	**	695	32	1,791
2007	1,049		786	**	780	201	2,816
2008	733		785	**	877	83	2,478
2009	333		771	**	892	266	2,262
2010	890		2,151	**	1,203	289	4,533
2011	409		772	**	721		1,902
2012	858		1,187	**	3,078	362	5,485
2013	556		805	**	1,522	285	3,168
2014	482		1,848	**	2,122	515	4,967
2015	66		1,077		1,154	213	2,510
2016	65		1,033		1,287	590	2,975
2017		119	2,412	unknown	1,677		4,208
Total	**12,188**	**119**	**14,009**		**20,511**	**2,836**	**49,663**

ICPRB - Interstate Commission on the Potomac River Basin
AWC - Anacostia Watershed Society
USFWS - U.S. Fish & Wildlife Service
VDGIF - Virginia Department of Game & Inland Fisheries
MD DNR - Maryland Department of Natural Resources
DC Fish - District of Columbia Dept. of the Environment Fisheries & Wildlife Division (DDOE)

* Little Falls Fish Passage Task Force (1995-2002), shad restoration in upper Potomac River
** ICPRB worked with VDGIF to collect brood shad to stock fry in Rappahannock & Potomac (2003-2014)
USFWS collected brood shad to stock fry in the Susquehanna River (2006-2017)
MD DNR collected brood shad to stock fry in MD tributaries (2001-2017)

Table 146. Potomac River historical commercial American shad harvest, 1814 – 2017.

Year	Pounds
1814	108,453,000
1815	106,356,000
1816	68,178,600
1817	62,960,400
1818	42,679,200
1819	34,012,800
1820	16,763,400
1821	28,953,600
1822	25,436,400
1823	31,185,000
1824	48,390,600
	-
1832	11,250,000
	-
1878	651,000
	-
1880	2,040,052
	-
1889	3,041,150
1890	2,571,002
1891	2,356,759
	-
1896	2,565,237
	-
1898	3,948,709
1899	2,571,000
1900	2,356,759
1901	2,979,233
	-
1904	1,397,425
	-
1909	764,892
	-
1915	664,008
1919	2,041,759
1920	1,979,780
1921	1,160,438
1922	3,115,571
1923	1,187,382
1924	578,210
1925	696,632
1926	1,034,206
1927	636,581
1928	2,077,622
1929	1,052,284
1930	601,193
1931	2,061,036
1932	2,264,168
1933	1,837,623
1934	567,100
1935	631,171
1936	359,800
1937	434,900
1938	519,635
1939	428,503
1940	322,800
1941	371,300
1942	328,175
	-
1944	883,000
1945	537,700
1946	536,100
1947	1,300,200
1948	721,300
1949	909,600
1950	931,600
1951	877,100
1952	1,161,400
1953	846,300
1954	897,300
1955	805,700
1956	721,900
1957	624,400
1958	167,300
1959	187,700
1960	189,400
1961	113,100
1962	263,000
1963	214,900
1964	466,293
1965	438,831
1966	243,012
1967	214,882
1968	393,872
1969	302,274
1970	405,884
1971	359,014
1972	421,318
1973	203,717
1974	83,955
1975	144,465
1976	120,302
1977	87,290
1978	67,967
1979	27,758
1980	17,328
1981	4,237
1982	2,133
1983	3,722
1984	2,531
1985	287
1986	478
1987	810
1988	1,894
1989	1,068
1990	2,282
1991	1,918
1992	1,553
1993	2,927
1994	1,305
1995	2,641
1996	2,292
1997	5,206
1998	2,372
1999	1,966
2000	1,508
2001	4,882
2002	2,762
2003	8,641
2004	5,344
2005	6,820
2006	4,669
2007	8,914
2008	6,975
2009	5,214
2010	3,922
2011	2,419
2012	4,742
2013	3,799
2014	4,013
2015	1,889
2016	1,149
2017	10,273

Table 147. Potomac River regulatory history (1963-2017) for Haul Seine (HS), Drift Gill Net (DG), Stake Gill Net (SG), Anchor Gill Net (AG), and Pound Net (PN). SG, AG and PN are fixed site non-moveable gear. Only "changes" to the previous or existing requirements are noted (Source: PRFC).

Year	Gear	Season	Size		Notes
			Length	Mesh	
1963	SG, DG	3/1- 5/26	1,200'		
	PN	All Year	1,200'		
	HS	All Year	1,800'		
1964	DG	4/1 –5/26		2.5"	
	SG	All Year		2.5"	
	HS		2,400'	2.5"	
	PN			2"	
1970	AG	All Year	600'	2.5"	New gear added
1972	SG	9/1 – 5/31	1,200'	2.5"	
	AG	9/1 – 5/31	1,200' L x 12' D	2.5"	36’ MLW max.
	DG	4/1 – 5/31			
1974	PN			1.5"	
1978	HS		1,200' & 2,400'		New length added
1979	SG, AG, DG			2.5" min, 7" max	
1980	AG	All Year			
1982	commercial				Shad limits imposed –2% bycatch by volume
	recreational				2/person/day
1983	DG		1,200' L x 12' D		Depth added
1984	SG, AG, DG	2/16 – 3/31 & 6/1 – 12/31	600' L x 12' D	3 ¼" min, 7" max	No new gill net licenses sold (limited entry)
1985	SG, AG, DG	6/1 – 12/31			
1986	SG, AG, DG	6/1 – 11/30			
1990	AG			5" min, 7" max	Hickory added to 2% bycatch
	commercial				Hickory added to 2% bycatch
1992	recreational				Hickory shad limit of 2/person/day
1994	DG				License repealed
	PN				Limited Entry Fishery
1996	commercial				2% bycatch capped at max. 1 bu. and limited to PN only
	recreational				American & hickory shad both closed
1998	HS		2400'		Combined in one license
2004	AG				Added bycatch for AG 1 bu. limit
2011	PN				PN cull panels required
2012	PN, AG				Increased bycatch to 2 bu. limit

Table 148. Potomac River American shad harvest (lbs) by gear, by sex, and landings (lbs) by state. (Source: PRFC)

Year	Pound Net	Gill Net	Haul Seine	Fyke Net	H & L	Misc.	ROE	BUCK	Landed in		TOTAL
									MD	VA	
1964	-	-	-	-	-	466,293	-	-	68,200	398,093	466,293
1965	-	-	-	-	-	438,831	-	-	153,764	285,067	438,831
1966	-	-	-	-	-	243,012	-	-	91,821	151,191	243,012
1967	-	-	-	-	-	214,882	-	-	67,724	147,158	214,882
1968	-	-	-	-	-	393,872	-	-	106,623	287,249	393,872
1969	-	-	-	-	-	302,274	-	-	106,090	196,184	302,274
1970	-	-	-	-	-	405,884	-	-	235,702	170,182	405,884
1971	-	-	-	-	-	359,014	-	-	185,499	173,515	359,014
1972	-	-	-	-	-	421,318	-	-	226,656	194,662	421,318
1973	-	-	-	-	-	203,717	-	-	86,998	116,719	203,717
1974	-	-	-	-	-	83,955	-	-	43,118	40,837	83,955
1975	-	-	-	-	-	144,465	-	-	88,419	56,046	144,465
1976	20,877	99,425	-	-	-	-	86,165	34,137	71,312	48,990	120,302
1977	13,742	71,451	-	-	-	2,094	72,762	14,528	57,964	29,326	87,290
1978	7,787	52,454	-	-	-	7,726	56,126	11,841	37,336	30,631	67,967
1979	3,932	23,826	-	-	-	-	23,051	4,707	15,399	12,359	27,758
1980	2,680	13,849	-	-	-	799	11,975	5,353	6,280	11,048	17,328
1981	1,776	2,461	-	-	-	-	2,671	1,566	498	3,739	4,237
1982	988	1,145	-	-	-	-	657	1,476	400	1,733	2,133
1983	1,416	2,306	-	-	-	-	1,891	1,831	840	2,882	3,722
1984	2,412	119	-	-	-	-	1,717	814	277	2,254	2,531
1985	272	15	-	-	-	-	139	148	51	236	287
1986	476	2	-	-	-	-	207	271	139	339	478
1987	810	-	-	-	-	-	391	419	259	551	810
1988	1,894	-	-	-	-	-	766	1,128	753	1,141	1,894
1989	1,068	-	-	-	-	-	543	525	169	899	1,068
1990	2,282	-	-	-	-	-	1,299	983	352	1,930	2,282
1991	1,918	-	-	-	-	-	1,062	856	431	1,487	1,918
1992	1,553	-	-	-	-	-	957	596	345	1,208	1,553
1993	2,927	-	-	-	-	-	1,480	1,447	252	2,675	2,927
1994	1,305	-	-	-	-	-	677	628	328	977	1,305
1995	2,638	-	-	3		-	1,458	1,183	324	2,317	2,641
1996	2,292	-	-	-	-	-	1,357	935	99	2,193	2,292
1997	5,083	-	120	3	-	-	2,773	2,433	98	5,108	5,206
1998	2,251	-	121	-	-	-	1,680	692	623	1,749	2,372
1999	1,966	-	-	-	-	-	1,049	917	44	1,922	1,966
2000	1,508	-	-	-	-	-	897	611	124	1,384	1,508
2001	4,882	-	-	-	-	-	3,390	1,492	794	4,088	4,882
2002	2,762	-	-	-	-	-	1,727	1,035	-	2,762	2,762
2003	8,141	-	-	93	-	407	7,229	1,412	2,916	5,725	8,641
2004	5,051	293	-	-	-	-	4,701	643	1,656	3,688	5,344
2005	6,019	801	-	-	-	-	6,044	776	2,972	3,848	6,820
2006	4,256	413	-	-	-	-	4,245	424	1,146	3,523	4,669
2007	6,604	2,310	-	-	-	-	7,929	985	4,532	4,382	8,914
2008	6,815	160	-	-	-	-	6,470	505	5,115	1,860	6,975
2009	5,005	209	-	-	-	-	4,601	613	5,210	4	5,214
2010	3,885	31	-	-	-	6	3,821	101	1,350	2,572	3,922
2011	2,419	-	-	-	-	-	2,167	252	969	1,450	2,419
2012	4,119	623	-	-	-	-	3,105	1,641	4,173	569	4,742
2013	3,796	3	-	-	-	-	2,946	853	3,796	3	3,799
2014	4,003	10	-	-	-	-	2,832	1,181	4,013	-	4,013
2015	1,877	12	-	-	-	-	1,135	754	1,877	12	1,889
2016	1,145	4	-	-	-	-	560	589	1,145	4	1,149
2017	10,273	-	-	-	-	-	7,904	2,369	2,493	7,780	10,273

Table 149. American shad commercial harvest and discards/releases for the Potomac River.

POTOMAC RIVER FISHERIES COMMISSION

AMERICAN SHAD Commercial Harvest (lbs) and Discard / Release (lbs)

	HARVEST					**DISCARD / RELEASE**							**PN**
Year	**Pound Net**				**Gill Net (other)**	**Pound Net**		**Gill Net**		**Other Gear**		**Total**	**CPUE C+D**
	Roe	Buck	Total	Net-days	Total	Roe	Buck	Roe	Buck	Roe	Buck		
1988	766	1,128	1,894	2,021									
1989	543	525	1,068	1,574									
1990	1,299	983	2,282	1,361									
1991	1,062	856	1,918	1,208									
1992	939	526	1,465	703	88								
1993	1,480	1,447	2,927	611									
1994	677	628	1,305	758									
1995	1,458	1,180	2,638	743	(FN-3)								
1996	1,357	935	2,292	553									
1997	2,773	2,310	5,083	737	(FN-3) (HS-120)								
1998	1,680	571	2,251	335									
1999	1,049	917	1,966	388		376	213	14	10			613	6.59
2000	897	611	1,508	258		28	56	55				139	6.17
2001	3,347	1,492	4,839	433		800	56	53		25		934	13.15
2002	1,727	1,035	2,762	348			59	25	2			86	8.11
2003	6,971	1,170	8,141	547	(FN-93) (FP-407)	22,790	17,566	9,393	670	204	73	50,696	88.66
2004	4,408	643	5,051	493	293	1,800	1,100	1,053	54			4,007	16.13
2005	5,255	764	6,019	493	801	15,171	3,008	170	0			18,349	49.08
2006	3,847	409	4,256	260	413	10,178	4,000	17	4			14,199	70.90
2007	5,662	942	6,604	388	2,310 (FN-4)	8,622	1,323	90		4		10,039	42.65
2008	6,310	505	6,815	274	160	8,282	2,000					10,282	62.40
2009	4,402	603	5,005	197	209	19,150	5,500			2		24,652	150.53
2010	3,790	95	3,885	117	31	3,907	131					4,038	67.72
2011	2,167	252	2,419	77	0	2,015	450					2,465	63.43
2012	2,478	1,641	4,119	177	623	21,515	11,040			4		32,559	207.20
2013	2,943	853	3,796	110	3	4,150	4,250	3				8,403	110.87
2014	2,822	1,181	4,003	80	10	320	106	13		24	10	473	55.95
2015	1,135	754	1,889	58	12	1,700	200			86	3	1,989	65.12
2016	556	589	1,145	50	4	3,500		2				3,502	92.90
2017	7,904	2,369	10,273	190	0	2,200	1725	16		10	14	3,965	74.94

Table 150. Historic landings data and CPUE calculated from Walburg and Sykes (1957) for 1944-1952.

Year	Effort	Virginia Catch	Maryland Catch	Total Catch	CPUE (lbs/net-day)
1944	8,615	670,000	9,041	679,041	78.82
1945	15,413	294,200	8,359	302,559	19.63
1946	11,019	268,000	11,142	279,142	25.33
1947	11,403	992,900	22,697	1,015,597	89.06
1948	16,813	351,200	13,494	364,694	21.69
1949	22,778	356,400	27,055	383,455	16.83
1950	21,367	455,200	20,396	475,596	22.26
1951	13,792	424,000	5,658	429,658	31.15
1952	15,653	451,674	25,636	477,310	30.49

Table 151. Catch-at-age of American shad collected by MD DNR from the Potomac River Broodstock Gill Net Collections.

Year	Age							Mean
	3	4	5	6	7	8	9	Age
2010	1	31	49	34	11	1	1	5.2
2011	0	5	21	14	4	1	0	5.4
2012	0	18	55	35	14	2	0	5.4
2013	1	47	51	24	2	0	0	4.8
2014	0	0	24	52	18	8	0	6.1
2015	2	19	50	37	9	4	0	5.4
2016	0	4	32	68	11	5	1	5.8
2017	2	21	52	34	15	1	0	5.3

Table 152. Mean length-at-age, expressed as total length to the nearest mm, of American shad collected by MD DNR from the Potomac River Broodstock Gill Net Collections.

Year	Age						
	3	4	5	6	7	8	9
2010	408	468	472	491	520	542	571
2011		488	488	494	493	550	
2012		469	471	484	490	520	
2013	469	493	494	504	495		
2014			493	482	483	528	
2015	447	487	490	486	485	479	
2016		429	470	501	516	535	535
2017	473	479	485	491	499	495	

Table 153. Catch-at-age of American shad from MD DNR Potomac River Striped Bass Spawning Stock Survey. From 2002-2016, scales were collected from all fish encountered and age determination was attempted for all samples. Beginning in 2017, scales were collected from a subsample of fish (10/20mm length bin/sex). Catch-at-age presented for 2017 was extrapolated to the entire sample using an age-length key. (Source: MD DNR)

Year	Age								Mean Age
	3	4	5	6	7	8	9	10	
2002	1	9	8	19	10	1	0	0	5.6
2003	1	31	44	37	16	11	1	0	5.5
2004	0	20	35	32	5	5	0	0	5.4
2005	1	33	27	24	9	1	1	1	5.2
2006	1	13	14	16	4	2	2	0	5.4
2007	14	113	53	15	2	2	1	0	4.4
2008	10	80	64	16	5	1	0	0	4.6
2009	0	5	6	12	5	2	0	1	5.9
2010	5	36	20	7	3	2	2	0	4.7
2011	7	10	20	15	4	0	0	0	5.0
2012	0	4	27	21	12	3	0	0	5.7
2013	0	1	11	52	31	9	0	1	6.4
2014	0	0	17	61	24	3	0	0	6.1
2015	4	10	55	42	9	0	0	0	5.4
2016	0	20	75	35	9	1	0	0	5.3
2017	2	19	70	48	1	0	0	0	5.2

Table 154. Mean length-at-age, expressed as total length to the nearest mm, of American shad captured by the MD DNR Potomac River Striped Bass Spawning Stock Survey, 2002-2017. (Source: MD DNR)

Year	Age							
	3	4	5	6	7	8	9	10
2002	376	439	460	510	536	568	-	-
2003	377	427	479	511	550	560	574	-
2004	-	439	477	519	553	572	-	-
2005	377	425	467	514	543	544	593	607
2006	385	453	470	500	537	559	576	-
2007	405	448	495	530	567	584	591	-
2008	387	452	478	530	548	534	-	-
2009	-	415	489	493	535	540	-	591
2010	387	452	460	510	551	562	575	-
2011	373	421	465	495	526	-	-	-
2012	-	393	444	476	502	533	-	-
2013	-	399	443	461	480	499	-	434
2014	-	-	456	488	496	496	-	-
2015	422	437	483	507	516	-	-	-
2016	-	428	453	501	504	527	-	-
2017	405	429	470	510	576	-	-	-
Mean Length	394	441	471	499	515	541	580	544

Table 155. Proportion of repeat spawning-at-age and by year of American shad captured by the MD DNR Potomac River Striped Bass Spawning Stock Survey, 2002-2017. (Source: MD DNR)

Year	Age								Yearly proportion
	3	4	5	6	7	8	9	10	
2002	0.00	0.00	0.75	1.00	1.00	1.00	-	-	0.75
2003	0.00	0.00	0.07	0.68	0.94	1.00	1.00	-	0.39
2004	-	0.00	0.37	0.69	1.00	1.00	-	-	0.46
2005	0.00	0.00	0.19	0.50	1.00	1.00	1.00	1.00	0.30
2006	0.00	0.00	0.21	0.88	1.00	1.00	1.00	-	0.48
2007	0.00	0.02	0.25	0.67	1.00	1.00	1.00	-	0.15
2008	0.00	0.08	0.64	1.00	1.00	1.00	-	-	0.39
2009	-	0.00	0.50	0.92	1.00	1.00	-	1.00	0.71
2010	0.00	0.00	0.60	0.86	1.00	1.00	1.00	-	0.33
2011	0.00	0.00	0.10	0.67	1.00	-	-	-	0.29
2012	-	0.00	0.30	0.48	0.83	1.00	-	-	0.46
2013	-	0.00	0.36	0.69	0.77	1.00	-	1.00	0.70
2014	-	-	0.59	0.82	0.88	1.00	-	-	0.80
2015	0.00	0.30	0.67	0.76	0.89	-	-	-	0.67
2016	-	0.35	0.40	0.89	1.00	1.00	-	-	0.56
2017	0.00	0.14	0.32	0.61	1.00	-	-	-	0.40

Table 156. Potomac River American shad yearly and geometric mean (GM) CPUE from the Potomac River Striped Bass Spawning Stock Survey, 1985-2017. CPUE (number of fish caught per 1000 yards2 of experimental drift gill net per hour fished) calculation uses all 10 meshes. An index with only the appropriate sized meshes for American shad would have the same trend.

Year	Effort	Catch	Yearly CPUE	GM CPUE	Year	Effort	Catch	Yearly CPUE	GM CPUE
1985	68.05	6	0.09	0.03	2002	60.27	69	1.14	0.26
1986	36.71	0	0.00	0.00	2003	52.51	150	2.86	0.44
1987	40.22	1	0.02	0.01	2004	44.88	113	2.52	0.45
1988	62.00	1	0.02	0.00	2005	45.66	132	2.89	0.54
1989	33.99	0	0.00	0.00	2006	49.66	55	1.11	0.21
1990	39.53	0	0.00	0.00	2007	59.46	225	3.78	0.54
1991	44.04	2	0.05	0.01	2008	58.60	194	3.31	0.47
1992	139.81	2	0.01	0.01	2009	49.56	35	0.71	0.15
1993	55.74	4	0.07	0.02	2010	44.23	78	1.76	0.32
1994	-	-	-	-	2011	51.12	58	1.13	0.21
1995	81.80	3	0.04	0.01	2012	46.28	71	1.53	0.29
1996	50.53	5	0.10	0.02	2013	60.25	105	1.74	0.28
1997	54.58	9	0.16	0.04	2014	46.27	107	2.31	0.43
1998	60.06	27	0.45	0.08	2015	39.13	127	3.25	0.57
1999	48.69	7	0.14	0.03	2016	45.11	144	3.19	0.65
2000	48.76	58	1.19	0.18	2017	41.13	141	3.43	0.72
2001	58.00	84	1.45	0.31					

Table 157. MD DNR Potomac River Striped Bass Spawning Stock Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
1991	588	0.00	0.0000010	0.99
1992	709	0.00	0.0000010	0.84
1993	638	0.01	0.0000021	0.63
1994	NA	NA	NA	NA
1995	619	0.00	0.0000008	0.77
1996	575	0.01	0.0000030	0.60
1997	490	0.01	0.0000046	0.57
1998	585	0.03	0.0000117	0.41
1999	458	0.01	0.0000041	0.60
2000	550	0.06	0.0000249	0.37
2001	385	0.11	0.0000342	0.47
2002	539	0.09	0.0000270	0.39
2003	504	0.13	0.0000680	0.35
2004	419	0.12	0.0000859	0.38
2005	515	0.15	0.0000855	0.37
2006	548	0.07	0.0000232	0.38
2007	580	0.15	0.0001330	0.37
2008	595	0.13	0.0000640	0.34
2009	545	0.05	0.0000199	0.40
2010	510	0.09	0.0000310	0.42
2011	545	0.07	0.0000426	0.42
2012	494	0.09	0.0000346	0.37
2013	605	0.08	0.0000495	0.39
2014	528	0.12	0.0000877	0.37
2015	519	0.13	0.0001353	0.38
2016	537	0.16	0.0001088	0.38
2017	545	0.16	0.0001268	0.38

ary of the number of American shad captured, eggs collected, fry released, and catch-per-unit-effort (CPUE) period 1995-2014, including estimates of shad returns.

1995	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	Totals	Avg.
135	166	245	105	119	373	338	245	240	387	246	316	441	349	183	379	244	418	239	275	5,443	272
78	51	92	50	44	93	135	141	120	127	49	72	93	150	48	226	122	418	212	320	2,641	132
3	1	0	8	10	9	27	25	15	27	2	11	118	43	29	31	31	47	21	40	498	25
78	157	207	153	116	282	235	247	240	435	209	283	397	191	102	460	235	249	239	302	4,817	241
294	**375**	**544**	**316**	**289**	**757**	**735**	**658**	**615**	**976**	**506**	**682**	**1049**	**733**	**333**	**890**	**409**	**858**	**556**	**482**	**12,057**	**603**
							1801	1494	1852	1101	1010	1858	903	444	1096	789	1129	711	987	15,175	1168
							1143	879	896	595	328	809	170	111	206	380	271	155	505	6,448	496
,405	4,353	5,744	2,626	2,594	6,383	6,565	5,943	5,327	5,773	8,129	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1/27	11/22	12/24	14/28	15/30	11/22	16/32	18/36	10/16	14/25	13/25	16/32	17/34	16/31	16/32	16/32	17/35	19/38	18/36	18/36	298/593	15/30
10.9	**17.0**	**22.7**	**11.3**	**9.6**	**34.4**	**22.9**	**18.3**	**35.9**	**39.0**	**20.2**	**21.3**	**30.9**	**23.6**	**10.4**	**27.8**	**11.7**	**22.6**	**15.4**	**13.4**	**419.4**	**21.0**
							50.0	**93.4**	**74.1**	**44.0**	**31.6**	**54.6**	**29.1**	**13.9**	**34.3**	**22.5**	**29.7**	**19.8**	**27.4**	**524.4**	**40.3**
7,800	**26,200**	**23,400**	**25,000**	**24,400**	**17,100**	**19,400**	**24,260**	**22,195**	**14,917**	**24,783**	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	21,769
,175	1,989	1,535	1,589	1,304	3,176	3,336	1,531	200	400	919	1,158	728	884	528	510	488	537	406	350	22,743	1,137
								1,200	3,100	3,400	6,265	4,453	4,832	2,718	3,943	4,116	5,995	4,265	4,156	48,443	2,422
,175	**1,989**	**1,535**	**1,589**	**1,304**	**3,176**	**3,336**	**1,531**	**1,400**	**3,500**	**4,319**	**7,423**	**5,181**	**5,716**	**3,246**	**4,453**	**4,604**	**6,532**	**4,671**	**4,506**	**71,186**	**3,559**
,000	5,300	2,800	5,000	4,500	4,200	4,500	2,326	2,435	3,586	5,690	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	4031
,487	**5,902**	**4,555**	**4,715**	**3,869**	**9,424**	**9,674**	**4,444**	**4,060**	**10,150**	**11,300**	**22,027**	**15,430**	**16,961**	**9,632**	**13,215**	**14,080**	**19,383**	**13,861**	**13,371**	**209,540**	**10,477**
11.9	15.7	8.4	14.9	13.4	12.4	13.5	6	5.9	10.6	14.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	11.6

nit-Effort, is calculated by two methods in this project. The first CPUE (Shad used/ net-set) is based upon the number of shad used for egg collections and re-stocking
tarting in 2003, the Rappahannock Rivers. It does not include shad which were netted but released, i.e., the unripe or green females, spent females no longer
nales (we try to keep a 1/1 ratio of males to females). Starting in 2002, all shad netted were counted and a second CPUE (Total shad/net-set) has been calculated this
ught to the boat, even those released. While this data reflects the strength of the yearly shad runs, neither the number nor catch-per-unit-effort of American shad
gg collections were a good indicator of the shad population strength. It did not track well with other indicators. This is most likely due to the way we would "tend the
uring the net's deployment in order to keep them alive and healthy, and in so doing we disrupted the normal catching ability of the net and created a sampling bias.
owingo Dam fish lifts (Hendricks 2000) found, on average, that it takes 337 hatchery fry stocked in the Susquehanna River to get one returning adult shad.
ve modified that number slightly, but in order to have a consistent estimate the 1 shad returning per 337 stocked fry ratio has been used since 2001 as an assumed

because these values could no longer be derived. Starting in 2006, we switched from using 1 boat to 2-3 boats for our collections (Watermen involved: Louis Harley
rley (starting in 2006), Brad Harley (starting in 2008), and Randy Kirby (2006-2007). Since 2005, shad from all boats are pooled together during the collection process,
icult to separate or accurately estimate egg or fry production for each individual boat. This table only reports shad caught in the ICPRB boat.

Table 159. Frequency of OTC marks in adult American shad collected in the Potomac River, 1998-2005.

Year	Statistic	Age									Total
		2	3	4	5	6	7	8	9	10	
1998	N	3	13	48	44	17	3	1	1	0	130
	N with OTC	0	0	0	1	0	0	0	0	0	1
	Fraction OTC	0	0	0	0.023	0	0	0	0	0	0.008
1999	N	0	3	8	9	1	0	0	0	0	21
	N with OTC	0	0	0	0	0	0	0	0	0	0
	Fraction OTC	0	0	0	0	0	0	0	0	0	0
2000	N	0	6	30	63	30	8	0	0	0	137
	N with OTC	0	0	1	4	0	0	0	0	0	5
	Fraction OTC	0	0	0.033	0.063	0	0	0	0	0	0.036
2001	N	0	6	12	39	29	6	0	0	0	92
	N with OTC		0	1	2	0	0	0	0	0	3
	Fraction OTC	0	0	0.083	0.051	0	0	0	0	0	0.033
2002	N	2	8	22	30	25	7	2	0	0	96
	N with OTC	0	0	0	4	2	1	0	0	0	7
	Fraction OTC	0	0	0	0.133	0.08	0.143	0	0	0	0.073
2005	N	0	0	8	7	18	9	6	2	1	51
	N with OTC	0	0	0	1	0	0	0	0	0	1
	Fraction OTC	0	0	0	0.143	0	0	0	0	0	0.020

Table 160. Catch-at-age of American shad captured by USFWS during the Potomac River Shad Egg Collections on one random spring night, 2006-2017. (Source: USFWS/PAFBC)

Year	Age								Mean Age
	3	4	5	6	7	8	9	10	
2006	0	4	17	15	3	0	1	0	5.5
2007	-	-	-	-	-	-	-	-	-
2008	0	4	6	9	2	0	0	0	5.4
2009	0	3	11	11	3	0	0	0	5.5
2010	2	7	33	27	7	3	0	0	5.5
2011	0	5	18	10	1	0	0	0	5.2
2012	0	2	24	13	4	0	1	0	5.5
2013	0	4	19	16	2	0	0	0	5.4
2014	0	1	22	39	18	0	0	0	5.9
2015	0	2	19	18	9	0	0	0	5.7
2016	0	2	18	12	6	1	0	0	5.6
2017	0	3	54	36	3	0	0	0	5.4

Table 161. Proportion of repeat spawning-at-age and by year of American shad captured by USFWS during the Potomac River Shad Egg Collections on one random spring night, 2006-2017. (Source: USFWS/PAFBC)

Year	Age								Yearly proportion
	3	4	5	6	7	8	9	10	
2006	-	0.50	0.41	0.67	1.00	-	1.00	-	0.58
2007	-	1.00	0.71	0.50	1.00	1.00	-	-	0.63
2008	-	0.50	0.67	0.89	1.00	-	-	-	0.76
2009	-	0.67	0.64	0.82	0.67	-	-	-	0.71
2010	0.00	0.57	0.52	0.70	1.00	0.67	-	-	0.62
2011	-	0.40	0.56	0.80	0.00	-	-	-	0.59
2012	-	0.50	0.25	0.15	0.50	-	1.00	-	0.27
2013	-	0.25	0.47	0.63	0.50	-	-	-	0.51
2014	-	1.00	0.68	0.85	0.89	-	-	-	0.81
2015	-	0.00	0.53	0.89	0.78	-	-	-	0.69
2016	-	0.00	0.39	0.67	0.50	1.00	-	-	0.49
2017	-	0.33	0.39	0.72	0.67	-	-	-	0.52

Table 162. Mean length-at-age, expressed as total length to the nearest mm, of American shad captured by USFWS during the Potomac River Shad Egg Collections on one random spring night, 2006-2017. (Source: USFWS/PAFBC)

Year	Age							
	3	4	5	6	7	8	9	10
2006	-	485	494	511	531	-	569	-
2007	-	-	-	-	-	-	-	-
2008	-	447	469	506	530	-	-	-
2009	-	495	478	488	469	-	-	-
2010	364	412	420	433	464	497	-	-
2011	-	456	477	501	505	-	-	-
2012	-	491	492	507	536	-	551	-
2013	-	439	487	498	510	-	-	-
2014	-	478	489	498	508	-	-	-
2015	-	470	495	500	502	-	-	-
2016	-	426	478	505	529	540	-	-
2017	-	440	477	492	524	-	-	-
Mean Length	364	451	475	491	507	508	560	-

Table 163. Spawning checks in American shad captured from the Potomac River, 2001. Analysis by Virginia Commonwealth University.

Scale Age (Sexes Combined)	N	# Repeat Spawn	% Repeat Spawn	# Specimens w /Spawning Checks By Age					
				2	3	4	5	6	7
2	1	0	-	1	-	-	-	-	-
3	8	0	0%	0	8	-	-	-	-
4	29	14	48%	2	17	29	-	-	-
5	32	30	94%	1	11	30	32	-	-
6	16	15	94%	1	8	11	14	16	-
7	2	2	100%	0	0	1	1	2	2
Total	**88**	**61**	**69%**	**5**	**44**	**71**	**47**	**18**	**2**

Scale Age (Female)	N	# Repeat Spawn	% Repeat Spawn	# Specimens w /Spawning Checks By Age					
				2	3	4	5	6	7
2	0	0		-	-	-	-	-	-
3	1	0	0%	0	1	-	-	-	-
4	14	8	57%	2	7	15	-	-	-
5	17	15	88%	0	5	15	17	-	-
6	11	10	91%	0	5	8	9	11	
7	1	1	100%	0	0	0	1	1	1
Total	**44**	**34**	**77%**	**2**	**18**	**38**	**27**	**12**	**1**

Scale Age (Male)	N	# Repeat Spawn	% Repeat Spawn	# Specimens w /Spawning Checks By Age					
				2	3	4	5	6	7
2	1	0	0%	1	-	-	-	-	-
3	7	0	0%	0	7	-	-	-	-
4	15	6	40%	0	10	14	-	-	-
5	15	15	100%	1	6	15	15	-	-
6	5	5	100%	1	3	3	5	5	-
7	1	1	100%	0	0	1	0	1	1
Total	**44**	**27**	**61%**	**3**	**26**	**33**	**20**	**6**	**1**

Table 164. Catch-at-age data from American shad collected by DC DDOE in 2015 from the Potomac River Stock Enhancement program.

American Shad Age, Length, and Weight Potomac River - 2015 (DDOE)

Year Class	2008	2009	2010	2011	2012	Total
Age	7	6	5	4	3	
Males						
Number	1	7	4	3	1	16
% by year class	6%	44%	25%	19%	6%	100%
Av. TL (mm)	473	485	480	467	430	
Av. Wt. (kg)	1.05	1.09	1.05	1.03	1.03	
Females						
Number	1	0	11	6	0	18
% by year class	6%	0%	61%	33%	0%	100%
Av. TL (mm)	495		492	499		
Av. Wt. (kg)	1.42		1.33	1.29		
Sexes Combined						
Number	2	7	15	9	1	34
% by year class	6%	21%	44%	26%	3%	100%
Av. TL (mm)	484	485	489	488	430	
Av. Wt. (kg)	1.24	1.09	1.25	1.20	1.03	

Table 165. Catch-at-age data from American shad collected by DDOE in 2016 from the Potomac River Stock Enhancement program.

American Shad Age, Length, and Weight
Potomac River - 2016 (DDOE)

Year Class	2009	2010	2011	2012	2013	Total
Age	7	6	5	4	3	
Males						
Number	0	1	3	5	4	13
% by year class	0%	8%	23%	38%	31%	100%
Av. TL (mm)		495	493	481	428	
Av. Wt. (kg)		1.00	0.96	0.89	0.70	
Females						
Number	2	11	15	15	4	47
% by year class	4%	23%	32%	32%	9%	100%
Av. TL (mm)	528	511	488	482	461	
Av. Wt. (kg)	1.27	1.18	1.10	0.95	0.96	
Sexes Combined						
Number	2	12	18	20	8	60
% by year class	3%	20%	30%	33%	13%	100%
Av. TL (mm)	528	510	489	482	444	
Av. Wt. (kg)	1.27	1.17	1.08	0.94	0.83	

Table 166. American shad juvenile abundance index from the MD DNR Potomac River Striped Bass Juvenile Seine Survey, 1959-2017.

Year	N	Geomean Index	95% CI (low)	95% CI (high)
1959	10	0.00	0.00	0.00
1960	10	0.41	0.04	0.92
1961	16	0.04	-0.04	0.14
1962	28	1.45	0.57	2.83
1963	28	0.88	0.27	1.78
1964	28	0.59	0.14	1.22
1965	28	1.44	0.57	2.81
1966	42	1.07	0.49	1.88
1967	42	0.78	0.32	1.38
1968	42	0.25	0.05	0.50
1969	42	0.00	0.00	0.00
1970	42	1.74	0.73	3.33
1971	42	0.80	0.36	1.39
1972	42	2.14	1.02	3.89
1973	42	0.31	0.11	0.55
1974	42	0.00	0.00	0.00
1975	42	0.94	0.48	1.56
1976	42	0.00	0.00	0.00
1977	42	0.02	-0.02	0.05
1978	42	0.98	0.40	1.82
1979	42	0.03	-0.01	0.08
1980	42	0.24	0.08	0.42
1981	42	0.00	0.00	0.00
1982	42	0.02	-0.02	0.05
1983	42	0.00	0.00	0.00
1984	42	0.12	0.00	0.25
1985	42	0.07	-0.01	0.16
1986	42	0.03	-0.01	0.08
1987	42	0.11	-0.04	0.27
1988	42	0.09	0.00	0.20
1989	42	0.38	0.08	0.76
1990	42	0.00	0.00	0.00
1991	42	0.17	0.03	0.35
1992	42	0.05	-0.01	0.11
1993	42	0.15	-0.01	0.34
1994	42	0.36	0.13	0.65
1995	42	0.59	0.21	1.07
1996	42	1.20	0.51	2.21
1997	42	0.81	0.35	1.43
1998	42	2.00	0.90	3.75
1999	42	0.31	0.09	0.57
2000	42	2.89	1.38	5.34
2001	42	4.75	2.01	9.96
2002	42	4.16	1.90	8.19
2003	42	2.73	1.32	4.99
2004	42	13.30	6.13	27.68
2005	42	4.66	2.03	9.56
2006	42	2.04	0.90	3.87
2007	42	5.07	2.30	10.15
2008	42	2.42	1.11	4.55
2009	42	3.63	1.59	7.26
2010	42	1.05	0.41	1.97
2011	42	1.99	1.22	3.02
2012	42	2.87	1.26	5.63
2013	42	5.97	2.79	11.80
2014	42	5.85	2.94	10.90
2015	42	19.81	9.30	41.05
2016	42	3.84	1.66	7.81
2017	42	3.79	1.72	7.43

Table 167. Juvenile abundance indices of American shad in the Potomac River from the DC DOEE Potomac River Juvenile Seine Survey, 1990-2017.

Year	N	Geometric Mean Index	95% CI (low)	95% CI (high)
1990	30	0.13	-0.11	0.45
1991	30	0.07	-0.03	0.18
1992	30	0.05	-0.04	0.15
1993	30	0	0	0
1994	30	0	0	0
1995	30	0.11	-0.1	0.38
1996	30	0	0	0
1997	30	0	0	0
1998	30	0.05	-0.04	0.15
1999	30	0.08	-0.04	0.21
2000	30	0.1	-0.08	0.31
2001	30	0.25	0.03	0.5
2002	30	0	0	0
2003	25	0.03	-0.03	0.09
2004	25	5.92	3.46	9.73
2005	25	3.08	1.48	5.71
2006	25	1.49	0.52	3.08
2007	25	2.85	1.55	4.82
2008	25	0.8	0.21	1.69
2009	25	0.89	0.33	1.69
2010	54	0.62	0.25	1.11
2011	54	4.35	2.68	6.78
2012	54	2.65	1.57	4.2
2013	54	3.34	2.03	5.2
2014	54	1.62	0.98	2.46
2015	54	10.87	6.86	16.92
2016	54	0.51	0.23	0.86
2017	54	1.03	0.54	1.67

Table 168. Juvenile abundance indices of American shad in the DC DOEE Potomac River Juvenile Pushnet Survey, 2005-2017.

Year	N	Geometric Mean Index	95% CI (low)	95% CI (high)
2005	90	28.22	2.27	39.14
2006	78	4.25	2.84	6.19
2007	66	14.64	9.59	22.11
2008	66	7.66	4.66	12.23
2009	54	1.22	0.73	1.86
2010	66	0.47	0.26	0.72
2011	66	21.68	15.89	29.47
2012	66	6.31	3.9	9.91
2013	66	11.26	7.38	16.95
2014	66	3.41	2.27	4.95
2015	66	60.95	43.33	79.11
2016	66	11.57	7.75	17.06
2017	66	3.52	2.24	5.31

Table 169. MD DNR Potomac River Striped Bass Juvenile Seine Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV	Year	n	Proportion Positive	Index	CV
1962	6	1.00	18.00	0.49	1990	9	0.00	0.00	0.00
1963	6	0.67	6.73	0.86	1991	9	0.33	1.34	0.55
1964	6	0.67	10.20	0.55	1992	9	0.11	0.14	1.15
1965	6	0.83	32.26	0.54	1993	9	0.11	0.00	0.00
1966	9	1.00	21.02	0.54	1994	9	0.56	1.39	0.60
1967	9	0.78	12.66	0.44	1995	9	0.56	6.49	0.43
1968	9	0.33	5.55	0.59	1996	9	0.89	10.55	0.41
1969	9	0.00	0.00	0.00	1997	9	0.78	6.20	0.43
1970	9	0.89	52.72	0.43	1998	9	0.89	41.82	0.49
1971	9	0.78	6.89	0.45	1999	9	0.78	3.42	0.45
1972	9	0.78	19.13	0.87	2000	9	1.00	39.15	0.49
1973	9	0.44	3.65	0.54	2001	9	1.00	139.11	0.40
1974	9	0.00	0.00	0.00	2002	9	1.00	77.09	0.40
1975	9	1.00	7.45	0.51	2003	9	0.89	39.51	0.40
1976	9	0.00	0.00	0.00	2004	9	1.00	433.07	0.42
1977	9	0.11	0.00	0.00	2005	9	1.00	191.06	0.40
1978	9	0.78	14.74	0.47	2006	9	1.00	39.30	0.40
1979	9	0.11	0.00	0.00	2007	9	1.00	128.09	0.42
1980	9	0.56	2.19	0.61	2008	9	1.00	44.21	0.40
1981	9	0.00	0.00	0.00	2009	9	1.00	60.68	0.40
1982	9	0.00	0.00	0.00	2010	9	0.67	14.13	0.41
1983	9	0.00	0.00	0.00	2011	9	1.00	13.37	0.41
1984	9	0.11	0.65	0.78	2012	9	0.89	94.54	0.40
1985	9	0.22	0.42	0.89	2013	9	1.00	109.05	0.40
1986	9	0.00	0.00	0.00	2014	9	0.78	98.56	0.40
1987	9	0.22	1.64	0.51	2015	9	1.00	329.46	0.40
1988	9	0.33	0.24	1.16	2016	9	1.00	124.71	0.40
1989	9	0.44	3.66	0.45	2017	9	1.00	75.06	0.40

Table 170. Mann-Kendall results for mean length-at-age over time of female and male American shad from the Potomac River.

Mean Length-at-age for Potomac River (Scales)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Potomac River	Potomac River Striped Bass Spawning Stock Survey	3	2007-2015	3	1	1.000	2003-2017	7	14	0.048
		4	2002-2017	11	-3	0.876	2003-2017	11	-5	0.755
		5	2002-2017	14	-35	0.063	2003-2017	12	-28	0.064
		6	2002-2017	14	-15	0.443	2003-2017	12	-14	0.373
		7	2002-2017	14	-17	0.381	2003-2016	9	-8	0.466
		8	2002-2016	10	-26	0.025	2003-2013	3	-1	1.000
		9	2003-2007	4	2	0.734				

Table 171. Potomac SCAA model parameter estimates.

Parameter	Mean	Standard Error	CV
log(R0)	6.96	0.15	0.02
Potomac River Striped Bass Spawning Stock Survey log(q)	-2.80	0.31	0.11
Potomac River Striped Bass Juvenile Seine Survey log(q)	-5.84	0.17	0.03
Potomac River Juvenile Pushnet Survey log(q)	-7.08	0.18	0.03
Potomac River Commercial Pound Net CPUE log(q)	-2.02	0.32	0.16
Gill Net Fleet selectivity A50	5.00	0.18	0.04
Gill Net Fleet selectivity slope	1.11	0.12	0.10
MDDNR SBSSS selectivity A50	4.69	0.22	0.05
MDDNR SBSSS selectivity slope	1.16	0.16	0.14
Female SSB Reference Point (metric tons)	11.56	1.71	0.15

Table 172. Potomac SCAA model recruitment deviations. Deviations for years prior to the model start year (1999) are for initial age structure estimates. For example, the 1998 deviation is for age-1 fish in 1999.

Year	Mean	Standard Error
1991	-2.09527	0.363888
1992	-1.74661	0.380974
1993	-1.89296	0.351955
1994	-1.77331	0.305245
1995	-1.34422	0.275297
1996	-0.91256	0.294599
1997	-0.74691	0.364977
1998	0.471708	0.190035
1999	-0.9689	0.280544
2000	-0.24009	0.191405
2001	0.133924	0.157671
2002	-0.30481	0.185179
2003	-0.47263	0.206498
2004	-0.00053	0.179192
2005	0.16338	0.160696
2006	-0.57022	0.192148
2007	0.391505	0.161003
2008	-0.12552	0.179765
2009	-0.30549	0.179588
2010	-1.30078	0.212012
2011	-0.07425	0.165094
2012	0.302501	0.166735
2013	0.367099	0.203105
2014	-0.24988	0.234411
2015	1.41198	0.235643
2016	0.351568	0.238643
2017	-0.36136	0.238829

Table 173. Potomac SCAA model age-6 direct anthropogenic mortality estimates.

Year	Mean	Standard Error	CV
1999	0.17	0.06	0.33
2000	0.20	0.07	0.33
2001	0.34	0.11	0.33
2002	0.31	0.10	0.31
2003	0.64	0.17	0.26
2004	0.28	0.07	0.24
2005	0.33	0.09	0.27
2006	0.33	0.09	0.27
2007	0.46	0.13	0.28
2008	0.44	0.14	0.31
2009	0.40	0.13	0.33
2010	0.37	0.12	0.33
2011	0.20	0.06	0.30
2012	0.49	0.15	0.30
2013	0.33	0.09	0.28
2014	0.46	0.14	0.29
2015	0.34	0.11	0.32
2016	0.28	0.09	0.34
2017	0.50	0.16	0.33

Table 174. Potomac SCAA model 1-spawning stock biomass per-recruit estimates.

Year	Mean	Standard Error	CV
1999	0.52	0.10	0.19
2000	0.57	0.10	0.17
2001	0.74	0.09	0.12
2002	0.70	0.08	0.12
2003	0.88	0.04	0.04
2004	0.67	0.07	0.10
2005	0.73	0.07	0.09
2006	0.73	0.07	0.09
2007	0.81	0.06	0.07
2008	0.80	0.07	0.08
2009	0.78	0.08	0.10
2010	0.75	0.08	0.11
2011	0.57	0.09	0.16
2012	0.82	0.06	0.07
2013	0.72	0.07	0.10
2014	0.81	0.06	0.07
2015	0.72	0.08	0.11
2016	0.67	0.09	0.14
2017	0.83	0.06	0.08

Table 175. Potomac SCAA model age-0 recruitment estimates (thousands of fish).

Year	Mean	Standard Error	CV
1999	344	104	0.30
2000	710	155	0.22
2001	1,026	189	0.18
2002	662	141	0.21
2003	559	132	0.24
2004	897	207	0.23
2005	1,057	230	0.22
2006	507	121	0.24
2007	1,328	244	0.18
2008	792	163	0.21
2009	661	134	0.20
2010	244	64	0.26
2011	833	191	0.23
2012	1,214	274	0.23
2013	1,296	334	0.26
2014	699	204	0.29
2015	3,683	1,081	0.29
2016	1,276	375	0.29
2017	635	187	0.29

Table 176. Potomac SCAA model abundance estimates for ages-3+ (thousands of fish).

Year	3	4	5	6	7	8+	Total
1999	21.5	7.9	3.1	1.7	1.2	1.4	36.8
2000	25.3	12.2	4.6	1.7	0.9	1.3	45.9
2001	85.1	14.3	7.0	2.5	0.8	1.1	110.8
2002	20.0	48.0	8.1	3.4	1.1	0.8	81.4
2003	41.3	11.3	27.5	4.1	1.5	0.9	86.7
2004	59.8	23.2	6.2	11.2	1.3	0.8	102.5
2005	38.5	33.7	13.3	3.2	5.2	1.0	94.9
2006	32.6	21.7	19.1	6.6	1.4	2.7	84.1
2007	52.2	18.4	12.4	9.5	2.9	1.8	97.2
2008	61.5	29.4	10.4	5.7	3.7	1.8	112.6
2009	29.6	34.7	16.6	4.8	2.3	2.1	90.0
2010	77.3	16.7	19.6	7.9	2.0	1.8	125.2
2011	46.1	43.6	9.5	9.6	3.3	1.6	113.8
2012	38.5	26.0	25.3	5.1	4.8	2.5	102.3
2013	14.2	21.7	14.7	11.5	1.9	2.7	66.7
2014	48.5	8.0	12.4	7.3	5.1	2.1	83.5
2015	70.7	27.4	4.6	5.8	2.8	2.7	114.0
2016	75.5	39.9	15.7	2.3	2.5	2.4	138.3
2017	40.7	42.6	23.0	8.1	1.1	2.3	117.9

Table 177. Potomac SCAA model female spawning stock biomass estimates (metric tons).

Year	Mean	Standard Error	CV
1999	2.57	1.05	0.41
2000	2.55	1.05	0.41
2001	2.32	1.08	0.47
2002	3.59	1.27	0.35
2003	2.99	1.12	0.37
2004	5.10	1.70	0.33
2005	5.01	1.72	0.34
2006	5.72	1.99	0.35
2007	4.25	1.91	0.45
2008	3.94	1.93	0.49
2009	4.67	2.18	0.47
2010	5.49	2.55	0.46
2011	7.76	2.96	0.38
2012	5.30	2.33	0.44
2013	6.54	2.67	0.41
2014	4.19	2.11	0.50
2015	4.26	2.09	0.49
2016	5.53	2.22	0.40
2017	5.00	2.36	0.47

Table 178. Potomac SCAA model relative female spawning stock biomass estimates.

Year	Mean	Standard Error	CV
2000	0.22	0.07	0.31
2001	0.20	0.07	0.36
2002	0.31	0.08	0.26
2003	0.26	0.08	0.29
2004	0.44	0.11	0.25
2005	0.43	0.11	0.24
2006	0.49	0.12	0.25
2007	0.37	0.13	0.34
2008	0.34	0.13	0.38
2009	0.40	0.14	0.35
2010	0.48	0.16	0.34
2011	0.67	0.18	0.26
2012	0.46	0.15	0.32
2013	0.57	0.16	0.29
2014	0.36	0.14	0.38
2015	0.37	0.13	0.36
2016	0.48	0.13	0.27
2017	0.43	0.15	0.34

Table 179. Number of fishermen with American shad by-catch permits, active permits, and fishing activity reported for the James, York, and Rappahannock Rivers, 2006-2017. Permits are considered active if one or more pounds of American shad were reported. *One fisherman in the Rappahannock River did not record the total number of shad caught, so 40 was used.

Water Body	Year	# Permit Holders	# Active Permits	Total Trips	# Shad Caught	# Shad Kept	% of Bycatch for Year
James River	2017	12	3	72	277	277	48
	2016	14	4	107	24	22	26
	2015	14	8	58	31	21	8
	2014	14	9	54	114	112	15
	2013	10	4	55	150	139	32
	2012	10	2	7	10	7	3
	2011	9	3	25	42	42	32
	2010	9	0	7	0	0	0
	2009	8	1	6	2	0	0
	2008	6	2	3	3	3	2
	2007	16	7	58	119	52	19
	2006	32	5	27	24	23	9
York River	2017	9	5	45	148	146	25
	2016	11	2	64	40	40	44
	2015	10	9	36	302	279	76
	2014	8	5	85	453	453	61
	2013	12	6	116	212	203	47
	2012	13	5	71	207	207	94
	2011	11	4	51	88	87	67
	2010	9	5	43	229	208	84
	2009	11	6	97	302	288	100
	2008	10	6	85	89	89	60
	2007	15	8	104	199	199	73
	2006	31	5	198	233	228	90
Rappahannock River	2017	9	4	48	155	155	27
	2016	5	4	129	27	27	30
	2015	6	5	25	63	63	16
	2014	8	4	49	182	173	23
	2013	7	6	24	273	89	21
	2012	2	1	2	7	7	3
	2011	3	1	1	1	1	1
	2010	7	2	10	40*	40*	16
	2009	1	0	0	0	0	0
	2008	3	1	8	81	57	38
	2007	5	2	23	22	20	7
	2006	14	2	8	3	3	2

Table 180. Summary of historical catch and effort data of American shad by staked gill nets in the Rappahannock River, Virginia. Historical data are taken from the voluntary logbooks of Mr. M. Delano, Urbanna, Virginia.

Year	Effort (10^3 m*days)	Duration of run (days)	Highest catch rate (female kg/m/day)	Mean catch rate (female kg/m/day)	Area under the catch curve
1980	43.4	35	0.121	0.036	1.79
1981	112.1	57	0.032	0.011	1.89
1982	82.3	51	0.046	0.009	1.68
1983	106.7	59	0.093	0.031	0.59
1984	30.5	48	0.139	0.033	0.60
1985	77.2	60	0.136	0.029	1.83
1986	34.9	43	0.155	0.039	2.18
1987	23.3	37	0.090	0.023	0.97
1988	23.2	53	0.073	0.025	1.25
1989	16.2	44	0.856	0.123	6.19
1990	41.3	55	0.092	0.023	1.31
1991	25.9	54	0.129	0.022	1.13
1992	8.6	51	0.299	0.044	1.44
Geometric mean					**1.45**

Table 181. Summary of recent catch and effort data of American shad by the Rappahannock River Adult Gill Net Survey.

Year	Effort (10^3 m*days)	Duration of run (days)	Highest catch rate (female kg/m/day)	Mean catch rate (female kg/m/day)	Area under the catch curve
1998	3.7	----	0.053	0.020	1.46
1999	5.8	42	0.055	0.026	1.30
2000	6.6	73	0.141	0.042	1.75
2001	6.6	72	0.167	0.070	5.77
2002	6.0	57	0.110	0.028	3.08
2003	7.3	72	0.311	0.094	7.10
2004	5.7	65	0.232	0.107	7.06
2005	5.7	65	0.164	0.054	3.69
2006	6.7	75	0.088	0.037	3.01
2007	5.8	64	0.130	0.042	2.60
2008	6.1	64	0.175	0.045	3.12
2009	5.6	50	0.259	0.093	5.36
2010	5.2	50	0.088	0.027	2.03
2011	6.8	85	0.216	0.074	6.51
2012	7.0	62	0.313	0.080	7.28
2013	7.0	78	0.289	0.080	6.98
2014	5.1	57	0.322	0.122	8.66
2015	2.7	63	0.200	0.053	5.08
2016	2.9	56	0.085	0.022	1.68
2017	2.0	47	0.173	0.071	4.14
Geometric mean					**3.74**

Table 182. Female American shad average catch-at-age from the Rappahannock River Adult Gill Net Survey. Ages in 1998 based on otoliths, all others based on scales.

Age	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**Av.**
2																					
3			1		1		2	1	1	1				1	1						**1.1**
4	15	7	55	47	4	35	45	9	34	21	15	55	5	62	69	35	18	1		2	**28.1**
5	45	25	59	127	24	175	123	61	79	53	83	140	39	137	163	173	148	34	6	28	**86.1**
6	8	36	11	41	43	75	98	63	22	23	41	74	28	68	63	82	122	27	25	38	**49.4**
7	1	9	6	13	31	33	28	23	8	11	16	17	7	18	25	25	27	17	10	15	**17.0**
8		1	2	2	9	12	15	11	5	1	5	5		3	8	11	6	5		1	**6.0**
9		1		2	2	5	2	2		2		1			1	2	2				**2.0**
10					1		1	1	1		2		1			1					**1.1**
11					1												1				**1.0**
12																					
13																					

Table 183. Female American shad average length by age (mm FL) from the Rappahannock River Adult Gill Net Survey. Ages in 1998 based on otoliths, all others based on scales.

AGE	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Av.
2																					
3			459.0		456.0		461.5	457.0	447.0	462.0				456.0	477.0						**459.4**
4	478.0	466.7	481.2	483.2	461.3	479.1	472.0	476.3	474.6	469.2	465.3	464.6	459.8	472.2	481.4	505.8	498.9	493.0		475.0	**476.7**
5	492.5	494.2	497.8	503.7	499.1	503.0	499.1	492.2	490.0	484.7	477.2	478.3	478.4	485.7	494.6	506.5	514.1	501.0	486.2	487.8	**493.3**
6	512.5	512.4	512.1	529.0	515.3	531.5	522.0	511.2	506.9	496.8	495.6	496.1	492.8	494.5	510.4	510.1	530.2	511.6	503.6	503.3	**509.9**
7	550.0	516.0	530.3	549.7	532.6	557.3	539.0	527.7	545.6	538.5	510.3	526.8	503.1	509.3	524.3	515.0	550.2	529.6	518.4	524.5	**529.9**
8		522.0	581.5	552.5	541.3	571.1	558.1	556.5	525.6	560.0	542.8	536.2		527.3	523.1	501.5	536.8	526.0		568.0	**543.0**
9		549.0		566.0	542.0	588.2	574.0	590.0		572.0		569.0			520.0	509.0	559.5				**558.1**
10					560.0		580.0	586.0	588.0		556.5		598.0			515.0					**569.1**
11					552.0												580.0				**566.0**
12																					
13																					

Table 184. Female American shad average weight by age (g) from the Rappahannock River Adult Gill Net Survey. Ages in 1998 based on otoliths, all others based on scales.

Age	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Av.
2																					
3			1,234.3		1,317.5		1,230.2	1,220.4	1,176.7	1,151.1				1,153.7	1,316.8						**1,225.1**
4	1,394.3	1,123.4	1,384.4	1,331.4	1,303.9	1,388.3	1,341.3	1,398.5	1,335.2	1,306.8	1,257.0	1,235.3	1,248.3	1,340.6	1,354.1	1,523.5	1,329.1	1,395.7		1,188.9	**1,325.3**
5	1,521.8	1,319.9	1,551.7	1,473.3	1,579.3	1,588.3	1,585.1	1,466.9	1,492.7	1,459.4	1,344.5	1,356.0	1,420.0	1,448.7	1,498.8	1,490.9	1,433.9	1,406.7	1,299.8	1,312.0	**1,452.5**
6	1,649.8	1,444.2	1,690.6	1,695.0	1,721.4	1,876.7	1,817.6	1,668.8	1,625.8	1,633.5	1,533.1	1,516.4	1,571.0	1,525.6	1,643.6	1,520.3	1,575.8	1,476.1	1,428.4	1,444.0	**1,602.9**
7	2,055.0	1,434.7	1,887.7	1,885.5	1,869.5	2,129.1	1,923.7	1,836.5	1,919.9	1,963.5	1,755.0	1,775.7	1,614.6	1,679.3	1,806.5	1,534.5	1,778.1	1,558.0	1,514.3	1,613.7	**1,776.8**
8		1,724.9	2,426.9	1,755.9	1,995.4	2,351.3	2,303.9	2,148.6	1,607.7	1,622.0	1,854.4	1,991.9		1,834.9	1,634.1	1,476.1	1,560.1	1,576.5		2,058.8	**1,877.8**
9		1,338.8		1,699.0	1,976.0	2,464.7	2,543.2	2,518.9		2,359.7		1,879.6			1,514.1	1,613.6	2,276.1				**2,016.7**
10					1,537.0		2,237.6	2,267.5	2,435.8		2,296.4		2,752.5			1,581.8					**2,158.4**
11					1,585.4												1,887.7				**1,736.6**
12																					
13																					

Table 185. Total numbers of hatchery-marked American shad taken from the Rappahannock River Adult Gill Net Survey, 2007-2017. Ages are based on examination of scales. Hatchery production data courtesy of the Virginia Department of Game and Inland Fisheries (E. Brittle). NA=not aged.

Hatchery Year Class	Hatchery Production (millions)	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total	% Total
2003	1.4													
2004	3.2		1	2	1								4	11.4
2005	3.4			1		1		1					3	8.6
2006	6.3					1	1						2	5.7
2007	4.5					1	5	1	1				8	22.9
2008	4.8						1	2	1				4	11.4
2009	2.7								4	1	1		6	17.1
2010	3.9									1	2		3	8.6
2011	4.1									1		1	2	5.7
2012	6.0													0.0
2013	4.3													0.0
2014	4.3													0.0
2015	0.0													0.0
2016	0.0													0.0
2017	0.0													0.0
NA	--						1		1		1		3	8.6
Total	48.9	0	1	3	1	3	8	4	7	3	4	1	35	100.0

Table 186. VIMS Rappahannock River Adult Gill Net Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
1998	14	0.93	7.78	0.14
1999	21	0.71	7.52	0.15
2000	24	0.88	13.36	0.14
2001	24	0.88	25.04	0.13
2002	22	0.82	11.05	0.19
2003	26	0.85	32.19	0.22
2004	21	0.90	27.10	0.13
2005	21	0.95	16.99	0.15
2006	24	1.00	15.04	0.11
2007	21	0.81	11.32	0.17
2008	22	0.95	16.60	0.15
2009	20	0.95	28.21	0.22
2010	19	0.68	8.15	0.17
2011	25	1.00	34.42	0.14
2012	26	0.73	27.04	0.14
2013	26	0.96	36.36	0.16
2014	19	0.95	37.43	0.16
2015	10	1.00	18.86	0.24
2016	11	0.82	10.85	0.45
2017	9	0.89	25.98	0.41

Table 187. VIMS Rappahannock River Juvenile Seine Survey number of observations (n), index values (numbers), and CVs.

Year	n	Index	CV	Year	n	Index	CV
1980	5	0.00	NA	1999	35	0.02	5.86
1981	6	0.00	NA	2000	34	0.08	3.07
1982	6	0.86	1.26	2001	35	0.34	1.28
1983	6	0.20	2.24	2002	35	0.00	NA
1984	6	0.26	2.18	2003	35	0.72	1.13
1985	8	0.00	NA	2004	35	0.81	1.16
1986	16	0.09	2.63	2005	33	0.27	2.43
1987	16	0.17	2.03	2006	34	0.11	2.75
1988	20	0.00	NA	2007	34	0.40	1.26
1989	32	0.42	2.00	2008	35	0.02	5.86
1990	35	0.03	6.19	2009	34	0.13	2.77
1991	31	0.00	NA	2010	33	1.19	0.98
1992	35	0.00	NA	2011	34	1.39	0.83
1993	31	0.25	2.11	2012	35	0.19	2.22
1994	34	0.11	2.74	2013	35	0.35	1.75
1995	33	0.00	NA	2014	35	3.79	0.41
1996	32	0.41	1.70	2015	35	5.14	0.30
1997	35	0.30	2.03	2016	35	4.17	0.39
1998	29	0.14	2.87	2017	35	0.87	1.46

Table 188. VDGIF Rappahannock River Boat Electrofishing Survey number of observations (n), index values (numbers), and CVs.

Year	n	Index	CV
1998	8	0.51	1.35
2000	16	2.94	1.18
2001	30	0.02	46.14
2002	51	7.76	1.27
2003	21	2.20	0.63
2004	16	0.84	1.93
2007	25	0.46	18.21
2008	52	2.49	0.55
2010	18	2.32	1.09
2011	55	2.18	0.46
2012	48	0.82	4.72
2013	68	4.05	1.01
2014	72	1.03	0.71
2015	67	0.75	1.31
2016	63	0.70	1.75
2017	56	0.88	0.87

Table 189. Mann-Kendall results for mean length-at-age over time of female American shad from the Rappahannock River.

Mean Length-at-age for Rappahannock River (Scales)

		Female					Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Rappahannock River	Rappahannock River Adult Gill Net Survey	3	2002-2012	7	6	0.448				
		4	2002-2017	15	27	0.198				
		5	2002-2017	16	0	1.000				
		6	2002-2017	16	-28	0.224				
		7	2002-2017	16	-34	0.137				
		8	2002-2017	14	-29	0.125				
		9	2002-2014	9	-16	0.118				
		10	2002-2013	7	1	1.000				

Table 190. Number of female American shad from York River spawning grounds sacrificed for egg taking.

Year	Females sacrificed
1997	854
1998	1,610
1999	1,417
2000	1,533
2001	1,359
2002	1,945
2003	1,375
2004	no data
2005	758
2006	no data
2007	no data
2008	no data
2009	no data
2010	379
2011	257
2012	514
2013	376
2014	376
2015	376
2016	153
2017	0

Table 191. Historical catch and effort data of American shad captured by staked gill nets in the York River, Virginia. 1950s historical data are taken from the voluntary logbooks of Malvin Green, Aberdeen Creek, Virginia. The data were originally recorded as numbers of female shad per meter of net per day and were converted to weight (kg) of female shad per meter of net per day, assuming an average female weight of 1.45kg. Catch rates were multiplied by 2.16 to adjust for the lower fishing power of multifilament nets compared to current monofilament nets. 1980s historical data are taken from the voluntary logbooks of Mr. R. Kellum, Achilles, Virginia.

Year	Effort (10^3m* days)	Duration of run (days)	Highest catch rate (female kg/m/day)	Mean catch rate (female kg/m/day)	Area under the catch curve
1953	36.0	56	0.549	0.443	14.88
1954	45.5	54	0.699	0.434	14.04
1955	40.1	55	0.310	0.270	8.70
1956	68.8	85	1.201	0.663	33.95
1957	56.2	65	0.955	0.667	26.14
Geometric mean					**17.44**
1980	79.4	44	0.556	0.268	10.15
1981	114.7	51	0.259	0.121	4.35
1982	86.4	44	0.326	0.101	5.31
1983	121.3	40	0.212	0.066	3.06
1984	171.4	48	0.548	0.139	8.21
1985	205.4	49	0.227	0.091	4.61
1986	185.2	38	0.145	0.055	2.17
1987	152.9	37	0.088	0.039	1.78
1988	126.2	40	0.134	0.028	1.34
1989	146.3	55	0.397	0.131	4.92
1990	106.9	38	0.951	0.037	1.31
1991	77.8	40	0.111	0.062	2.72
1992	60.8	41	0.079	0.041	1.60
Geometric mean					**3.22**

Table 192. Summary of recent catch and effort data of American shad by the York River Adult Gill Net Survey.

Year	Effort (10^3m* days)	Duration of run (days)	Highest catch rate (female kg/m/day)	Mean catch rate (female kg/m/day)	Area under the catch curve
1998	6.6	78	1.080	0.190	14.71
1999	6.3	65	0.209	0.075	5.42
2000	7.1	76	0.276	0.086	7.52
2001	5.7	79	0.627	0.163	12.97
2002	6.7	70	0.306	0.073	7.47
2003	6.1	70	0.390	0.111	8.98
2004	5.2	65	0.448	0.157	9.72
2005	5.8	73	0.135	0.063	4.64
2006	5.5	62	0.146	0.042	2.85
2007	5.8	70	0.243	0.069	5.04
2008	5.4	65	0.228	0.050	3.28
2009	6.0	69	0.131	0.042	2.92
2010	6.0	44	0.227	0.055	4.19
2011	6.0	58	0.219	0.060	4.58
2012	6.0	66	0.206	0.045	3.17
2013	7.1	78	0.189	0.045	3.98
2014	5.7	70	0.611	0.139	10.06
2015	2.8	58	0.033	0.020	1.93
2016	2.6	58	0.062	0.023	1.54
2017	2.4	46	0.047	0.022	1.27
Geometric mean					**4.72**

Table 193. Female American shad average catch-at-age from the York River Adult Gill Net Survey. Ages in 1998 based on otoliths, all others based on scales.

Age	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Av.
2																					
3	8	2	12	6		1	5	1	3	4											**4.7**
4	165	33	116	193	16	27	48	21	44	47	21	9	15	23	41	20	45	1			**49.2**
5	344	114	121	267	112	163	164	77	68	109	79	60	74	87	81	102	156	19	2	14	**110.7**
6	105	81	59	74	166	149	158	68	13	51	40	60	80	77	31	62	118	11	23	10	**71.8**
7	49	27	15	26	62	92	185	41	11	13	20	16	30	21	9	10	43	3	13	6	**34.6**
8	30	7	3	11	11	35	88	44	4	5	3	7	9	3		11	17	3	1	1	**15.4**
9	3	6	2	3	4	11	23	24	5	3	1	1	4	1			5		2		**6.1**
10	1		1	1	1	2	5	2	2	2	1		1			1	2				**1.7**
11									1	1	1										**1.0**
12							1														**1.0**
13																					

Table 194. Female American shad average length by age (mm FL) from the York River Adult Gill Net Survey. Ages in 1998 based on otoliths, all others based on scales.

AGE	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Av.
2																					
3	450.1	450.0	451.7	471.0		462.0	446.2	459.0	460.0	471.5											**457.9**
4	468.5	485.2	473.8	482.1	484.9	480.0	466.5	472.5	464.5	477.8	461.7	462.6	466.2	472.8	473.0	497.9	490.8	489.0			**476.1**
5	482.3	491.8	487.8	497.0	494.6	502.9	495.6	488.3	476.0	481.4	473.7	478.3	475.1	487.3	479.5	506.9	515.4	504.3	495.0	498.8	**490.6**
6	506.4	507.8	512.9	517.9	502.3	527.8	521.8	512.7	510.1	497.4	488.8	488.5	490.0	495.3	495.5	507.2	526.2	513.1	504.2	501.3	**506.4**
7	535.0	524.3	513.0	533.8	513.2	540.2	539.6	529.9	536.8	524.8	506.1	508.3	510.1	501.2	519.7	509.9	542.0	525.0	517.1	533.0	**523.2**
8	542.3	545.7	546.3	543.2	530.2	548.8	548.6	550.5	554.0	533.8	534.7	529.4	530.6	507.3		512.6	541.4	541.7	510.0	516.0	**535.1**
9	587.3	566.0	560.0	573.7	530.5	563.0	561.6	568.9	557.6	568.7	571.0	542.0	529.0	488.0			535.6		556.5		**553.7**
10	562.0		572.0	548.0	548.0	560.0	570.2	597.5	574.5	584.0	561.0		539.0			504.0	551.0				**559.3**
11									602.0	574.0	578.0										**584.7**
12							574.0														**574.0**
13																					

Table 195. Female American shad average weight by age (g) from the York River Adult Gill Net Survey. Ages in 1998 based on otoliths, all others based on scales.

Age	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Av.
2																					
3	1,057.1	1,043.6	1,072.8	1,242.1			1,094.3	1,050.0	1,174.9	1,243.0											**1,122.2**
4	1,291.3	1,279.3	1,312.7	1,267.2	1,398.3	1,155.1	1,270.7	1,281.3	1,249.5	1,360.9	1,229.2	1,268.2	1,241.9	1,336.3	1,330.3	1,382.5	1,241.4	1,180.8			**1,282.1**
5	1,393.4	1,319.0	1,418.0	1,372.1	1,482.8	1,319.3	1,498.6	1,378.2	1,342.9	1,409.4	1,317.5	1,371.9	1,347.6	1,441.4	1,444.4	1,439.2	1,419.1	1,348.4	1,356.2	1,378.9	**1,389.9**
6	1,598.6	1,431.0	1,555.8	1,493.1	1,563.2	1,515.3	1,613.8	1,536.0	1,581.9	1,535.0	1,473.0	1,438.4	1,473.4	1,511.3	1,532.9	1,428.7	1,526.6	1,365.2	1,397.1	1,430.9	**1,500.1**
7	1,792.1	1,451.1	1,562.8	1,554.6	1,677.1	1,672.4	1,643.0	1,604.3	1,661.0	1,886.5	1,551.0	1,656.8	1,592.1	1,508.2	1,752.4	1,490.4	1,634.5	1,326.0	1,407.8	1,667.4	**1,604.6**
8	1,765.6	1,743.5	1,888.4	1,523.6	1,794.7	1,648.3	1,609.0	1,709.8	1,911.2	1,610.6	1,767.4	1,848.0	1,799.6	1,657.9		1,439.6	1,617.8	1,294.3	1,293.9	1,590.9	**1,658.6**
9	2,102.0	1,773.8	1,834.8	1,648.5	1,815.3	1,722.1	1,617.2	1,777.6	1,843.9	1,971.1	2,441.3	2,048.1	1,485.0	1,642.0			1,474.2		1,614.5		**1,800.7**
10	1,945.4		2,452.5	1,924.2	2,479.6	1,739.3	1,701.5	2,344.6	2,022.7	2,179.2	2,359.7		1,505.5			1,284.1	1,773.7				**1,977.8**
11						1,576.0			1,870.3	1,627.1	1,806.8										**1,720.0**
12							1,744.9														**1,744.9**
13																					

Table 196. VIMS York River Adult Gill Net Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
1998	24	0.83	54.69	0.18
1999	23	0.83	22.80	0.16
2000	26	0.85	25.54	0.17
2001	21	1.00	60.23	0.15
2002	24	0.96	29.83	0.14
2003	22	1.00	64.07	0.25
2004	19	0.95	41.24	0.13
2005	21	0.95	27.12	0.20
2006	20	0.95	13.98	0.14
2007	21	1.00	21.09	0.12
2008	20	0.95	15.54	0.16
2009	22	0.86	13.34	0.14
2010	22	0.82	15.38	0.17
2011	22	0.91	21.43	0.18
2012	22	0.91	18.75	0.25
2013	26	0.88	17.51	0.15
2014	21	1.00	43.84	0.13
2015	9	1.00	8.14	0.39
2016	10	0.90	9.81	0.45
2017	9	0.89	6.62	0.19

Table 197. VIMS York River Juvenile Seine Survey (Mattaponi River Stations) number of observations (n), index values (numbers), and CVs.

Year	n	Index	CV	Year	n	Index	CV
1980	25	2.26	0.47	1999	47	0.26	2.25
1981	32	0.54	1.39	2000	47	5.54	0.23
1982	24	9.11	0.14	2001	49	0.58	1.20
1983	24	1.66	0.61	2002	48	0.23	2.16
1984	24	12.38	0.11	2003	50	8.57	0.15
1985	32	7.53	0.18	2004	47	7.52	0.19
1986	32	1.47	0.71	2005	50	1.66	0.81
1987	32	0.35	1.74	2006	48	0.93	0.99
1988	40	0.05	4.06	2007	47	0.30	1.70
1989	49	1.22	0.91	2008	50	0.11	2.75
1990	50	0.69	1.05	2009	47	0.97	0.17
1991	50	0.33	1.85	2010	50	1.16	0.89
1992	49	0.01	9.90	2011	48	1.16	1.20
1993	50	0.31	2.02	2012	49	0.01	9.90
1994	50	1.73	0.67	2013	50	0.15	2.66
1995	50	0.28	2.09	2014	50	1.58	0.60
1996	49	14.66	0.09	2015	49	2.96	0.41
1997	50	2.25	0.49	2016	50	0.99	1.05
1998	48	2.33	0.53	2017	50	0.60	1.36

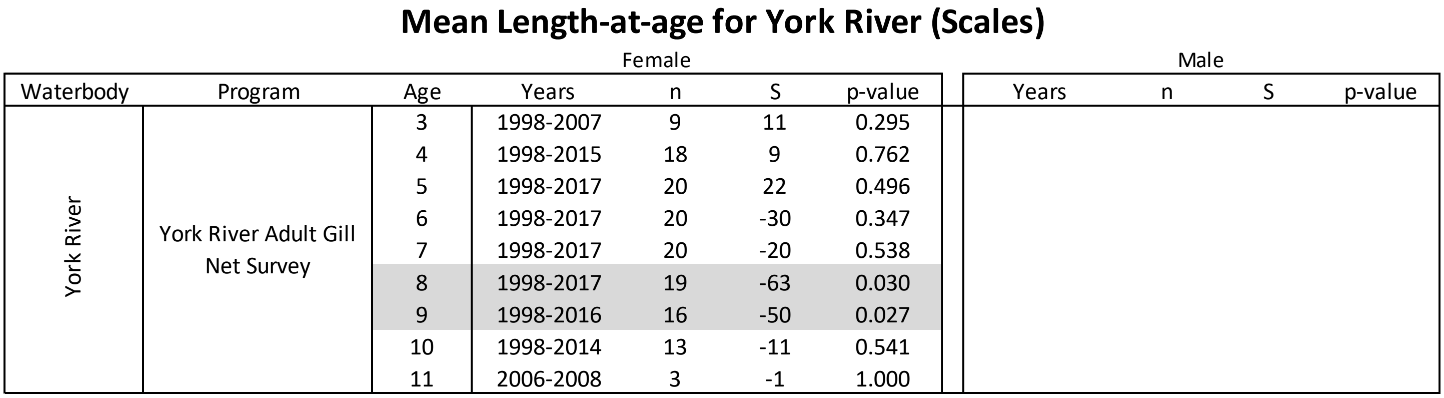
Table 198. VIMS York River Juvenile Seine Survey (Pamunkey River Stations) number of observations (n), index values (numbers), and CVs.

Year	n	Index	CV	Year	n	Index	CV
1980	16	0.50	1.43	1999	38	0.00	NA
1981	32	0.41	1.52	2000	39	0.07	3.29
1982	18	0.70	0.76	2001	40	0.15	2.38
1983	18	0.78	1.02	2002	40	0.02	5.48
1984	18	0.33	1.56	2003	39	13.11	0.08
1985	24	0.98	1.05	2004	38	0.10	2.87
1986	24	0.09	3.45	2005	40	0.05	4.06
1987	24	0.00	NA	2006	37	0.09	3.91
1988	30	0.00	NA	2007	36	0.00	NA
1989	40	0.02	5.48	2008	40	0.00	NA
1990	40	0.08	5.22	2009	40	0.00	NA
1991	39	0.02	5.55	2010	38	0.27	0.70
1992	40	0.00	NA	2011	35	0.27	2.05
1993	39	0.00	NA	2012	39	0.02	5.55
1994	39	0.15	2.90	2013	40	0.05	4.06
1995	40	0.03	5.79	2014	41	0.12	2.32
1996	39	2.05	0.63	2015	40	0.89	0.99
1997	40	0.48	1.63	2016	40	0.36	1.96
1998	38	0.08	5.97	2017	40	0.13	3.77

Table 199. VIMS York River Juvenile Seine Survey (York River Stations) number of observations (n), index values (numbers), and CVs.

Year	n	Index	CV	Year	n	Index	CV
1980	47	1.22	0.80	1999	89	0.13	3.37
1981	64	0.48	1.43	2000	91	1.71	0.76
1982	42	3.71	0.37	2001	94	0.35	1.65
1983	42	1.24	0.76	2002	93	0.12	3.12
1984	42	3.97	0.40	2003	94	9.04	0.14
1985	56	3.56	0.40	2004	90	2.21	0.66
1986	56	0.74	1.23	2005	95	0.70	1.56
1987	56	0.19	2.52	2006	90	0.47	1.62
1988	70	0.03	5.14	2007	88	0.15	2.62
1989	94	0.53	1.69	2008	95	0.06	3.75
1990	95	0.36	1.75	2009	92	0.01	11.45
1991	94	0.17	2.75	2010	93	0.47	1.75
1992	94	0.01	7.15	2011	88	0.67	1.66
1993	94	0.15	3.16	2012	93	0.02	5.05
1994	94	0.81	1.22	2013	95	0.10	3.21
1995	95	0.15	3.01	2014	96	0.72	1.14
1996	93	5.89	0.27	2015	94	1.69	0.67
1997	95	1.19	0.87	2016	95	0.64	1.42
1998	91	0.95	1.16	2017	95	0.36	1.94

Table 200. Mann-Kendall results for mean length-at-age over time for female American shad in the York River.



Mean Length-at-age for York River (Scales)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
York River	York River Adult Gill Net Survey	3	1998-2007	9	11	0.295				
		4	1998-2015	18	9	0.762				
		5	1998-2017	20	22	0.496				
		6	1998-2017	20	-30	0.347				
		7	1998-2017	20	-20	0.538				
		8	1998-2017	19	-63	0.030				
		9	1998-2016	16	-50	0.027				
		10	1998-2014	13	-11	0.541				
		11	2006-2008	3	-1	1.000				

Table 201. Summary of historical catch and effort data of American shad by staked gill nets in the James River, Virginia. Historical data are taken from the voluntary logbooks of the Brown family, Rescue, Virginia.

Year	Effort (10^3m*days)	Duration of run (days)	Highest catch rate (female kg/m/day)	Mean catch rate (female kg/m/day)	Area under the catch curve
1980	20.5	41	2.239	0.699	29.20
1981	67.7	41	0.547	0.130	5.20
1982	49.3	35	0.331	0.115	4.20
1983	94.0	57	1.274	0.297	16.50
1984	89.7	50	0.897	0.036	19.30
1985	91.3	45	0.295	0.103	4.90
1986	31.5	26	1.289	0.152	6.10
1987	30.1	30	0.352	0.085	2.70
1988	19.1	20	0.487	0.193	9.30
1989	31.5	30	0.331	0.176	6.40
1990	29.7	25	0.184	0.079	2.10
1991	28.3	40	0.138	0.062	1.90
1992	59.8	50	0.562	0.232	7.70
Geometric mean					**6.40**

Table 202. Summary of recent catch and effort data of American shad by the James River Adult Gill Net Survey.

Year	Effort (10^3m* days)	Duration of run (days)	Highest catch rate (female kg/m/day)	Mean catch rate (female kg/m/day)	Area under the catch curve
1998	4.6	50	0.198	0.051	2.57
1999	6.0	66	0.183	0.042	2.99
2000	7.1	70	0.279	0.086	6.61
2001	7.3	78	0.285	0.064	5.01
2002	6.5	71	0.205	0.054	5.62
2003	6.6	79	0.284	0.112	9.34
2004	5.9	78	0.234	0.090	7.41
2005	5.6	72	0.357	0.099	7.16
2006	4.6	54	0.078	0.032	1.74
2007	5.7	58	0.159	0.068	4.45
2008	5.2	58	0.069	0.025	1.51
2009	6.6	55	0.130	0.035	2.69
2010	6.9	57	0.513	0.082	6.90
2011	6.2	78	0.357	0.091	9.00
2012	5.1	72	0.294	0.076	6.06
2013	6.6	74	0.222	0.056	4.48
2014	5.1	60	0.251	0.113	7.35
2015	2.1	49	0.057	0.023	1.25
2016	2.5	56	0.032	0.015	0.96
2017	2.9	55	0.097	0.051	3.83
Geometric mean					**4.03**

Table 203. VIMS James River Adult Gill Net Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
1998	16	0.94	16.00	0.17
1999	22	0.95	14.76	0.15
2000	26	0.85	34.94	0.15
2001	27	0.85	25.02	0.14
2002	24	0.92	29.07	0.12
2003	24	0.96	51.52	0.14
2004	22	0.95	43.48	0.13
2005	21	0.95	38.99	0.17
2006	17	0.88	10.07	0.18
2007	21	0.86	22.15	0.13
2008	19	0.79	7.49	0.19
2009	24	0.83	14.30	0.19
2010	24	0.75	29.62	0.19
2011	23	0.96	45.40	0.13
2012	19	0.84	36.91	0.20
2013	24	0.92	24.30	0.16
2014	19	0.95	44.51	0.16
2015	8	0.88	9.92	0.26
2016	9	0.78	7.67	0.40
2017	11	0.82	20.51	0.17

Table 204. Female American shad average catch-at-age from the James River Adult Gill Net Survey. Ages in 1998 based on otoliths, all others based on scales.

Age	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Av.
2																					
3	2		15	2	1	2		2		4			1	2							**3.4**
4	56	19	127	77	12	52	33	21	29	61	4	19	57	47	39	38	16	1			**39.3**
5	58	75	142	102	97	225	176	127	49	91	32	66	178	167	100	93	138	11	5	22	**97.7**
6	7	33	31	37	95	116	82	110	5	38	19	41	126	99	53	62	105	16	14	43	**56.6**
7	3	4	3	16	44	34	27	34	2	7	3	14	27	22	12	14	43	3	6	10	**16.4**
8	1	2	2	4	17	12	14	15	1	1	2		4	6	2	6	12	2	2	2	**5.6**
9						2	5	3			1		3			1	7				**3.1**
10					1.0	1.0				2.0	1.0										**1.3**
11					1.0																**1.0**
12																					
13																					

Table 205. Female American shad average length by age (mm FL) from the James River Adult Gill Net Survey. Ages in 1998 based on otoliths, all others based on scales.

AGE	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Av.
2																					
3	465.0		460.7	444.0	449.0	459.5		481.5		453.5			448.0	464.0							**458.4**
4	468.6	490.6	476.8	483.4	488.3	483.2	478.3	487.7	466.0	473.7	447.5	456.6	468.8	470.1	479.2	501.6	490.9	481.0			**477.4**
5	494.2	506.0	494.1	500.8	499.5	506.3	497.4	501.1	488.3	481.4	494.2	480.8	480.5	486.1	484.9	499.8	516.1	492.5	485.2	496.2	**494.3**
6	520.6	516.3	509.6	526.2	503.9	525.2	524.9	516.2	524.6	494.8	495.4	491.0	492.6	490.5	499.5	510.0	527.0	514.1	495.5	503.1	**509.0**
7	565.7	551.0	539.7	547.6	516.8	556.2	536.6	535.7	579.5	504.1	537.3	507.8	519.0	489.9	520.8	501.9	539.3	529.3	510.5	525.6	**530.7**
8	536.0	534.0	558.0	557.0	527.4	553.8	552.0	551.4	550.0	562.0	546.5		545.5	530.3	521.0	505.0	549.1	569.5	534.0	518.5	**542.2**
9						582.5	556.4	553.3			512.0		530.3			491.0	554.7				**540.0**
10					547.0	575.0				567.0	548.0										**559.3**
11					544.0																**544.0**
12																					
13																					

Table 206. Female American shad average weight by age (g) from the James River Adult Gill Net Survey. Ages in 1998 based on otoliths, all others based on scales.

Age	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Average
2																					
3	1154.7		1149.8	1083.7	790.8	1240.0		1147.5		1202.7			1114.5	1154.3							**1115.3**
4	1267.9	1277.7	1320.5	1270.7	1363.2	1389.8	1359.6	1346.4	1253.4	1318.0	1154.1	1189.5	1260.6	1316.2	1393.5	1459.5	1221.4	1259.1			**1301.2**
5	1450.3	1396.0	1476.4	1383.5	1533.4	1575.2	1518.6	1513.2	1400.6	1401.3	1481.0	1365.6	1364.6	1419.0	1444.7	1410.7	1390.8	1289.2	1247.6	1326.5	**1419.4**
6	1638.3	1438.8	1652.0	1590.9	1586.9	1764.7	1767.3	1628.9	1787.0	1562.2	1566.8	1458.1	1486.0	1457.6	1613.5	1462.6	1483.0	1370.1	1264.0	1396.4	**1548.8**
7	2097.3	1757.4	2060.8	1705.8	1697.5	2026.1	1877.5	1838.9	2551.1	1592.1	1884.4	1710.2	1764.3	1475.2	1786.9	1431.0	1582.3	1425.7	1383.8	1580.5	**1761.4**
8	2126.4	1434.1	2256.0	1485.2	1885.9	1951.0	1988.7	2056.6	1906.2	2151.0	2164.6		1930.8	1851.0	1632.0	1422.1	1679.2		1419.3	1753.4	**1838.5**
9						2476.7	1947.1	1927.5			1538.9		1518.3			1295.1	1784.2	1997.2			**1810.6**
10					2168.5	2158.7				1510.7	2268.5										**2026.6**
11					2148.1																**2148.1**
12																					
13																					

Table 207. Total numbers of hatchery-marked American shad taken from the James River Adult Gill Net Survey, 1998-2017. Ages are based on examination of scales. Hatchery production data courtesy of the Virginia Department of Game and Inland Fisheries (E. Brittle). NA = not aged.

Hatchery Year Class	Hatchery Production (millions)	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total	% Total
1992	0.05		1																			1	0.1
1993	0.5	7	2	1																		10	1.0
1994	1.6	7	3	9			1															20	1.9
1995	5.3			59	9	8	4	3														83	8.0
1996	5.8			53	62	43	10	4	1													173	16.7
1997	5.9			2	27	78	57	5	4		1											174	16.8
1998	10					13	52	17	13													95	9.2
1999	7.3						14	29	7													50	4.8
2000	8.9						1	5	9		1											16	1.5
2001	9.3								3	4	3											10	1.0
2002	8.4									4	20	7	2									33	3.2
2003	8.7										12	8	1	1	2							24	2.3
2004	6.6										2	3	2	13	4							24	2.3
2005	6.0												1	18	22	2	1					44	4.3
2006	7.0													11	35	5		3				54	5.2
2007	6.5														5	10	14	6				35	3.4
2008	6.2															4	19	13	2			38	3.7
2009	3.8																9	18	6			33	3.2
2010	3.7																	3	3	4	3	13	1.3
2011	2.4																			1	2	3	0.3
2012	5.4																				2	2	0.2
2013	4.8																						0.0
2014	3.3																						0.0
2015	3.5																						0.0
2016	1.01																						0.0
2017	1.88																						0.0
NA	--					12	3	5	3	1	9	2	2	11	15	7	9	16	1	1	2	99	9.6
Total	130.95	14	6	124	98	154	142	68	40	9	48	20	8	54	83	28	52	59	12	6	9	1034	100

Table 208. Number of fish with hatchery tags from rivers other than the James River detected in the James River Adult Gill Net Survey.

Year	Number	River of Release
1999	1	Patuxent River (Maryland)
2000	7	Pamunkey River (Virginia) and Juniata River (Pennsylvania)
2001	3	Pamunkey River, Juniata River, and the western branch of the Susquehanna River (Pennsylvania)
2002	4	2 = Pamunkey River, 2 = unknown tag
2003	0	
2004	0	
2005	3	tentatively Pamunkey River and Mattaponi River (Virginia)
2006	0	
2007	1	Pamunkey River (Virginia)
2008	1	Undetermined
2009	1	Chemung River (New York)
2010	2	Susquehanna River (Pennsylvania)
2011	0	
2012	0	
2013	0	
2014	0	
2015	0	
2016	0	
2017	0	

Table 209. Indices of abundance of juvenile American shad collected in beach seine surveys (1980-2017) on the James, Chickahominy and Rappahannock rivers. The index is the geometric mean catch per haul. Means are reported for five year increments for years 1980 – 1999. Abbreviations are: SD, standard deviation; N, number of seine hauls.

Year	James	SD	N	Chickahominy	SD	N	Rappahannock	SD	N
1980 - 84	0.08	0.36	18	0		5	0.32	2.77	4
1985 - 89	0.01	0.22	34	0		8	0.16	0.49	16
1990 - 94	0.01	0.16	62	0		10	0.08	0.35	32
1995 - 99	0.01	0.11	65	0		10	0.17	0.46	33
2000	0		70	0		10	0.08	0.25	34
2001	0		70	0		10	0.34	0.43	35
2002	0		69	0		10	0		35
2003	0.10	0.30	70	0		10	0.59	0.66	28
2004	0.05	0.20	67	0		10	0.81	0.94	35
2005	0		66	0		10	0.27	0.66	33
2006	0.21	0.44	64	0.23	0.34	10	0.11	0.30	34
2007	0.04	0.26	65	0		10	0.40	0.50	34
2008	0.01	0.09	64	0		10	0.02	0.12	35
2009	0.02	0.12	65	0.07	0.22	10	0.13	0.36	34
2010	0.02	0.12	65	0		10	1.19	1.17	33
2011	0.15	0.39	59	0		10	1.15	1.05	27
2012	0.01	0.09	57	0		10	0.19	0.42	35
2013	0		65	0		10	0.35	0.61	35
2014	0.07	0.24	55	0.15	0.29	10	3.79	1.55	35
2015	0.25	0.57	59	0.56	0.94	10	4.19	1.52	28
2016	0.01	0.09	65	0		10	4.17	1.63	35
2017	0		65	0		10	0.87	1.27	35

Table 210. VIMS James River Juvenile Seine Survey number of observations (n), index values (numbers), and CVs.

Year	n	Index	CV	Year	n	Index	CV
1980	18	0.04	4.08	1999	69	0.00	NA
1981	38	0.19	2.83	2000	70	0.00	NA
1982	24	0.00	NA	2001	70	0.00	NA
1983	24	0.00	NA	2002	69	0.00	NA
1984	24	0.03	4.72	2003	70	0.10	3.03
1985	32	0.00	NA	2004	67	0.05	3.89
1986	32	0.06	3.77	2005	66	0.00	NA
1987	32	0.00	NA	2006	64	0.21	2.10
1988	40	0.00	NA	2007	65	0.04	6.37
1989	65	0.00	NA	2008	64	0.01	8.66
1990	65	0.00	NA	2009	65	0.02	6.03
1991	65	0.00	NA	2010	65	0.02	6.03
1992	65	0.00	NA	2011	64	0.14	2.69
1993	65	0.00	NA	2012	62	0.05	4.04
1994	63	0.03	5.42	2013	65	0.00	NA
1995	63	0.01	8.73	2014	65	0.08	3.11
1996	64	0.00	NA	2015	65	0.25	2.20
1997	65	0.00	NA	2016	65	0.01	8.60
1998	64	0.02	6.08	2017	65	0.00	NA

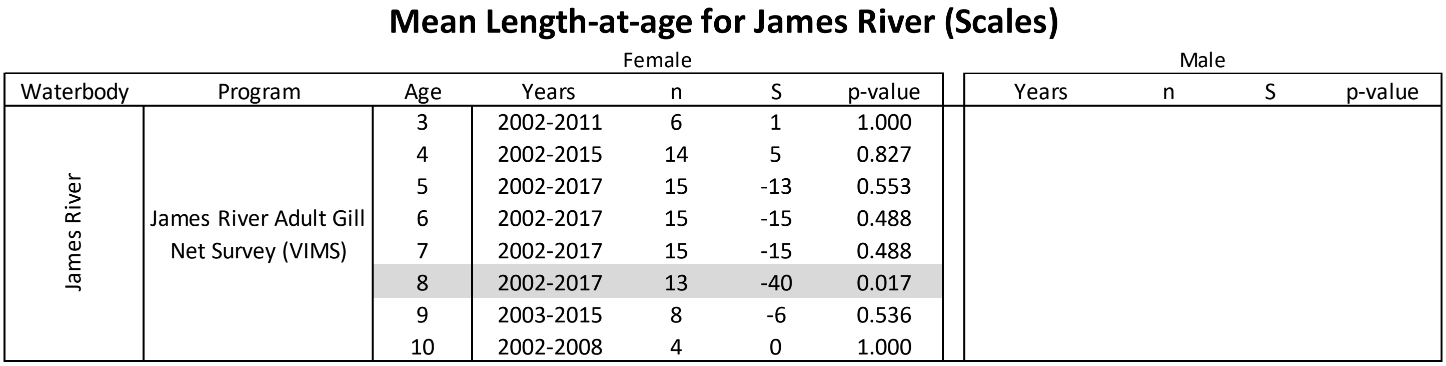
Table 211. VDGIF James River Boat Electrofishing Survey number of observations (n), index values (numbers), and CVs.

Year	n	Index	CV
2000	9	0.79	0.18
2001	6	1.14	0.19
2002	73	2.25	0.25
2003	90	4.13	0.17
2004	59	1.42	0.20
2005	68	1.06	0.18
2006	58	1.46	0.23
2007	43	1.26	0.41
2008	71	1.63	0.09
2009	82	3.36	0.12
2010	89	1.79	0.13
2011	84	3.43	0.13
2012	76	1.58	0.15
2013	120	3.32	0.14
2014	115	2.81	0.17
2015	94	2.07	0.16
2016	93	1.22	0.16
2017	94	1.26	0.13

Table 212. Counts and CPUE (#/hour) of American shad through the fishway at Bosher's Dam on the James River.

Year	AMS Passed	Day Hrs Viewed (0600-2100)	#/hr
1999	14	117	0.12
2000	133	499	0.27
2001	410	744	0.55
2002	751	1026	0.73
2003	182	627	0.29
2004	79	989	0.08
2005	46	798	0.06
2006	84	1039	0.08
2007	37	862	0.04
2008	62	829	0.07
2009	100	659	0.15
2010	116	741	0.16
2011	696	669	1.04
2012	184	622	0.30
2013	176	330	0.53
2014	24	943	0.03
2015	68	1159	0.06
2016	36	1187	0.03
2017	44	1353	0.03

Table 213. Mann-Kendall results for mean length-at-age over time for female American shad in the James River.



Mean Length-at-age for James River (Scales)

		Female					Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
James River	James River Adult Gill Net Survey (VIMS)	3	2002-2011	6	1	1.000				
		4	2002-2015	14	5	0.827				
		5	2002-2017	15	-13	0.553				
		6	2002-2017	15	-15	0.488				
		7	2002-2017	15	-15	0.488				
		8	2002-2017	13	-40	0.017				
		9	2003-2015	8	-6	0.536				
		10	2002-2008	4	0	1.000				

Table 214. Commercial harvest seasons for American shad 2012-2019.

System	**2012***	**2013**	**2014-2019**
Albemarle Sound Roanoke River	2/1 - 4/14	2/15 - 4/14	3/3 - 3/24
Tar-Pamlico	2/1 - 4/14	2/15 - 4/14	2/15 - 4/14
Neuse	2/1 - 4/14	2/15 - 4/14	2/15 - 4/14
Cape Fear	2/1 - 4/14	2/20 - 4/11	2/20 - 4/11
All Other Areas	2/1 – 4/14	2/15 – 4/14	2/15 – 4/14

*last year prior to SFMP implementation

Table 215. Recreational creel restrictions for American shad 2012-2019. All numbers represent limits within an overall 10-fish aggregate creel limit for American and Hickory Shad combined.

System	**2012***	**2013**	**2014-2019**
Albemarle Sound (AS) Roanoke River (RR)	AS-10-fish RR-1-fish	AS-10-fish IW AS-1-fish CJW RR-1-fish	AS-10-fish IW** AS-1-fish CJW RR-1-fish
Tar-Pamlico	10-fish	10-fish	10-fish
Neuse	1-fish IW 10-fish CJW	1-fish	1-fish
Cape Fear	10-fish	5-fish	5-fish
All Other Areas	10-fish	10-fish	10-fish

*last year prior to SFMP implementation; IW=Inland Waters; CJW = Coastal and Joint Waters, blank=all waters

** AS-IW changed to 1 fish in 2019, to correct inconsistency.

Table 216. Roanoke River American Shad Restoration Program broodfish totals from multiple source rivers, 1998–2017. Use of hormone injection to induce spawning is also included.

	Broodfish Source River							
Year	Roanoke	Meherrin	Nottoway	Tar	Neuse	Cape Fear	Total	Hormone Injection
1998		1,332		613			1,945	Yes
1999		308		451			759	Yes
2000		274		476	88		838	Yes
2001		47		513	99		659	Yes
2002				406	33		439	Yes
2003	58			716	61		835	Yes
2004	55		60	569		683	1,367	Yes
2005				565		428	993	Yes
2006	51			370	170	371	962	Yes
2007		36		382	263	366	1,047	Yes
2008				482	128	411	1,021	Yes
2009	74			514	149	355	1,092	No
2010	149			309		236	694	No
2011	384						384	No
2012	303						303	No
2013	399						399	No
2014	408						408	No
2015	367						367	No
2016	314						314	No
2017	368						368	No
Total	2,930	1,997	60	6,366	991	2,850	15,194	

Table 217. American shad fry stocked into the Roanoke River Basin from 1998–2017.Stockings downstream of the lower-most dam occur at Weldon, NC, stockings upstream of John H. Kerr Dam occur at either Altavista or Clover Landing, VA, stockings upstream of Gaston Dam occur at Bracey, VA, and stockings upstream of Roanoke Rapids Dam occur at Roanoke Rapids, NC. Hatchery evaluation techniques have transitioned from Oxytetracycline (OTC) marks to parentage-based tagging (PBT) methods using genetic microsatellite markers.

		Fry Totals (millions) by Stocking Location					
Year	Total Fry Stocked (millions)	Weldon, NC	Altavista, VA	Clover Landing, VA	Bracey, VA	Roanoke Rapids, NC	Hatchery Evaluation Technique
1998	0.5	0.5	-	-	-	-	OTC
1999	0.3	0.3	-	-	-	-	OTC
2000	0.8	0.8	-	-	-	-	OTC
2001	2.1	2.1	-	-	-	-	OTC
2002	0.8	0.8	-	-	-	-	OTC
2003	2.3	1.2	1.1	-	-	-	OTC
2004	2.3	1.2	1.1	-	-	-	OTC
2005	2.5	1.3	1.2	-	-	-	OTC
2006	2.4	1.4	1.0	-	-	-	OTC
2007	4.3	2.2	2.1	-	-	-	OTC
2008	8.2	4.3	3.9	-	-	-	OTC
2009	8.6	4.5	4.1	-	-	-	OTC
2010	7.8	6.9	0.9	-	-	-	OTC/PBT
2011	4.4	4.0	-	0.4	-	-	OTC/PBT
2012	4.8	3.8	-	1.0	-	-	OTC/PBT
2013	4.5	2.4	-	1.3	0.8	-	PBT
2014	7.5	3.5	-	1.4	2.6	-	PBT
2015	4.8	2.6	-	0.8	1.5	-	PBT
2016	3.8	1.3	-	-	2.5	2.5	PBT
2017	2.7	0.3	-	-	-	2.5	PBT
Total	75.4	45.3	15.4	4.9	7.4	2.5	

Table 218. Albemarle Sound Commercial CPUE number of observations (n) and index values (weight).

Year	n	Index
1994	2,135	23.28
1995	1,829	33.27
1996	2,143	30.78
1997	2,586	24.65
1998	2,839	59.33
1999	2,850	24.59
2000	3,196	40.55
2001	3,492	27.21
2002	2,722	64.33
2003	2,937	95.57
2004	2,526	71.88
2005	2,350	53.99
2006	2,317	52.55
2007	2,343	90.18
2008	1,447	55.20
2009	1,609	73.35
2010	2,666	69.35
2011	2,097	76.34
2012	2,318	76.77
2013	2,096	93.77
2014	758	144.13
2015	891	71.44
2016	634	64.31
2017	668	93.84

Table 219. NCDMF Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
1996	60	0.00	0.00	NA
1997	84	0.08	0.58	0.49
1998	87	0.01	0.11	0.63
1999	85	0.05	0.17	0.53
2000	92	0.13	2.31	0.52
2001	93	0.09	0.42	0.48
2002	99	0.25	1.68	0.43
2003	70	0.40	7.06	0.55
2004	73	0.25	1.13	0.51
2005	99	0.24	2.04	0.39
2006	106	0.09	0.32	0.47
2007	102	0.02	0.02	1.31
2008	295	0.12	0.30	0.26
2009	167	0.12	0.72	0.31
2010	167	0.08	0.61	0.39
2011	156	0.19	1.31	0.34
2012	156	0.12	0.39	0.35
2013	157	0.17	0.61	0.35
2014	167	0.29	2.15	0.34
2015	152	0.24	2.79	0.37
2016	147	0.16	19.78	0.43
2017	166	0.17	1.16	0.36

Table 220. NCDMF Albemarle Sound Independent Gill Net Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
1993	2,252	0.48	0.0015	0.12
1994	1,954	0.59	0.0012	0.09
1995	2,128	0.63	0.0018	0.11
1996	2,064	0.59	0.0019	0.10
1997	2,160	0.54	0.0028	0.14
1998	2,110	0.55	0.0020	0.13
1999	2,235	0.53	0.0021	0.12
2000	2,138	0.54	0.0026	0.13
2001	2,026	0.53	0.0025	0.11
2002	2,064	0.56	0.0039	0.10
2003	2,352	0.56	0.0022	0.11
2004	2,159	0.48	0.0015	0.11
2005	2,038	0.56	0.0017	0.14
2006	1,959	0.66	0.0030	0.09
2007	1,990	0.63	0.0020	0.10
2008	1,923	0.82	0.0069	0.08
2009	1,621	0.70	0.0029	0.10
2010	1,532	0.55	0.0015	0.09
2011	1,517	0.74	0.0034	0.08
2012	1,152	0.73	0.0044	0.11
2013	1,428	0.72	0.0054	0.10
2014	1,410	0.59	0.0031	0.14
2015	1,824	0.68	0.0029	0.14
2016	1,829	0.66	0.0033	0.11
2017	1,655	0.58	0.0026	0.12

Table 221. NCWRC Roanoke River Adult Spawning Area Electrofishing Survey number of observations (n), index values (numbers), and CVs.

Year	n	Index	CV
2001	9	11.90	0.21
2002	26	18.87	0.92
2003	28	8.38	0.24
2004	7	9.20	0.19
2005	15	14.17	0.19
2006	14	22.24	0.36
2007	12	18.61	0.17
2008	17	22.51	0.12
2009	17	24.83	0.15
2010	23	9.97	0.16
2011	28	15.93	0.16
2012	28	35.46	0.18
2013	61	18.64	0.10
2014	83	15.96	0.11
2015	65	6.11	0.13
2016	89	3.11	0.13
2017	75	11.26	0.17

Table 222. Number of parameters and likelihood components from the final Albemarle Sound ASAP model.

Run58	Value
N_parameters	56
total	1745.2
catch.total	-40.2
discard.total	0
index.fit.total	-3.7
index.fit.ind01	-4.9
index.fit.ind02	11.8
index.fit.ind03	-10.5
catch.age.comp	639.3
discards.age.comp	0
index.age.comp	1149.7
sel.param.total	0
index.sel.param.t	0
q.year1	0
q.devs	0
Fmult.year1.total	0
Fmult.devs.total	0
N.year1	0
Recruit.devs	0
SR.steepness	0
SR.scaler	0
Fmult.Max.penalty	0
F.penalty	0

Table 223. Annual January-1 biomass (January-1 B, metric tons), spawning stock biomass (SSB, metric tons), exploitable biomass (Exploitable B, metric tons), and fully-recruited fishing mortality (F) estimates from the final Albemarle Sound ASAP model.

	January 1 B	SSB	Exploitable B	F
2000	701	25	34	2.856
2001	691	37	47	1.369
2002	709	44	72	1.855
2003	746	36	73	3.959
2004	786	27	50	3.328
2005	847	28	45	2.149
2006	867	37	52	1.616
2007	857	47	67	2.534
2008	864	55	67	0.807
2009	931	63	87	1.028
2010	908	54	89	1.754
2011	812	46	73	1.66
2012	733	55	78	1.545
2013	656	58	89	1.597
2014	589	50	84	0.99
2015	566	45	75	0.598
2016	767	47	73	0.353
2017	2472	49	84	0.484

Table 224. Abundance-at-age estimates (thousands of fish) from the final Albemarle Sound ASAP model.

	0	1	2	3	4	5	6	7	8
2000	720.41	448.93	362.05	240.5	146.1	86.42	20.24	1.53	0
2001	1085.14	450.22	280.46	225.78	148.61	86.15	40.9	4.46	0.1
2002	1220.75	678.19	281.33	175.1	140.34	90.33	47.12	15.51	0.98
2003	1313.06	762.93	423.75	175.58	108.63	84.46	47.12	14.97	2.38
2004	1025.99	820.57	476.55	264.03	108.01	62.64	35.9	6.95	0.46
2005	794.21	641.18	512.6	297.07	162.83	63.08	28.31	6.66	0.33
2006	961.32	496.35	400.61	319.84	184.08	97.42	31.98	8.08	0.8
2007	1573.64	600.8	310.14	250.07	198.61	111.33	52.02	11.08	1.53
2008	1046.66	983.46	375.36	193.46	154.71	117.89	54.36	12.9	1.04
2009	639.66	654.15	614.59	234.45	120.52	95.12	68.11	25.31	4.59
2010	645.36	399.78	408.78	383.81	145.93	73.77	53.79	29.26	8.12
2011	738.38	403.33	249.8	255.14	238.2	88.01	38.87	17.73	5.54
2012	545.91	461.47	252.02	155.92	158.41	143.93	46.79	13.26	3.7
2013	711.35	341.18	288.35	157.32	96.85	95.94	77.39	16.64	2.98
2014	547.3	444.58	213.19	180	97.7	58.6	51.32	27.01	3.37
2015	2210.68	342.05	277.82	133.14	112.05	59.84	33.26	22.35	8.58
2016	18805.84	1381.66	213.76	173.56	83.01	69.19	35.29	16.71	11.71
2017	1126.67	11753.57	863.49	133.57	108.32	51.51	41.78	19.39	13.07

Table 225. Age-specific fishery and IGNS selectivity estimates from the final Albemarle Sound ASAP model.

	fishery	IGNS
0	0	0
1	0	0
2	0	0.005
3	0.004	0.044
4	0.02	0.16
5	0.097	0.371
6	0.365	0.62
7	0.78	1
8	1	1

Table 226. Fishing mortality-at-age estimates from the final Albemarle Sound ASAP model.

	0	1	2	3	4	5	6	7	8
2000	0	0	0	0.011	0.058	0.278	1.042	2.227	2.856
2001	0	0	0	0.005	0.028	0.133	0.499	1.067	1.369
2002	0	0	0	0.007	0.038	0.181	0.677	1.446	1.855
2003	0	0	0	0.016	0.081	0.386	1.445	3.087	3.959
2004	0	0	0	0.013	0.068	0.324	1.214	2.595	3.328
2005	0	0	0	0.009	0.044	0.209	0.784	1.675	2.149
2006	0	0	0	0.006	0.033	0.157	0.59	1.26	1.616
2007	0	0	0	0.01	0.052	0.247	0.924	1.976	2.534
2008	0	0	0	0.003	0.016	0.079	0.294	0.629	0.807
2009	0	0	0	0.004	0.021	0.1	0.375	0.801	1.028
2010	0	0	0	0.007	0.036	0.171	0.64	1.367	1.754
2011	0	0	0	0.007	0.034	0.162	0.606	1.294	1.66
2012	0	0	0	0.006	0.031	0.15	0.564	1.205	1.545
2013	0	0	0	0.006	0.033	0.156	0.583	1.245	1.597
2014	0	0	0	0.004	0.02	0.096	0.361	0.772	0.99
2015	0	0	0	0.002	0.012	0.058	0.218	0.466	0.598
2016	0	0	0	0.001	0.007	0.034	0.129	0.275	0.353
2017	0	0	0	0.002	0.01	0.047	0.177	0.377	0.484

Table 227. Mann-Kendall results for mean length-at-age over time for the Albemarle Sound (scales).

Mean Length-at-age for Albemarle Sound (Scales)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Albemarle Sound	Albemarle Sound Commercial Fishery Moinitoring	3	1982-2006	5	-4	0.462	1972-2014	18	-31	0.256
		4	1972-2014	29	-115	0.032	1972-2014	36	-332	0.000
		5	1972-2017	40	-470	0.000	1972-2014	36	-254	0.001
		6	1970-2017	41	-484	0.000	1972-2014	35	-211	0.003
		7	1970-2017	41	-438	0.000	1972-2014	33	-213	0.001
		8	1970-2017	35	-193	0.006	1972-2014	19	-29	0.327
		9	1970-2017	17	-6	0.837	1979-2014	3	-3	1.000
	Albemarle Sound Independent Gill Net Survey	3	2004-2017	7	-13	0.072	2004-2017	10	-1	1.000
		4	2004-2017	12	-35	0.019	2004-2017	12	-32	0.034
		5	2004-2017	12	-24	0.115	2004-2017	12	-16	0.304
		6	2004-2017	12	-20	0.193	2007-2017	10	17	0.152
		7	2004-2017	12	-30	0.047	2004-2017	10	-1	1.000
		8	2004-2017	10	-29	0.012				
Roanoke River	Roanoke River Adult Spawning Area Electrofishing Survey	3					2002-2010	9	6	0.602
		4					2000-2010	11	19	0.161
		5					2000-2010	11	17	0.213
		6					2000-2010	10	18	0.127
		7					2000-2004	5	10	0.027
		8					2000-2002	3	3	1.000

Table 228. American shad fry stocked into the Neuse River Basin at NC Highway 117 bridge near Goldsboro and juvenile hatchery contribution based on parentage-based tagging analysis, 2012–2017.

Year	Fry Stocked	Out-migrating Juvenile Hatchery Contribution
2012	573,582	2%
2013	1,184,303	6%
2014	1,377,375	13%
2015	708,045	1%
2016	609,720	0%*
2017	440,161	--
Total	4,893,186	

*Sample size only 7 fish

Table 229. Tar-Pamlico Commercial CPUE number of observations (n) and index values (weight).

Year	n	Index
1994	347	11.64
1995	359	26.67
1996	316	27.94
1997	320	30.72
1998	304	40.61
1999	299	23.48
2000	471	35.59
2001	415	20.80
2002	398	39.37
2003	456	41.60
2004	459	37.56
2005	484	30.35
2006	294	23.49
2007	359	52.75
2008	204	37.76
2009	385	29.47
2010	223	30.84
2011	180	27.41
2012	329	39.46
2013	260	37.60
2014	228	33.08
2015	237	14.43
2016	99	7.73
2017	225	19.63

Table 230. Mean length-at-age for the Tar-Pamlico River from scales and Mann-Kendall results.

Mean Length-at-age for Tar-Pamlico River (Scales)

		Female					Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Tar River	Tar River Adult Spawning Area Electrofishing Survey	2					2001-2008	4	4	0.308
		3					2000-2010	11	1	1.000
		4	2000-2010	11	3	0.876	2000-2010	11	-1	1.000
		5	2000-2010	11	1	1.000	2000-2010	11	3	0.876
		6	2000-2010	10	-11	0.371	2000-2007	7	3	0.764
		7	2000-2009	6	5	0.452	2004-2007	4	2	0.734
Tar-Pamlico River	Tar-Pamlico Commercial Fishery Moinitoring	3	2003-2005	3	1	1.000				
		4	1975-2012	17	-12	0.650				
		5	1975-2017	27	-199	0.000				
		6	1975-2017	27	-199	0.000				
		7	1975-2017	27	-173	0.000				
		8	2002-2017	14	-7	0.742				
		9	2008-2013	3	-3	1.000				

Table 231. Neuse River Commercial CPUE number of observations (n) and index values (weight).

Year	n	Index
1994	426	16.94
1995	380	40.29
1996	486	50.29
1997	443	38.72
1998	243	48.21
1999	320	24.12
2000	258	35.74
2001	304	35.11
2002	548	73.31
2003	479	75.38
2004	446	75.42
2005	511	47.49
2006	541	64.53
2007	425	72.34
2008	324	33.30
2009	287	41.86
2010	263	41.07
2011	286	53.31
2012	300	79.94
2013	314	54.66
2014	189	60.10
2015	177	16.89
2016	131	19.00
2017	286	39.91

Table 232. NCWRC Neuse River Adult Spawning Area Electrofishing Survey number of observations (n), index values (numbers), and CVs.

Year	n	Index	CV
2000	28	10.33	0.24
2001	23	20.21	0.23
2002	29	10.99	0.22
2003	47	19.39	0.16
2004	17	14.52	0.29
2005	27	10.37	0.15
2006	17	6.28	0.35
2007	33	10.36	0.17
2008	34	11.71	0.14
2009	36	7.63	0.20
2010	31	10.97	0.15
2011	25	12.95	0.16
2012	36	14.93	0.13
2013	31	28.45	0.14
2014	37	13.74	0.15
2015	36	7.02	0.17
2016	35	15.56	0.15
2017	33	23.95	0.14

Table 233. Mean length-at-age for the Neuse River from scales and Mann-Kendall results.

Mean Length-at-age for Neuse River (Scales)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Neuse River	Neuse River Commercial Fishery Moinitoring	3					1977-2006	5	4	0.462
		4	1977-2014	18	-43	0.112	1977-2006	10	-9	0.474
		5	1977-2017	27	-167	0.001	1977-2006	10	-5	0.721
		6	1977-2017	27	-211	0.000	1977-2003	9	8	0.466
		7	1977-2017	25	-165	0.000	1977-2003	4	-4	0.308
		8	1988-2017	16	-40	0.079				

Table 234. Cape Fear River Commercial CPUE number of observations (n) and index values (weight).

Year	n	Index
1994	207	52.52
1995	154	72.80
1996	323	83.03
1997	260	59.94
1998	148	75.29
1999	153	44.48
2000	150	73.98
2001	157	80.13
2002	181	105.99
2003	263	131.33
2004	285	100.94
2005	256	67.62
2006	243	66.38
2007	326	90.34
2008	232	68.58
2009	217	87.68
2010	255	93.01
2011	270	83.32
2012	134	77.17
2013	192	129.62
2014	233	198.06
2015	173	144.73
2016	121	106.92
2017	91	121.42

Table 235. NCWRC Cape Fear River Adult Spawning Area Electrofishing Survey number of observations (n), index values (numbers), and CVs.

Year	n	Index	CV
2001	6	31.43	0.39
2002	10	89.92	0.28
2003	11	21.56	0.28
2004	12	41.30	0.19
2005	17	17.29	0.27
2006	21	6.56	0.18
2007	26	14.31	0.78
2008	24	7.60	0.33
2009	12	11.67	0.19
2010	18	8.19	0.13
2011	24	9.05	0.12
2012	23	17.19	0.28
2013	26	30.46	0.21
2014	42	44.49	0.22
2015	38	31.17	0.16
2016	38	31.78	0.16
2017	37	19.71	0.26

Table 236. Mean length-at-age for the Cape Fear River from scales and Mann-Kendall results.

Mean Length-at-age for Cape Fear River (Scales)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Cape Fear River	Cape Fear River Commercial Fishery Moinitoring	3	2004-2008	4	-4	0.308				
		4	1984-2016	18	-38	0.161				
		5	1984-2017	20	-104	0.001				
		6	1984-2017	20	-112	0.000				
		7	1984-2017	17	-66	0.007				
		8	2003-2017	15	-37	0.075				
	Cape Fear River Adult Spawning Area Electrofishing Survey	3					2001-2010	10	-7	0.592
		4					2001-2010	10	3	0.858
		5					2001-2010	10	3	0.858
		6					2001-2009	8	6	0.536
		7					2001-2005	4	6	0.089

Table 237. Commercial CPUE (kg/trip) for Winyah Bay System (Winyah Bay, Black, Pee Dee, and Waccamaw Rivers combined to preserve confidentiality).

Year	Landings (kg)	Trips	CPUE (kg/trip)
1999	8,871	468	18.95
2000	37,254	778	47.88
2001	57,168	888	64.38
2002	96,387	934	103.20
2003	90,085	994	90.63
2004	77,845	1040	74.85
2005	32,728	998	32.79
2006	42,434	689	61.59
2007	25,121	659	38.12
2008	97,404	988	98.59
2009	40,374	814	49.60
2010	37,517	867	43.27
2011	40,938	873	46.89
2012	51,725	989	52.30
2013	33,147	690	48.04
2014	44,344	498	89.04
2015	31,498	460	68.47
2016	9,017	409	22.05
2017	34,271	512	66.93

Table 238. Black River Commercial CPUE index values (weight from set nets only) and CVs.

Year	Index	CV
2001	1.13	1.27
2002	0.94	1.48
2003	0.42	0.93
2004	0.28	1.50
2005	0.72	3.41
2006	0.21	1.49
2007	0.28	2.96
2008	0.39	1.04
2009	4.08	NA
2010	0.45	0.87
2011	0.52	1.22
2012	1.80	0.47
2013	1.12	0.28
2014	1.13	0.20
2015	0.89	0.49
2016	1.18	0.40
2017	1.45	0.33

Table 239. Great Pee Dee River Commercial CPUE index values (weight from set nets only) and CVs.

Year	Index	CV
2001	1.16	1.50
2002	1.80	1.63
2003	2.05	1.74
2004	0.68	1.22
2005	0.46	2.48
2006	0.85	1.95
2007	0.61	1.85
2008	1.57	1.49
2009	0.88	1.59
2010	0.47	2.46
2011	0.83	5.06
2012	1.19	1.91
2013	1.05	1.50
2014	1.53	1.59
2015	0.81	1.50
2016	0.44	2.26
2017	0.62	1.56

Table 240. Waccamaw River Commercial CPUE index values (weight from set nets only) and CVs.

Year	Index	CV
2001	3.88	0.62
2002	1.98	0.78
2003	0.67	1.21
2004	1.45	3.94
2005	0.04	1.16
2006	1.43	1.92
2007	0.28	NA
2008	1.08	1.24
2009	0.33	0.81
2010	0.33	1.38
2012	0.80	0.48
2013	0.53	0.59
2014	1.14	0.76
2015	0.12	0.20
2016	0.53	1.01
2017	1.42	0.57

Table 241. Mean length-at-age for the Winyah Bay scales and Mann-Kendall results.

Mean Length-at-age for Winyah Bay (Scales)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Waccamaw River	Waccamaw River Commercial Fishery Monitoring	3	2003-2014	6	1	1.000				
		4	1979-2014	14	15	0.443				
		5	1979-2014	13	-28	0.100				
		6	1979-1985	7	3	0.764				
		7	1982-1985	4	2	0.734				

Table 242. Commercial total catch and effort for the Santee River.

Year	Landings (kg)	Trips
1999	69,865	850
2000	174,468	903
2001	83,090	727
2002	113,625	676
2003	74,220	538
2004	85,483	696
2005	53,788	577
2006	78,622	466
2007	61,339	490
2008	52,718	607
2009	61,431	712
2010	86,092	846
2011	126,521	797
2012	77,102	667
2013	65,325	441
2014	101,998	464
2015	82,760	583
2016	23,324	370
2017	46,265	366

Table 243. Santee River Commercial CPUE index values (weight from set nets only) and CVs.

Year	Index	CV
2001	1.14	1.31
2002	1.29	2.10
2003	1.66	1.37
2004	0.78	2.60
2005	0.67	1.29
2006	1.13	2.28
2007	0.82	0.97
2008	0.74	2.19
2009	0.79	1.77
2010	1.93	1.58
2011	0.77	1.14
2012	0.86	1.53
2013	1.04	2.04
2014	1.56	4.99
2015	0.86	1.68
2016	0.33	1.73
2017	0.65	1.68

Table 244. **Annual total number of American shad passed at St. Stephens Fish Lock from 1986 to 2018. Counts make by hydroacoustic gear (1986 and 1987), real time counts (1988 to 1994), and counts from video recordings (1995 to 2018).**

Year	American Shad
1988	10,000
1989	27,000
1990	81,000
1991	176,000
1992	147,000
1993	159,000
1994	212,000
1995	445,000
1996	477,047
1997	387,755
1998	543,681
1999	306,493
2000	592,321
2001	165,875
2002	140,398
2003	298,902
2004	145,201
2005	215,428
2006	283,225
2007	328,828
2008	29,002
2009	389,197
2010	346,879
2011	272,961
2012	150,082
2013	336,728
2014	42,525
2015	85,417
2016	41,375
2017	46,522
2018	320,092

Table 245. Cooper River Recreational Creel Survey summary results, 2000 to 2016. Results include summarized details of survey effort and catch.

Year	Start Date	End Date	N Surveys	Catch Surveyed	Catch Estimated
2000	1-Mar	7-Apr	263	2,701	3,661
2001	28-Feb	13-Apr	251	2,212	2,829
2002	28-Feb	5-Apr	303	2,050	3,037
2003	19-Feb	6-Apr	425	3,421	5,101
2004	16-Feb	15-Apr	285	2,128	8,228
2005	21-Feb	15-Apr	598	6,757	14,629
2006	27-Feb	8-Apr	185	954	2,767
2007	27-Feb	6-Apr	125	815	3,750
2008	26-Feb	18-Apr	420	5,519	8,429
2009	9-Feb	15-Apr	1251	5,264	5,351
2010	1-Feb	30-Apr	1354	4,119	4,508
2011	1-Feb	29-Apr	794	2,083	2,158
2012	28-Jan	1-Apr	1135	3,855	7,965
2013	10-Jan	11-Apr	1187	4,244	10,938
2014	14-Jan	19-Apr	932	9,216	16,626
2015	21-Jan	8-Apr	807	6,379	11,537
2016	27-Jan	11-Apr	828	5,119	9,642
Average			655	3,554	6,438

Table 246. Cooper River Recreational Creel Survey index values (numbers) and CVs.

Year	Index	CV
2000	0.62	0.06
2001	0.66	0.09
2002	0.59	0.07
2003	1.01	0.06
2004	0.96	0.07
2005	1.60	0.07
2006	0.60	0.10
2007	0.70	0.10
2008	1.47	0.01
2009	1.24	0.04
2010	0.83	0.05
2011	0.81	0.07
2012	2.12	0.03
2013	2.86	0.02
2014	2.57	0.03
2015	2.70	0.03
2016	2.31	0.03

Table 247. Santee River Adult Gill Net Survey index values (numbers) and CVs.

Year	Index	CV
2008	8.92	0.20
2009	13.42	0.13
2010	8.16	0.21
2011	9.22	0.16
2012	7.39	0.28
2013	11.48	0.29
2014	11.20	0.23
2015	8.45	0.21
2016	4.05	0.20
2017	9.56	0.27

Table 248. Mean length-at-age for the Santee-Cooper River and Mann-Kendall results.

Mean Length-at-age for Santee-Cooper River (Scales)

			Female				Male			
Waterbody	Program	Age	Years	n	S	p-value	Years	n	S	p-value
Santee River	Santee River Commercial Fishery Monitoring	3	2001-2017	9	8	0.466				
		4	1979-2017	16	36	0.115				
		5	1979-2017	16	-12	0.620				
		6	1979-1985	5	0	1.000				
		7	1981-1985	3	3	1.000				

Table 249. Commercial CPUE (kg/trip) for the ACE Basin (Edisto and Combahee Rivers combined to preserve confidentiality).

Year	Landings (kg)	Trips	CPUE (kg/trip)
1999	2,566	397	6.46
2000	4,000	814	4.91
2001	1,704	609	2.80
2002	2,435	515	4.73
2003	2,174	596	3.65
2004	3,186	464	6.87
2005	2,085	488	4.27
2006	1,883	512	3.68
2007	1,544	528	2.92
2008	622	405	1.54
2009	333	360	0.93
2010	1,032	251	4.11
2011	1,134	304	3.73
2012	1,241	376	3.30
2013	1,455	276	5.27
2014	1,632	235	6.94
2015	648	177	3.66
2016	491	198	2.48
2017	935	183	5.11

Table 250. Edisto River Commercial CPUE index values (weight from set nets only) and CVs.

Year	Index	CV
2001	0.54	2.75
2002	1.40	1.80
2003	0.68	3.37
2004	1.02	1.92
2005	0.52	1.63
2006	0.96	1.96
2007	0.90	1.59
2008	0.22	2.01
2009	0.40	2.76
2010	1.68	1.48
2011	0.95	1.30
2012	1.61	1.56
2013	1.42	1.57
2014	1.66	1.09
2015	0.78	1.40
2016	0.81	2.27
2017	1.45	1.36

Table 251. Savannah River Commercial CPUE (SCDNR) index values (weight from set nets only) and CVs.

Year	Index	CV
2001	0.64	0.77
2002	0.66	0.66
2003	1.49	0.54
2004	0.44	0.73
2005	0.91	0.68
2006	1.09	0.22
2007	0.64	0.73
2008	0.64	0.60
2009	0.64	0.44
2010	0.85	0.81
2011	1.19	0.76
2012	0.97	0.65
2013	1.89	0.58
2014	1.71	0.60
2015	1.26	0.55
2016	0.96	0.34
2017	1.02	0.50

Table 252. Savannah River Commercial CPUE (GADNR) number of observations (n), proportion positive observations, index values (weight), and CVs.

Year	n	Proportion Positive	Index	CV
2001	25	1.00	13.50	0.18
2002	48	1.00	11.04	0.10
2003	54	1.00	19.01	0.09
2004	87	1.00	12.57	0.10
2005	100	1.00	13.35	0.09
2006	104	1.00	16.02	0.06
2007	71	1.00	11.96	0.11
2008	72	1.00	9.22	0.09
2009	48	1.00	11.93	0.10
2010	36	1.00	9.60	0.12
2011	51	1.00	13.54	0.07
2012	32	1.00	6.80	0.13
2013	48	1.00	19.67	0.10
2014	27	1.00	13.57	0.22
2015	77	1.00	6.56	0.13
2016	40	1.00	4.36	0.19
2017	52	1.00	6.02	0.16

Table 253. Altamaha River Commercial CPUE number of observations (n), proportion positive observations, index values (weight), and CVs.

Year	n	Proportion Positive	Index	CV
2002	75	1.00	6.86	0.13
2003	40	1.00	6.47	0.14
2004	121	1.00	7.74	0.08
2005	273	1.00	8.58	0.05
2006	385	1.00	12.55	0.05
2007	289	1.00	9.95	0.05
2008	226	1.00	9.54	0.05
2009	269	1.00	9.31	0.04
2010	195	1.00	10.46	0.06
2011	174	1.00	12.19	0.06
2012	284	1.00	10.02	0.05
2013	253	1.00	14.10	0.06
2014	212	1.00	16.79	0.06
2015	229	1.00	9.11	0.07
2016	196	1.00	10.03	0.07
2017	243	1.00	8.60	0.08

Table 254. Altamaha River Tagging Survey index values (numbers).

Year	Index	Year	Index
1982	0.75	2000	1.75
1983	1.30	2001	1.09
1984	1.05	2002	1.23
1985	0.65	2003	1.07
1986	1.10	2004	1.18
1987	1.26	2005	0.59
1988	1.14	2006	2.10
1989	1.15	2007	1.94
1990	0.88	2008	1.75
1991	0.92	2009	2.06
1992	1.16	2010	1.75
1993	1.10	2011	2.20
1994	1.67	2012	3.14
1995	2.99	2013	2.80
1996	2.71	2014	2.90
1997	2.34	2015	3.00
1998	3.66	2016	2.80
1999	1.58	2017	2.80

Table 255. **Annual commercial landings in pounds of *alosa* in Florida. Landings are presumably all American shad, but reporting did not distinguish between American and hickory shad. Data is restricted to reporting from Nassau, Duval, and St. Johns counties (all coastal), and Putnam county (inland). A fishing year (July-June) is used because the spawning run begins as early as November and continues for several months. Data source: Florida Marine Fisheries Information System.**

Fishing Year	Ocean Landings	Total Landings
1986-1987	142,026	155,430
1987-1988	266,251	266,374
1988-1989	164,839	165,112
1989-1990	169,881	289,293
1990-1991	58,810	71,592
1991-1992	49,633	49,798
1992-1993	24,503	24,503
1993-1994	24,930	24,968
1994-1995	26,791	26,886
1995-1996	3,650	3,650
1996-1997	54	54
1997-1998	18	18
1998-1999	480	480
1999-2000	800	800
2000-2017	0	0

Table 256. Florida St. Johns River American Shad Management Benchmarks and Triggers.

River System	Index	Index Years	Benchmark Value	Benchmark Level	Management Trigger
St. Johns River	St. Johns River Spawning Ground Electrofishing Survey CPUE	2003-2016	4.04 shad/ standard sample	25th percentile	3 consecutive years below the benchmark
St. Johns River	St. Johns River Juvenile Pushnet Survey	2007-2016	2.33 shad/ standard sample	25th percentile	3 consecutive year below the benchmark

Table 257. Percent of American shad at age in the spawning run of the St. Johns River, Florida by catch year. Ages from 1958 were scale ages reported in Walburg 1960. Ages from 1972 and 1973 are scale ages reported in Williams et al. 1975. The ages from 2011 – 2017 are otolith ages from FWC fishery-independent monitoring. A robust 2010 year class is highlighted in red.

Male

AGE	1958	1972	1973	2011	2012	2013	2014	2015	2016	2017
2				0.89	1.63	0.13	2.57	3.32	2.09	1.70
3	29.60	44.81	22.89	14.51	22.10	34.12	10.09	12.02	9.41	12.50
4	48.00	25.97	72.29	39.65	36.41	29.66	41.65	10.23	13.24	15.91
5	20.80	27.27	2.81	30.34	25.18	31.10	24.04	45.27	13.94	42.05
6	1.60	1.95	2.01	14.62	14.67	4.86	16.33	22.76	56.79	6.25
7						0.13	5.32	5.37	4.53	17.61
8								1.02		3.98
9										
TOTAL	100	100	100	100	100	100	100	100	100	100

Female

AGE	1958	1972	1973	2011	2012	2013	2014	2015	2016	2017
2			0.48							
3	4.27	1.86	2.40	2.01	14.17	7.49	6.39	6.90	8.10	9.85
4	56.41	11.80	69.71	19.53	43.75	25.45	36.10	9.85	14.76	14.39
5	31.62	73.29	16.83	58.76	21.25	49.10	15.65	40.39	10.95	22.73
6	5.98	13.04	10.10	19.34	14.58	10.78	36.10	27.09	59.52	10.61
7	1.71		0.48	0.36	6.25	4.79	5.75	15.76	5.24	40.91
8						2.40			1.43	1.52
9										
TOTAL	100	100	100	100	100	100	100	100	100	100

Table 258. Summary of relative abundance data suitable for monitoring the trend in abundance of the American shad spawning stock from the St. Johns River, Florida from 2003 – 2017. Samples are those that followed the standard electrofishing protocol of 10-minute daytime samples using 2-dipnetters during the months January through March.

Summary of January - March American Shad Electrofishing Relative Abundance						
	CA Stratum			PZ and SR50 Strata Combined		
Year	N Samples	Geometric Mean	Standard Deviation	N Samples	Geometric Mean	Standard Deviation
2003	55	2.05	1.31	20	5.94	1.73
2004	69	0.20	0.52	72	5.84	1.42
2005	64	0.21	0.52	50	3.75	1.61
2006	71	0.59	0.97	60	3.82	1.62
2007	70	0.67	0.90	61	4.46	2.04
2008	59	0.56	0.79	70	3.30	1.79
2009	70	0.60	0.86	60	6.53	1.82
2010	20	1.77	1.29	60	4.60	2.02
2011	20	2.14	1.43	64	6.02	2.44
2012	20	2.26	1.55	70	5.83	2.13
2013	20	3.26	1.65	70	9.17	1.47
2014	20	1.86	2.40	60	7.32	1.48
2015	20	6.49	1.74	60	4.05	1.46
2016	20	3.77	1.41	60	4.04	1.46
2017	20	1.26	1.42	57	2.53	1.63

Table 259. Available pushnet data from the rkm 125 – 164 reach of the St. Johns River. Sampling frequency increased over time and the beginning of sampling was moved up a month to better capture the peak abundance. *In 2010 sampling was only scheduled to occur in the rkm 210 to 249 river stretch. A late season sampling trip was sent down to rkm 125 – 164 after another survey encountered an unusual number of YOY American shad. That event prompted the re-introduction of the lower river into JAI monitoring. Peak abundance occurred in May or June of every year so it is assumed that the peak abundance in 2010 was much higher than the CPUE in that single August trip.

Year	Sample Months	N Tows	N Fish	Mean	SD	Zero hauls	Peak Night	N Tows	N Fish	Mean	SD	Zero Hauls
2007	5,6,7	33	12	0.25	0.47	24	6/6	12	8	0.66	0.7	4
2008	5,6,7	36	159	2.79	1.39	5	6/23	12	85	4.85	1.46	0
2009	5,6,7	34	48	0.61	1.07	20	5/27	12	44	2.06	1.38	2
2010*	8	12	113	5.89	1.69	1	8/30	12	113	5.89	1.69	1
2011	6,7	24	104	1.2	1.32	11	6/21	12	34	1.59	1.53	5
2012	5,6,7	60	403	2.87	2.16	16	5/15	12	225	11.7	2.13	1
2013	5,6,7	72	400	2.09	2.24	28	5/29	12	167	8.33	1.99	0
2014	4,5,6,7	96	260	1.46	1.35	34	6/17	12	69	3.2	1.6	1
2015	5,6,7	84	724	5.29	1.66	8	6/16	12	228	15.3	0.92	0
2016	4,5,6,7	72	712	5.57	1.88	7	6/8	12	232	14.39	1.23	0
2017	4,5,6,7	72	260	2.61	1.05	10	5/10	12	61	4.02	0.71	1
2018	4,5,6,7	72	440	2.91	1.63	17	5/23	12	102	7.96	0.42	0

Table 260. St. Johns River Spawning Ground Electrofishing Survey number of observations (n), index values (numbers), and CVs.

Year	n	Index	CV
2003	89	8.76	0.22
2004	167	4.07	0.14
2005	146	2.63	0.23
2006	151	4.28	0.15
2007	154	3.44	0.17
2008	157	2.49	0.15
2009	154	4.41	0.16
2010	110	5.43	0.19
2011	100	5.69	0.17
2012	90	7.75	0.16
2013	90	9.91	0.16
2014	90	7.06	0.18
2015	80	11.30	0.29
2016	90	7.71	0.22
2017	77	2.64	0.21

Table 261. St. Johns River Juvenile Pushnet Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
2007	82	0.15	0.20	0.29
2008	84	0.54	2.25	0.16
2009	82	0.32	1.09	0.18
2010	12	0.92	9.42	0.40
2011	61	0.43	1.98	0.20
2012	60	0.73	6.72	0.18
2013	72	0.61	5.56	0.17
2014	96	0.64	2.77	0.15
2015	85	0.91	8.66	0.15
2016	87	0.82	8.78	0.15
2017	96	0.81	3.08	0.15

Table 262. U.S. Atlantic Coast commercial landings of American shad from 1950-2017.

Year	Landings	Year	Landings	Year	Landings	Year	Landings
1950	8,222,700	1967	5,706,300	1984	4,781,815	2001	1,545,419
1951	8,477,500	1968	6,158,000	1985	3,665,916	2002	1,788,511
1952	10,522,500	1969	5,985,800	1986	5,646,634	2003	1,468,477
1953	7,799,100	1970	7,502,100	1987	5,497,014	2004	1,308,044
1954	8,667,600	1971	4,429,600	1988	5,242,563	2005	748,736
1955	8,601,100	1972	4,744,297	1989	5,027,808	2006	658,906
1956	9,671,400	1973	4,286,618	1990	3,753,338	2007	862,583
1957	11,367,100	1974	3,007,332	1991	3,005,385	2008	574,982
1958	8,191,100	1975	2,389,759	1992	2,617,027	2009	510,582
1959	8,191,600	1976	2,057,720	1993	2,242,473	2010	621,250
1960	5,964,100	1977	2,715,453	1994	1,679,418	2011	670,463
1961	6,329,200	1978	3,364,124	1995	1,758,960	2012	680,874
1962	7,272,600	1979	2,790,429	1996	2,012,330	2013	639,742
1963	5,941,400	1980	3,829,243	1997	1,918,316	2014	709,388
1964	6,104,000	1981	3,207,167	1998	2,182,897	2015	459,985
1965	7,693,800	1982	3,294,446	1999	1,431,043	2016	242,950
1966	5,957,500	1983	3,165,300	2000	1,752,381	2017	349,943

Table 263. Atlantic Ocean Commercial Logbooks (NJ DFW) number of observations (n) and index values (weight).

Year	n	Proportion Positive	Index	CV
2000	236	0.97	0.00124	0.16
2001	191	1.00	0.00173	0.11
2002	193	0.99	0.00283	0.12
2003	144	0.96	0.00217	0.25
2004	178	0.99	0.00203	0.29
2005	56	0.96	0.00334	0.23
2006	37	1.00	0.00123	0.62
2007	67	0.96	0.00024	0.23
2008	54	0.91	0.00091	0.40
2009	30	1.00	0.00091	0.26
2010	14	1.00	0.00037	0.40
2011	NA	NA	NA	NA
2012	6	1.00	0.00001	0.47
2013	4	0.00	0.00000	0.00

Table 264. Atlantic Ocean Commercial CPUE (NC DMF) number of observations (n) and index values (weight).

Year	n	Index
1994	615	55.11
1995	1,178	87.51
1996	1,385	42.36
1997	1,435	68.51
1998	1,208	97.70
1999	632	52.15
2000	767	144.63
2001	135	87.70
2002	163	51.40
2003	150	83.43
2004	108	65.38

Table 265. Delaware Bay Commercial Logbooks (NJ DFW) number of observations (n), proportion positive observations, index values (weight), and CVs.

Year	n	Proportion Positive	Index	CV
2000	214	0.99	0.01	0.13
2001	250	1.00	0.01	0.20
2002	134	1.00	0.01	0.08
2003	195	0.98	0.01	0.08
2004	192	0.99	0.01	0.07
2005	255	1.00	0.01	0.11
2006	177	0.98	0.01	0.07
2007	100	1.00	0.00	0.12
2008	128	0.99	0.00	0.11
2009	92	0.96	0.00	0.23
2010	82	0.94	0.00	0.14
2011	60	0.98	0.00	0.18
2012	76	1.00	0.00	0.14
2013	91	1.00	0.00	0.09
2014	111	0.99	0.00	0.14
2015	85	0.99	0.00	0.11
2016	91	1.00	0.00	0.10
2017	103	1.00	0.00	0.36

Table 266. Delaware Bay Commercial Logbooks (DE DFW) number of observations (n) and index values (weight).

Year	Index	Year	Index
1985	3.53	2002	0.14
1986	2.86	2003	0.32
1987	3.28	2004	0.30
1988	3.44	2005	0.31
1989	0.42	2006	0.10
1990	0.40	2007	0.23
1991	0.28	2008	0.13
1992	0.19	2009	0.04
1993	0.28	2010	0.05
1994	0.28	2011	0.11
1995	0.20	2012	0.04
1996	0.27	2013	0.05
1997	0.26	2014	0.61
1998	0.21	2015	0.16
1999	0.23	2016	0.20
2000	0.19	2017	0.06
2001	0.47		

Table 267. Canadian Maritimes region commercial landings of American shad from 2001-2017. Data from 2016-2017 are considered preliminary and subject to change.

Year Landed	Province Landed	Weight Landed (pounds)	Year Landed	Province Landed	Weight Landed (pounds)
2001	**NEW BRUNSWICK**	28,647	**2009**	**NOVA SCOTIA**	12,072
2001	**NOVA SCOTIA**	62,481	**2010**	**NEW BRUNSWICK**	40,819
2002	**NEW BRUNSWICK**	17,591	**2010**	**NOVA SCOTIA**	10,576
2002	**NOVA SCOTIA**	75,006	**2011**	**NEW BRUNSWICK**	37,578
2003	**NEW BRUNSWICK**	31,612	**2011**	**NOVA SCOTIA**	8,239
2003	**NOVA SCOTIA**	104,241	**2012**	**NEW BRUNSWICK**	113,981
2004	**NEW BRUNSWICK**	22,317	**2012**	**NOVA SCOTIA**	22,386
2004	**NOVA SCOTIA**	53,427	**2013**	**NEW BRUNSWICK**	21,643
2005	**NEW BRUNSWICK**	44,353	**2013**	**NOVA SCOTIA**	18,230
2005	**NOVA SCOTIA**	52,957	**2014**	**NEW BRUNSWICK**	43,442
2006	**NEW BRUNSWICK**	34,604	**2014**	**NOVA SCOTIA**	25,410
2006	**NOVA SCOTIA**	21,766	**2015**	**NEW BRUNSWICK**	43,629
2007	**NEW BRUNSWICK**	26,603	**2015**	**NOVA SCOTIA**	10,997
2007	**NOVA SCOTIA**	13,618	**2016**	**NEW BRUNSWICK**	30,219
2008	**NEW BRUNSWICK**	15,858	**2016**	**NOVA SCOTIA**	12,998
2008	**NOVA SCOTIA**	10,430	**2017**	**NEW BRUNSWICK**	30,503
2009	**NEW BRUNSWICK**	36,268	**2017**	**NOVA SCOTIA**	14,806

Table 268. Mesh-size categories for bottom trawls and gill net gears in ocean fisheries intercepting American shad.

Mesh category	Bottom Trawl	Gill Net
small	mesh ≤ 3.5	mesh < 5.5
medium	3.5 < mesh < 5.5	---
large	mesh ≥ 5.5	5.5 ≤ mesh < 8
x-large	---	mesh ≥ 8

Table 269. **Total number of trips recorded for each fleet in the observer, dealer and VTR databases for the Mid-Atlantic. Landings from the VTR database were used as the raising factor to estimate catch in the midwater fleets. For all other fleets, the dealer database was used.**

	Number of trips									
	Bottom trawl						Midwater trawl			
	Small mesh		Medium mesh		Large mesh		Single		Paired	
Year	Observer	Dealer	Observer	Dealer	Observer	Dealer	Observer	VTR	Observer	VTR
1989	29	4,180	7	412	4	2,627				
1990	31	3,745	19	386	0	2,864			0	0
1991	61	3,994	20	361	4	3,699	5	0	0	0
1992	39	3,080	12	283	14	4,719			9	0
1993	9	2,965	7	103	12	5,904			14	0
1994	8	3,857	8	156	21	4,865	1	64	30	44
1995	60	4,731	3	330	55	6,745	0	120	33	50
1996	70	4,699	10	652	18	6,500	0	252	0	14
1997	41	5,174	10	692	9	6,554	0	205	0	6
1998	29	5,269	4	784	13	6,866	0	238	0	34
1999	28	4,655	9	777	8	6,712	0	207	0	26
2000	28	4,575	12	806	26	5,938	5	193	1	74
2001	42	3,783	13	879	50	6,493	0	169	0	58
2002	15	3,475	18	998	39	6,958	0	71	1	107
2003	21	2,168	53	795	16	7,107	0	115	5	196
2004	111	2,408	156	692	109	6,796	2	99	8	249
2005	74	1,422	109	466	93	8,441	4	75	11	224
2006	101	2,349	54	736	71	6,938	8	74	6	184
2007	86	2,196	139	714	160	5,976	1	86	2	84
2008	68	2,253	86	701	132	6,159	8	17	8	146
2009	169	2,504	126	661	167	6,945	5	27	20	166
2010	183	2,305	193	420	276	5,555	4	15	13	84
2011	235	2,283	155	585	254	6,297	4	3	22	44
2012	133	2,420	111	738	169	5,115	4	35	7	40
2013	219	2,229	195	949	251	4,749	1	45	2	33
2014	228	2,113	227	895	269	4,177	1	47	0	18
2015	176	1,717	201	811	231	4,367	2	32	1	25
2016	394	2,378	298	1029	286	4,184	2	26	1	14
2017	612	2,614	370	991	332	3,184	4	32	2	14

Table 269 Continued

	Number of trips							
	Gill Net						Other	
	Small mesh		Large mesh		X-large mesh			
Year	Observer	Dealer	Observer	Dealer	Observer	Dealer	Observer	Dealer
1989	0	67	0	1,646			0	15,494
1990	0	137	0	2494	0	3	1	16,633
1991	0	121	0	3364			8	17,948
1992	0	100	0	2627			15	17,042
1993	0	80	0	2856			42	17,467
1994	83	85	58	2844	20	24	42	15,086
1995	137	185	207	4028	73	294	44	13,440
1996	146	343	174	5073	65	638	24	14,109
1997	106	422	136	10134	111	1,021	27	18,541
1998	104	699	132	5750	73	1,403	36	16,378
1999	44	848	23	5402	19	1,443	57	15,424
2000	49	1,110	18	4972	18	1,954	75	15,308
2001	54	1,280	17	3834	17	2,193	97	15,747
2002	34	1,267	10	3701	11	2,139	96	16,653
2003	25	750	4	3838	13	2,104	115	17,997
2004	12	1,303	6	3292	38	1,409	330	16,892
2005	19	1,270	4	4122	82	1,739	408	23,185
2006	20	1,160	7	3512	32	1,470	144	25,122
2007	19	1,231	13	5760	32	2,045	245	27,634
2008	7	905	2	4558	44	2,029	514	25,958
2009	9	1,252	8	7132	43	1,693	435	25,787
2010	12	851	52	3851	91	1,455	282	16,538
2011	11	1,529	24	5901	62	2,275	261	22,035
2012	0	1,142	3	4719	68	2,035	225	20,543
2013	8	890	9	7392	29	1,789	202	22,373
2014	29	1,181	44	5914	85	1,623	318	19,222
2015	162	1,118	141	5100	126	1,427	395	20,431
2016	246	1,182	249	5624	162	1,304	552	21,642
2017	359	1,121	205	5172	152	1,138	551	19,515

Table 270. Total number of trips recorded for each fleet in the observer, dealer and VTR databases for New England. Landings from the VTR database were used as the raising factor to estimate catch in the midwater fleets. For all other fleets, the dealer database was used.

	Number of trips									
	Bottom trawl						Midwater trawl			
	Small mesh		Medium mesh		Large mesh		Single		Paired	
Year	Observer	Dealer	Observer	Dealer	Observer	Dealer	Observer	VTR	Observer	VTR
1989	72	5,060	15	528	57	21,439			0	0
1990	33	4,850	4	355	54	21,518			0	0
1991	84	4,372	13	156	78	22,429	2	0	0	0
1992	56	4,157	1	120	68	22,518	0	0	0	0
1993	21	5,054	10	153	44	21,468	0	0	7	0
1994	13	5,522	5	239	36	21,084	0	306	4	53
1995	37	4,217	3	154	68	20,376	4	785	2	11
1996	48	3,893	2	52	44	19,750	0	897	0	18
1997	19	3,788	4	100	29	17,417	0	701	0	93
1998	5	4,198	1	94	13	18,156	0	512	0	170
1999	19	3,915	0	214	41	16,345	1	521	2	164
2000	8	3,338	9	124	103	17,473	7	462	0	368
2001	8	2,834	11	173	157	17,372	1	336	0	629
2002	35	2,184	30	221	220	17,480	0	373	0	653
2003	46	2,226	27	184	387	16,813	2	251	18	617
2004	88	1,822	85	152	531	13,384	23	253	60	585
2005	84	1,507	173	131	1350	11,902	43	265	91	465
2006	49	1,939	37	299	619	10,612	10	194	21	490
2007	58	2,145	18	213	621	10,760	10	87	11	235
2008	46	2,381	16	175	753	11,013	11	33	36	185
2009	195	2,296	26	270	879	10,936	10	47	67	225
2010	206	2,601	55	251	1054	9,423	29	57	106	215
2011	164	1,854	31	246	1597	8,351	24	59	89	252
2012	138	2,146	30	390	1551	8,357	30	122	131	246
2013	191	1,855	56	510	1095	7,343	27	181	69	235
2014	281	1,972	56	540	1198	6,404	28	141	74	237
2015	242	2,092	60	538	897	6,106	6	154	10	193
2016	282	3,097	60	711	632	5,091	21	163	28	131
2017	589	2,616	166	597	633	5,069	12	92	17	124

Table 270 Continued

	Number of trips							
	Gill Net						Other	
	Small mesh		Large mesh		X-large mesh			
Year	Observer	Dealer	Observer	Dealer	Observer	Dealer	Observer	Dealer
1989	0	10	0	12,688	0	1	40	28,547
1990	0	10	0	13303	0	26	32	30,641
1991	0	50	0	13336	0	2	79	33,019
1992	0	5	0	13367	0	47	144	33,575
1993	0	2	0	13184	0	81	118	33,704
1994	0	3	61	13510	40	934	107	28,590
1995	0	8	105	12798	46	2,030	101	31,949
1996	0	21	55	10957	23	1,533	62	35,391
1997	0	12	51	9487	19	1,214	32	35,427
1998	3	14	115	9579	15	1,061	15	32,176
1999	1	7	98	7122	21	1,352	74	25,032
2000	0	17	107	7547	50	1,881	234	21,397
2001	1	17	69	7086	33	2,530	28	22,574
2002	0	14	91	7095	41	2,827	30	23,240
2003	0	20	326	7857	190	2,990	72	20,577
2004	1	16	699	5922	536	2,973	240	16,706
2005	0	39	587	5833	459	2,958	489	39,381
2006	0	67	142	6683	79	2,421	262	47,112
2007	2	78	132	7905	164	2,102	319	43,577
2008	3	27	170	9453	112	2,274	370	55,743
2009	2	12	313	10014	76	1,989	243	66,370
2010	0	22	1267	7837	771	2,653	384	150,358
2011	0	9	1589	6515	715	2,847	375	161,043
2012	0	6	1379	5844	454	2,502	611	170,606
2013	0	4	620	3432	323	2,272	432	168,246
2014	0	9	919	3338	588	2,339	364	168,043
2015	0	4	471	1951	450	2,451	564	170,042
2016	1	6	278	2021	218	2,525	368	183,969
2017	1	3	225	1626	310	2,792	510	178,262

Table 271. American shad total annual incidental catch (metric tons), discards (metric tons) and associated coefficients of variation across all fleets and regions. Midwater trawl estimates were only included beginning in 2005.

	Total incidental catch		Discards	
	Estimate	CV	Estimate	CV
1989	229.10	0.98	211.74	1.00
1990	45.20	0.34	39.48	0.37
1991	176.09	0.25	169.65	0.25
1992	168.95	0.28	146.64	0.31
1993	211.34	1.00	202.83	1.04
1994	109.93	0.64	103.69	0.67
1995	127.43	0.38	31.49	0.67
1996	64.52	0.39	27.33	0.62
1997	65.95	0.61	41.25	0.96
1998	161.03	0.23	61.48	0.35
1999	82.03	0.41	32.55	0.67
2000	262.42	0.78	64.65	2.06
2001	67.82	0.39	3.41	0.35
2002	43.81	0.40	26.55	0.50
2003	60.20	0.54	22.40	1.03
2004	53.06	0.36	43.36	0.40
2005	94.50	0.28	32.60	0.27
2006	78.23	9.73	22.83	0.99
2007	79.08	0.56	24.76	1.12
2008	74.04	0.29	52.89	0.30
2009	106.70	1.99	52.08	3.43
2010	60.61	0.16	45.05	0.20
2011	103.34	0.12	82.67	0.11
2012	76.53	0.16	68.23	0.17
2013	73.34	0.41	68.28	0.44
2014	63.54	0.19	57.90	0.20
2015	46.45	0.15	44.98	0.15
2016	41.95	0.17	37.17	0.19
2017	44.23	0.14	36.59	0.14

tion of 2005-2017 incidental catch of American shad by region, fleet and quarter for the dominant gears.

BT			Gill Net			Paired MWT	Single MWT	Total MWT	Grand Total
sm	med	lg	sm	lg	xlg				
0.034	0.008	0.003	0.002	0.037	0.000	0.046	0.006	0.051	0.136
0.033	0.004	0.002	0.000	0.025	0.000	0.004	0.000	0.005	0.070
0.068	0.001	0.002	0.000	0.019	0.000	0.000	0.000	0.000	0.090
0.023	0.006	0.003	0.001	0.025	0.000	0.001	0.000	0.001	0.057
0.157	**0.019**	**0.010**	**0.004**	**0.105**	**0.000**	**0.051**	**0.006**	**0.057**	**0.353**
0.046	0.002	0.022	0.000	0.030	0.000	0.008	0.003	0.011	0.110
0.041	0.001	0.023	0.000	0.052	0.001	0.016	0.005	0.021	0.138
0.058	0.001	0.017	0.000	0.114	0.001	0.021	0.008	0.029	0.220
0.036	0.001	0.019	0.000	0.074	0.000	0.033	0.014	0.047	0.178
0.181	**0.005**	**0.080**	**0.000**	**0.270**	**0.002**	**0.078**	**0.030**	**0.107**	**0.647**
0.339	**0.025**	**0.091**	**0.004**	**0.376**	**0.002**	**0.129**	**0.036**	**0.165**	**1.000**

Table 273. American shad total annual incidental catch estimates (metric tons; retained plus discarded catch) and corresponding CVs by gear and mesh from 1989-2017 (across all areas fished). MWT fleets are only included beginning in 2005.

	BT						Gill Net						Single MWT		Paired MWT		Other	
	Sm		Med		Lg		Sm		Lg		Xlg							
Year	Catch	CV	Catch	CV	Catch	CV	Catch	CV	Catch	CV	Catch	CV	Catch	CV	Catch	CV	Catch	CV
1989	107.47	0.82	0		121.46	1.69	0		0		0						0.18	1.02
1990	16.56	0.38	0		25.84	0.53	0		0		0						2.79	0.56
1991	50.64	0.37	12.95	0.92	107.96	0.34	0		0		0						4.54	1.11
1992	71.72	0.34	0		94.21	0.42	0		0		0						3.01	0.41
1993	79.7	0.61	0.44	0.67	130.63	1.57	0		0		0						0.57	0.97
1994	91.1	0.77	0.01	5.7	10.79	0.38	0.42	0.11	7.44	0.91	0						0.16	0.76
1995	3.14	1.16	0.23	0.4	16.49	1.25	0.92	0.38	106.43	0.41	0.04	0.84					0.16	1.05
1996	4.31	1.78	0.08	2.19	0.82	1.02	4.51	0.42	54.77	0.44	0						0.03	1.1
1997	13.09	2.95	5.1	0.39	11.45	0.71	1.41	0.2	30.4	0.23	0.17	0.9					4.31	0.6
1998	37.81	0.51	0.65	1	21.32	0.93	10.93	0.58	88.56	0.26	1.76	0.64					0	
1999	1.37	2.83	0.19	0.91	19.13	1.09	6.61	0.91	51.85	0.5	1.4	1.15					1.48	1.33
2000	0.17	0.5	0		2.15	1.08	0	1.08	197.74	0.77	0.12	0.95					62.24	2.17
2001	2.2	0.82	0.22	1.95	1.6	0.55	58.84	0.44	4.96	0.49	0						0	
2002	7.4	1.44	0		0.24	0.72	1.65	0.48	34.46	0.41	0.08	1.07					0	
2003	24.44	1	0.07	1.38	1.73	0.3	0.12	0.7	33.26	0.64	0.56	0.88					0.03	0.81
2004	43	0.44	0.18	1.16	1.59	0.36	0.13	0.39	7.98	0.18	0.14	0.73					0.04	0.82
2005	28.44	0.31	0.37	0.72	1.97	0.29	0		3.7	0.29	0.08	0.38	2.47	0.88	57.48	0.43	0	
2006	4.84	0.71	0	0.65	0.85	0.33	0.11	0.34	68.17	11.17	0		3.93	1.07	0.18	0.63	0.15	1.06
2007	6.54	2.82	3.07	0.76	0.93	0.28	0.44	1.06	50.79	0.75	0		0		17.27	0.78	0.03	0.95
2008	4.58	0.72	0.4	0.52	2.74	0.3	0		45.86	0.34	0.03	1.1	3.9	0.74	16.5	0.81	0.04	0.99
2009	25.91	0.49	0.54	0.66	2.57	0.23	0.69	2.17	48.62	4.36	0.18	0.79	20.96	0.67	6.83	0.33	0.42	0.83
2010	25.83	0.33	0.79	0.44	5.68	0.13	0		16.75	0.19	0.06	0.43	0.11	0.49	11.38	0.35	0	
2011	61.66	0.19	0.43	0.38	8.47	0.14	0		28.87	0.11	0.52	0.26	0.12	0.56	3.27	0.41	0	
2012	25.38	0.45	0.2	0.65	10.75	0.15	0		34.09	0.1	0.16	0.51	0.63	0.41	4.15	0.45	1.17	0.48
2013	34.47	0.86	1.29	0.27	12.64	0.16	0		23.4	0.12	0.19	0.39	0.15	1.46	1.14	0.89	0.07	0.66
2014	24.37	0.45	4.28	0.43	11.45	0.12	0.18	0.56	16.35	0.12	0.43	0.48	0.01	0	1.67	0.58	4.8	0.73
2015	24.52	0.24	7.57	0.34	10.33	0.22	0.12	0.6	3.75	0.15	0.15	0.37	0		0		0	
2016	23.46	0.22	1.53	0.29	8.01	0.56	0.5	0.4	6.69	0.3	0.33	0.43	1.38	0.68	0.04	1.03	0.01	0.94
2017	26.83	0.2	2.6	0.42	8.48	0.18	1.25	0.3	4.5	0.46	0.05	0.55	0		0.5	1.07	0.01	0.92

Table 274. Proportion of American shad total annual incidental catch estimates that is discarded for each of the most dominant fleets. MWT fleets are only included beginning in 2005.

Year	Small-mesh bottom trawl	Large-mesh gill net	Single MWT	Paired MWT
1989	0.84			
1990	0.81			
1991	0.88			
1992	0.82			
1993	0.89			
1994	1.00	0.21		
1995	0.25	0.13		
1996	0.63	0.43		
1997	1.00	0.28		
1998	0.92	0.02		
1999	1.00	0.18		
2000	1.00	0.06		
2001	0.31	0.22		
2002	0.10	0.74		
2003	0.80	0.03		
2004	0.82	0.82		
2005	0.99	0.65	0.20	0.00
2006	1.00	0.25	0.00	0.38
2007	0.60	0.34		0.13
2008	0.89	1.00	0.00	0.00
2009	0.22	0.87	0.01	0.01
2010	0.92	0.88	0.02	0.01
2011	0.80	0.83	0.00	0.00
2012	0.96	0.96	0.01	0.00
2013	0.92	0.98	0.01	0.01
2014	0.92	0.95	0.13	0.00
2015	0.95	0.95		
2016	0.87	0.96	0.05	0.01
2017	0.78	0.88		0.00

Table 275. Maine/New Hampshire Trawl Survey (Spring) number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
2001	81	0.26	0.12	0.35
2002	64	0.44	0.69	0.29
2003	64	0.42	0.32	0.29
2004	64	0.30	0.09	0.33
2005	64	0.53	0.32	0.29
2006	90	0.77	2.04	0.26
2007	89	0.56	0.49	0.26
2008	92	0.36	0.38	0.26
2009	92	0.52	0.26	0.28
2010	97	0.39	0.32	0.27
2011	96	0.63	0.88	0.26
2012	99	0.61	0.92	0.27
2013	97	0.58	0.67	0.27
2014	97	0.45	0.32	0.27
2015	123	0.56	0.61	0.25
2016	122	0.58	0.75	0.26
2017	121	0.59	0.64	0.24

Table 276. Maine/New Hampshire Trawl Survey (Fall) number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
2000	78	0.18	0.16	1.32
2001	51	0.06	0.00	693.70
2002	55	0.16	0.18	1.08
2003	48	0.29	0.85	0.77
2004	57	0.28	0.12	1.11
2005	43	0.47	0.37	0.95
2006	73	0.29	0.07	1.05
2007	73	0.37	0.96	0.69
2008	66	0.36	0.17	0.90
2009	78	0.23	0.32	0.80
2010	74	0.24	0.10	1.02
2011	73	0.27	0.08	1.19
2012	86	0.26	0.09	0.89
2013	85	0.27	0.17	0.81
2014	94	0.30	0.05	0.95
2015	80	0.33	0.78	0.73
2016	83	0.36	0.09	0.87
2017	101	0.32	0.13	0.82

Table 277. Rhode Island Coastal Trawl Survey (Monthly Segment) number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
1990	137	0.01	0.01	1.03
1991	90	NA	0.00	4518860.69
1992	131	0.01	0.01	1.01
1993	100	NA	0.00	4742741.82
1994	144	0.01	0.01	0.72
1995	165	0.16	0.23	0.23
1996	145	0.10	0.24	0.24
1997	151	0.18	0.38	0.22
1998	166	0.17	0.21	0.24
1999	152	0.19	0.30	0.23
2000	113	0.12	0.17	0.29
2001	112	0.04	0.09	0.40
2002	145	0.23	0.23	0.25
2003	121	0.05	0.07	0.34
2004	120	0.10	0.05	0.42
2005	148	0.20	0.01	1.01
2006	122	0.18	0.00	4857344.12
2007	156	0.22	0.18	0.26
2008	204	0.36	1.37	0.15
2009	156	0.07	0.07	0.31
2010	154	0.08	0.07	0.32
2011	204	0.37	0.53	0.17
2012	183	0.37	1.24	0.17
2013	174	0.21	0.72	0.18
2014	159	0.20	0.38	0.20
2015	161	0.25	0.54	0.19
2016	189	0.35	0.87	0.16
2017	165	0.13	0.94	0.17

Table 278. Rhode Island Coastal Trawl Survey (April Segment) number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV	Year	n	Proportion Positive	Index	CV
1979	52	NA	NA	NA	1999	55	0.40	0.73	0.47
1980	52	NA	NA	NA	2000	46	0.22	0.38	0.71
1981	65	NA	0.00	1966.73	2001	37	NA	NA	NA
1982	70	NA	0.00	1794.21	2002	43	0.09	0.18	1.12
1983	71	NA	0.00	1964.58	2003	44	0.18	0.65	0.58
1984	77	0.18	1.68	0.29	2004	39	0.13	0.16	1.30
1985	61	0.02	0.04	2.25	2005	57	0.47	0.00	2638.29
1986	58	0.07	0.00	2065.67	2006	53	0.30	0.00	4256.26
1987	52	0.04	0.05	2.25	2007	51	0.29	0.00	2361.41
1988	43	NA	0.00	2038.53	2008	59	0.41	8.49	0.11
1989	42	NA	0.00	1710.87	2009	42	0.05	0.08	1.59
1990	42	NA	0.00	1611.09	2010	43	0.02	0.04	2.25
1991	43	NA	NA	NA	2011	63	0.48	1.01	0.34
1992	42	NA	0.00	1663.17	2012	56	0.30	4.74	0.17
1993	26	NA	NA	NA	2013	52	0.29	4.41	0.18
1994	40	NA	0.00	2177.41	2014	55	0.35	0.66	0.43
1995	58	0.38	1.41	0.29	2015	61	0.46	1.75	0.26
1996	44	0.09	0.00	2176.55	2016	87	0.75	1.88	0.23
1997	45	0.22	0.54	0.60	2017	52	0.21	8.43	0.13
1998	42	0.12	0.32	0.85					

Table 279. Long Island Sound Trawl Survey (Spring) number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV	Year	n	Proportion Positive	Index	CV
1984	32	0.06	0.10	0.80	2001	120	0.11	0.08	0.28
1985	46	0.46	1.36	0.32	2002	120	0.26	0.60	0.24
1986	116	0.31	0.57	0.21	2003	120	0.19	0.20	0.22
1987	120	0.45	0.92	0.17	2004	119	0.27	0.34	0.21
1988	120	0.28	0.44	0.20	2005	120	0.20	0.28	0.24
1989	120	0.39	0.90	0.22	2006	80	0.16	0.25	0.34
1990	120	0.26	0.34	0.22	2007	120	0.28	0.43	0.23
1991	120	0.33	0.54	0.21	2008	120	0.30	0.56	0.24
1992	80	0.40	0.75	0.20	2009	120	0.32	0.56	0.20
1993	120	0.23	0.29	0.21	2010	78	0.36	0.52	0.25
1994	120	0.33	0.68	0.21	2011	92	0.28	0.49	0.24
1995	120	0.24	0.49	0.23	2012	120	0.23	0.45	0.26
1996	120	0.27	0.48	0.23	2013	120	0.25	0.43	0.23
1997	120	0.41	1.08	0.20	2014	120	0.28	0.40	0.21
1998	120	0.39	0.86	0.20	2015	120	0.33	0.48	0.18
1999	120	0.40	0.80	0.19	2016	116	0.29	0.84	0.26
2000	120	0.23	0.38	0.25	2017	64	0.05	0.03	0.56

Table 280. Long Island Sound Trawl Survey (Fall) number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV	Year	n	Proportion Positive	Index	CV
1984	70	0.59	3.13	0.27	2001	80	0.26	0.41	0.26
1985	80	0.13	0.19	0.35	2002	80	0.30	0.76	0.26
1986	80	0.15	0.27	0.34	2003	40	0.28	0.75	0.47
1987	80	0.16	0.29	0.33	2004	80	0.40	0.94	0.23
1988	80	0.51	2.66	0.23	2005	80	0.30	0.54	0.25
1989	80	0.50	3.10	0.24	2006	40	0.13	0.12	0.48
1990	80	0.28	0.65	0.28	2007	80	0.24	0.38	0.27
1991	80	0.34	0.72	0.25	2008	40	0.18	0.41	0.43
1992	80	0.28	0.54	0.29	2009	80	0.24	0.46	0.34
1993	80	0.28	1.16	0.30	2010	NA	NA	NA	NA
1994	80	0.51	1.82	0.23	2011	80	0.24	0.42	0.29
1995	80	0.49	1.90	0.23	2012	80	0.24	0.44	0.29
1996	80	0.20	0.27	0.28	2013	80	0.21	0.31	0.30
1997	80	0.39	0.91	0.22	2014	79	0.15	0.20	0.35
1998	80	0.36	1.22	0.25	2015	80	0.38	0.71	0.23
1999	80	0.46	1.73	0.25	2016	80	0.38	0.85	0.26
2000	80	0.25	0.54	0.29	2017	80	0.31	0.62	0.29

Table 281. Delaware Bay 30' Trawl Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV	Year	n	Proportion Positive	Index	CV
1979	100	0.10	0.95	0.58	2001	90	0.10	0.30	0.85
1980	96	0.05	0.16	0.80	2002	68	0.21	3.32	0.57
1981	102	0.04	0.37	0.72	2003	63	NA	0.00	22369621
1982	46	0.02	0.80	1.41	2004	90	0.20	14.10	0.51
1983	43	0.02	0.00	20077543	2005	90	0.10	1.13	0.57
1984	50	0.02	0.07	1.42	2006	90	0.11	7.15	0.52
1990	61	0.05	0.77	0.78	2007	90	0.03	0.07	1.08
1991	72	0.10	2.10	0.56	2008	90	0.11	0.89	0.59
1992	89	0.16	3.24	0.53	2009	90	0.07	12.60	0.51
1993	83	0.33	4.02	0.54	2010	90	0.17	3.01	0.54
1994	71	0.27	6.55	0.52	2011	90	0.16	7.57	0.52
1995	88	0.13	1.63	0.59	2012	90	0.11	2.21	0.56
1996	76	0.18	0.64	0.79	2013	90	0.17	0.62	0.63
1997	89	0.15	3.86	0.57	2014	90	0.08	0.15	0.84
1998	80	0.15	2.60	0.66	2015	90	0.08	0.24	0.75
1999	87	0.30	3.17	0.57	2016	90	0.07	0.67	0.62
2000	90	0.30	1.48	0.61	2017	90	0.02	0.20	0.82

Table 282. New Jersey Ocean Trawl Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV	Year	n	Proportion Positive	Index	CV
1989	96	0.44	12.25	0.42	2004	109	0.39	13.28	0.37
1990	99	0.36	3.81	1.04	2005	108	0.28	7.18	0.47
1991	112	0.34	8.96	0.46	2006	108	0.30	2.02	1.56
1992	112	0.38	5.63	0.53	2007	108	0.30	3.50	0.74
1993	109	0.39	2.69	0.81	2008	108	0.50	9.93	0.45
1994	108	0.40	5.74	0.49	2009	108	0.29	3.30	0.70
1995	110	0.47	11.39	0.43	2010	108	0.20	2.45	0.76
1996	111	0.40	2.19	0.75	2011	108	0.35	11.40	0.45
1997	70	0.36	6.65	0.78	2012	108	0.36	27.02	0.37
1998	110	0.39	7.96	0.63	2013	108	0.27	11.03	0.42
1999	108	0.38	6.75	0.51	2014	108	0.24	4.47	0.56
2000	108	0.16	3.05	0.68	2015	108	0.36	8.66	0.49
2001	108	0.24	2.66	0.71	2016	108	0.38	41.49	0.29
2002	109	0.28	34.17	0.40	2017	108	0.16	0.68	2.02
2003	109	0.39	2.57	0.74					

Table 283. Northeast Area Monitoring and Assessment Program Trawl Survey number of observations (n), proportion positive observations, index values (numbers), and CVs.

Year	n	Proportion Positive	Index	CV
2008	300	0.30	3.33	0.45
2009	320	0.27	9.12	0.36
2010	300	0.28	7.93	0.39
2011	300	0.22	21.10	0.30
2012	300	0.29	8.69	0.37
2013	300	0.30	35.87	0.28
2014	300	0.21	25.67	0.32
2015	300	0.25	115.34	0.42
2016	300	0.31	35.48	0.35

Table 284. American shad stratified mean number-per-tow and weight (kg)-per-tow derived from the NEFSC Bottom Trawl Survey (R/V Albatross; Spring) 1979-2008.

	Number-per-tow			Weight-per-tow		
Year	**Mean**	**Standard error**	**CV**	**Mean**	**Standard error**	**CV**
1979	0.53	0.18	34.54	0.13	0.05	35.55
1980	0.19	0.04	20.29	0.07	0.02	30.15
1981	0.42	0.16	38.24	0.10	0.03	32.38
1982	0.19	0.08	41.80	0.05	0.02	35.57
1983	0.18	0.05	27.50	0.07	0.04	60.58
1984	0.31	0.10	32.45	0.09	0.03	31.50
1985	0.35	0.07	21.06	0.19	0.08	41.14
1986	0.28	0.17	62.05	0.26	0.17	64.85
1987	0.15	0.04	29.03	0.06	0.02	34.91
1988	0.13	0.03	24.96	0.09	0.02	23.49
1989	0.25	0.06	25.63	0.09	0.03	33.71
1990	0.37	0.15	40.20	0.11	0.06	52.11
1991	0.54	0.17	31.64	0.17	0.05	28.54
1992	0.46	0.09	19.34	0.10	0.02	16.14
1993	0.31	0.06	19.86	0.13	0.03	24.26
1994	1.18	0.86	72.33	0.52	0.42	82.36
1995	0.16	0.04	27.28	0.07	0.04	50.26
1996	0.38	0.06	16.42	0.07	0.01	20.48
1997	0.43	0.09	21.98	0.17	0.04	26.82
1998	0.25	0.08	29.85	0.10	0.02	24.11
1999	0.34	0.05	15.39	0.17	0.05	30.47
2000	0.37	0.08	20.24	0.13	0.04	27.26
2001	0.37	0.13	35.08	0.16	0.06	36.10
2002	0.33	0.07	20.67	0.10	0.03	26.50
2003	0.29	0.07	23.22	0.04	0.01	25.61
2004	0.25	0.09	33.86	0.06	0.02	40.51
2005	0.35	0.12	33.50	0.16	0.12	74.25
2006	0.58	0.08	13.00	0.03	0.01	15.48
2007	0.61	0.18	29.29	0.12	0.04	36.74
2008	0.39	0.10	25.24	0.10	0.03	33.35

Table 285. American shad stratified mean number-per-tow and weight (kg)-per-tow derived from the NEFSC Bottom Trawl Survey (R/V Albatross; Fall) 1979-2008.

	Number-per-tow			Weight-per-tow		
Year	**Mean**	**Standard error**	**CV**	**Mean**	**Standard error**	**CV**
1979	0.08	0.03	39.5	0.04	0.01	32.39
1980	0.17	0.12	71.26	0.04	0.02	53.19
1981	0.62	0.28	44.66	0.09	0.04	39.83
1982	1.23	0.06	4.56	0.28	0.05	17.32
1983	0.72	0.69	95.48	0.14	0.13	93.6
1984	0.04	0.02	44.83	0.01	0.00	39.71
1985	0.12	0.04	30.85	0.02	0.01	32.5
1986	0.06	0.02	31.94	0.02	0.01	44.09
1987	1.22	0.10	8.42	0.38	0.08	20.95
1988	0.07	0.03	44.78	0.01	0.01	33.82
1989	0.11	0.03	26.58	0.03	0.01	36.24
1990	0.12	0.03	27.55	0.07	0.06	83.31
1991	0.05	0.02	46.87	0.02	0.01	60.82
1992	4.32	3.83	88.48	0.56	0.44	78.89
1993	0.08	0.04	49.34	0.02	0.01	44.85
1994	1.00	0.53	52.88	0.16	0.08	51.58
1995	0.34	0.11	32.67	0.22	0.10	44.31
1996	0.29	0.15	51.65	0.09	0.03	38.45
1997	0.20	0.08	40.91	0.10	0.05	49.10
1998	0.23	0.05	23.83	0.10	0.03	32.10
1999	0.16	0.10	62.14	0.04	0.02	60.95
2000	0.28	0.09	30.56	0.07	0.02	33.88
2001	0.17	0.03	20.47	0.06	0.01	25.14
2002	0.21	0.07	33.86	0.14	0.06	42.03
2003	0.21	0.08	38.94	0.08	0.01	15.04
2004	0.16	0.05	28.93	0.06	0.02	31.07
2005	0.17	0.09	55.91	0.07	0.06	82.07
2006	0.24	0.07	27.11	0.04	0.01	25.47
2007	0.18	0.05	25.51	0.04	0.01	28.09
2008	0.62	0.32	51.62	0.30	0.23	78.14

Table 286. **American shad stratified mean number-per-tow and weight (kg)-per-tow derived from the NEFSC Bottom Trawl Survey (R/V Bigelow; Spring) 2009-2017. The full strata set was not sampled in 2014 due to delays in the survey (offshore strata 61-68 south of Maryland were not sampled).**

	Number-per-tow			Weight-per-tow		
Year	Mean	Standard error	CV	Mean	Standard error	CV
2009	0.81	0.15	18.11	0.10	0.02	25.70
2010	0.49	0.13	25.56	0.05	0.01	24.15
2011	1.03	0.34	32.92	0.09	0.03	27.11
2012	2.27	0.62	27.29	0.38	0.10	26.42
2013	1.70	0.44	25.67	0.23	0.06	25.70
2014	0.89	0.23	25.60	0.17	0.04	21.05
2015	0.79	0.11	13.64	0.13	0.02	17.89
2016	0.86	0.28	32.39	0.11	0.04	34.82
2017	0.76	0.14	18.55	0.13	0.03	24.38

Table 287. **American shad stratified mean number-per-tow and weight (kg)-per-tow derived from the NEFSC Bottom Trawl Survey (R/V Bigelow; Fall) 2009-2017. Indices from the 2017 fall bottom trawl survey are treated as missing because the full survey was not completed due to vessel mechanical issues.**

	Number-per-tow			Weight-per-tow		
Year	Mean	Standard error	CV	Mean	Standard error	CV
2009	0.17	0.06	32.51	0.02	0.01	35.24
2010	0.48	0.10	20.19	0.08	0.03	34.82
2011	0.98	0.21	21.58	0.17	0.04	21.62
2012	0.55	0.11	20.04	0.12	0.02	19.68
2013	0.46	0.10	22.93	0.08	0.02	26.54
2014	1.75	0.38	21.40	0.30	0.07	22.01
2015	1.66	0.32	19.05	0.32	0.05	17.3
2016	1.29	0.85	65.92	0.17	0.08	47.92
2017	NA	NA	NA	NA	NA	NA

Table 288. Summary statistics from ARIMA model fits to American shad trawl survey data. W is the Shapiro-Wilk test statistic for normality of residuals; p is the corresponding p-value of the Shapiro-Wilk test; P(>2005) is the probability of the terminal year being above the bootstrapped fitted 2005 index value; r1 - r3 are the first three autocorrelations; θ is the moving average parameter; SE is the standard error of θ; and σ^2c is the variance of the index.

Region	Survey (Season)	Ages	First Year	Terminal Year	n	W	p	P(>2005)	r1	r2	r3	θ	SE	σ^2_c
Northern	Maine/New Hampshire Trawl Survey (Fall)	Sub Adults	2000	2017	18	0.948	0.394	0.777	-0.510	0.120	-0.010	0.500	0.200	0.380
Northern	Maine/New Hampshire Trawl Survey (Spring)	Sub Adults	2001	2017	17	0.933	0.240	0.786	-0.070	-0.610	-0.020	0.890	0.230	0.390
Northern	Rhode Island Coastal Trawl Survey (Monthly Segment)	All	1990	2017	28	0.976	0.758	0.867	-0.310	-0.230	0.150	0.450	0.180	0.760
Northern	Rhode Island Coastal Trawl Survey (April Segment)	All	1981	2017	39	0.973	0.464	0.861	-0.450	-0.080	0.190	0.740	0.110	2.060
Northern	Long Island Sound Trawl Survey (Spring)	Sub Adults	1984	2016	33	0.919	0.017	0.496	-0.490	0.200	-0.070	1.000	0.170	0.360
Northern	Long Island Sound Trawl Survey (Fall)	Sub Adults	1984	2009	26	0.968	0.581	0.454	-0.150	-0.190	-0.380	0.870	0.140	0.790
Southern	New Jersey Ocean Trawl Survey (All)	Sub Adults	1989	2017	29	0.968	0.510	0.403	-0.190	-0.450	0.100	0.940	0.160	0.280
Southern	NEAMAP Trawl Survey (Spring)	All	2008	2016	9	0.887	0.186	0.500	-0.230	-0.420	-0.020	1.000	0.340	0.320
Southern	Delaware Bay 30' Trawl Survey (Spring)	Adults	1990	2017	28	0.848	0.001	0.275	-0.640	0.390	-0.350	0.840	0.120	0.760
Coast	NEFSC Bottom Trawl Survey (R/V Albatross Fall)	Sub Adults	1979	2008	30	0.956	0.238	0.506	-0.630	0.340	-0.230	1.000	0.090	1.130
Coast	NEFSC Bottom Trawl Survey (R/V Albatross; Spring)	Sub Adults	1976	2008	30	0.954	0.220	0.518	-0.500	0.040	0.080	0.880	0.120	0.230
Coast	NEFSC Bottom Trawl Survey (R/V Bigelow; Fall)	Sub Adults	2009	2016	8	0.933	0.548	0.997	-0.100	-0.670	0.190	0.440	0.580	0.520
Coast	NEFSC Bottom Trawl Survey (R/V Bigelow; Spring)	Sub Adults	2009	2017	9	0.843	0.063	0.784	0.120	-0.580	-0.200	1.000	0.370	0.130

8 FIGURES

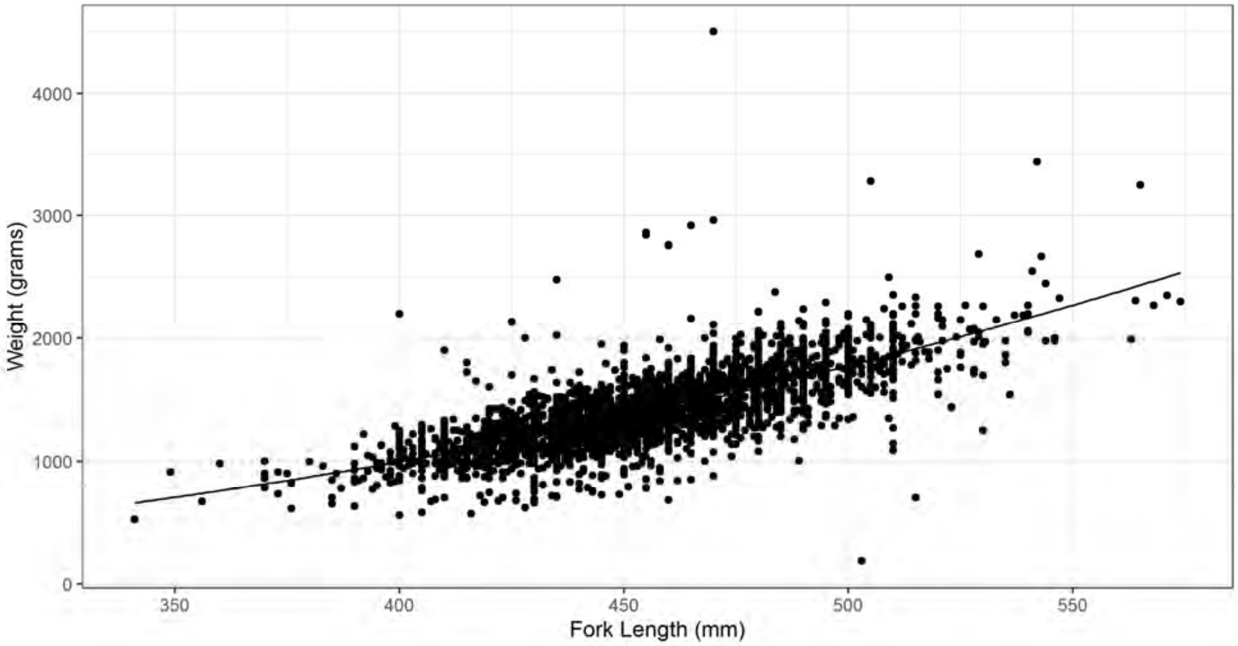


Figure 1. Predicted (line) and observed (circles) length-weight relationship of female American shad from the northern iteroparous region.

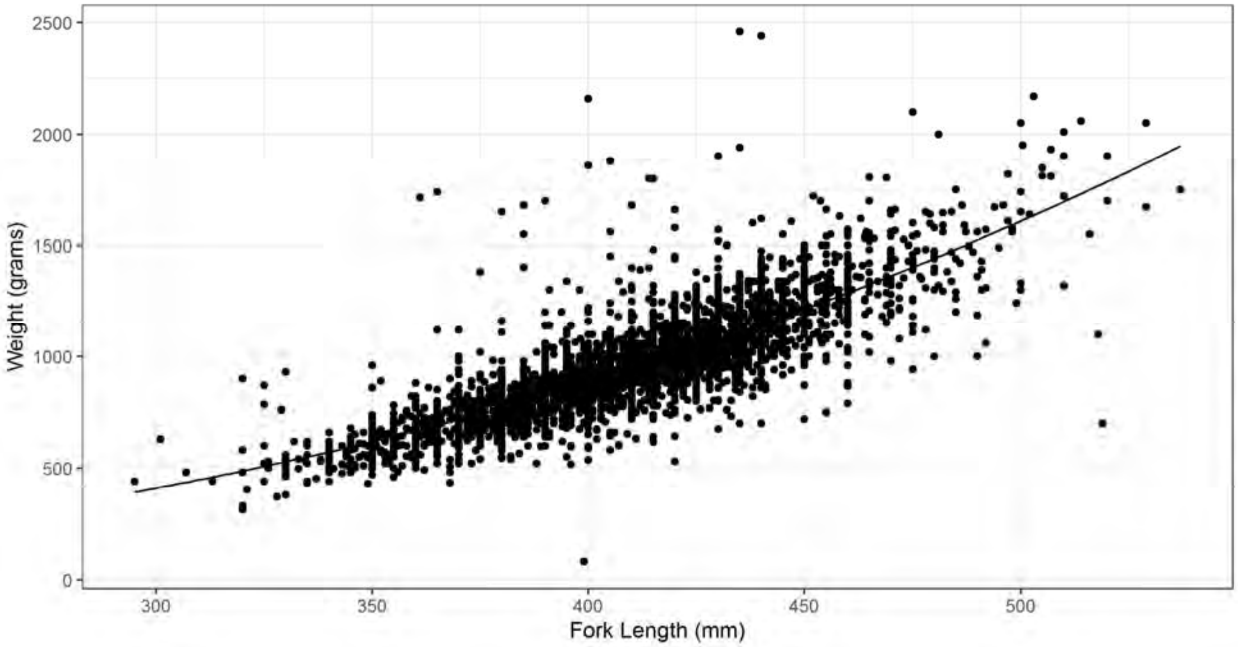


Figure 2. Predicted (line) and observed (circles) length-weight relationship of male American shad from the northern iteroparous region.

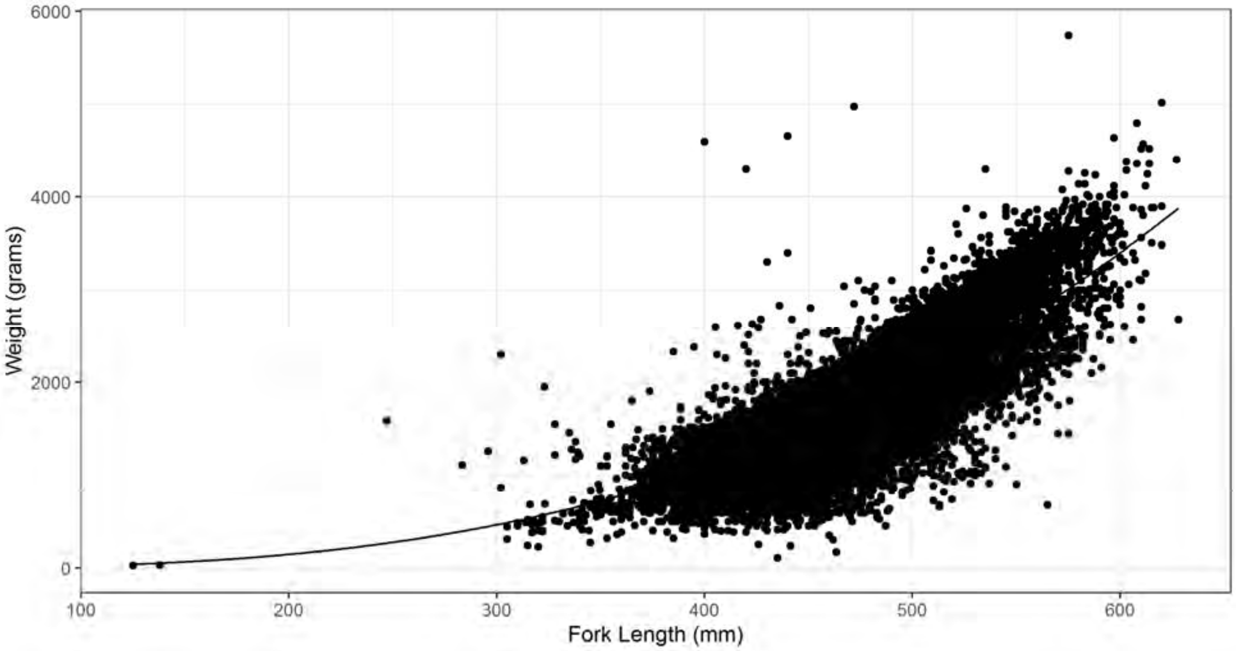


Figure 3. **Predicted (line) and observed (circles) length-weight relationship of female American shad from the southern iteroparous region.**

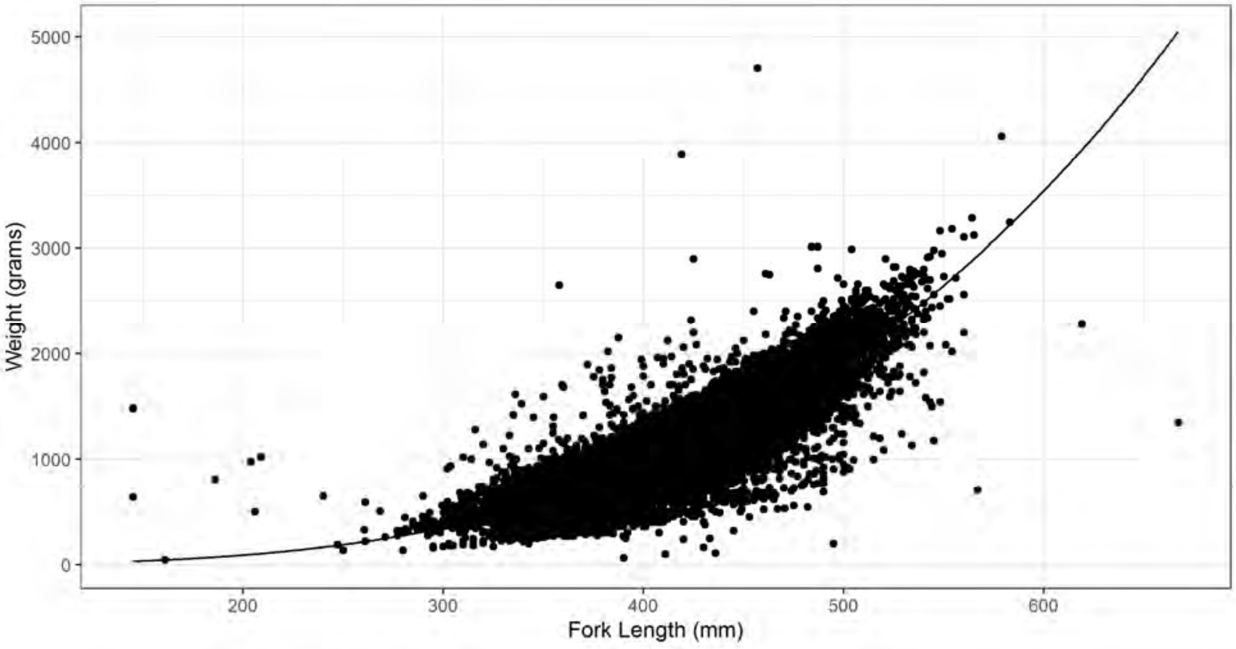


Figure 4. **Predicted (line) and observed (circles) length-weight relationship of male American shad from the southern iteroparous region.**

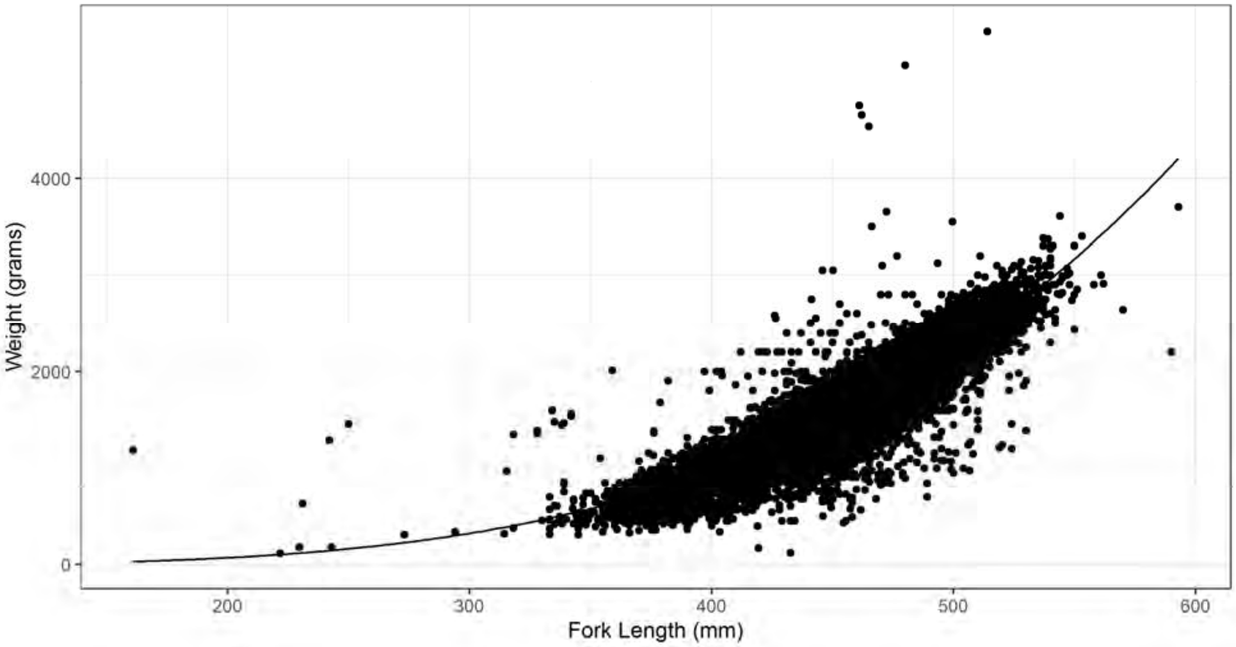


Figure 5. Predicted (line) and observed (circles) length-weight relationship of female American shad from the semelparous region.

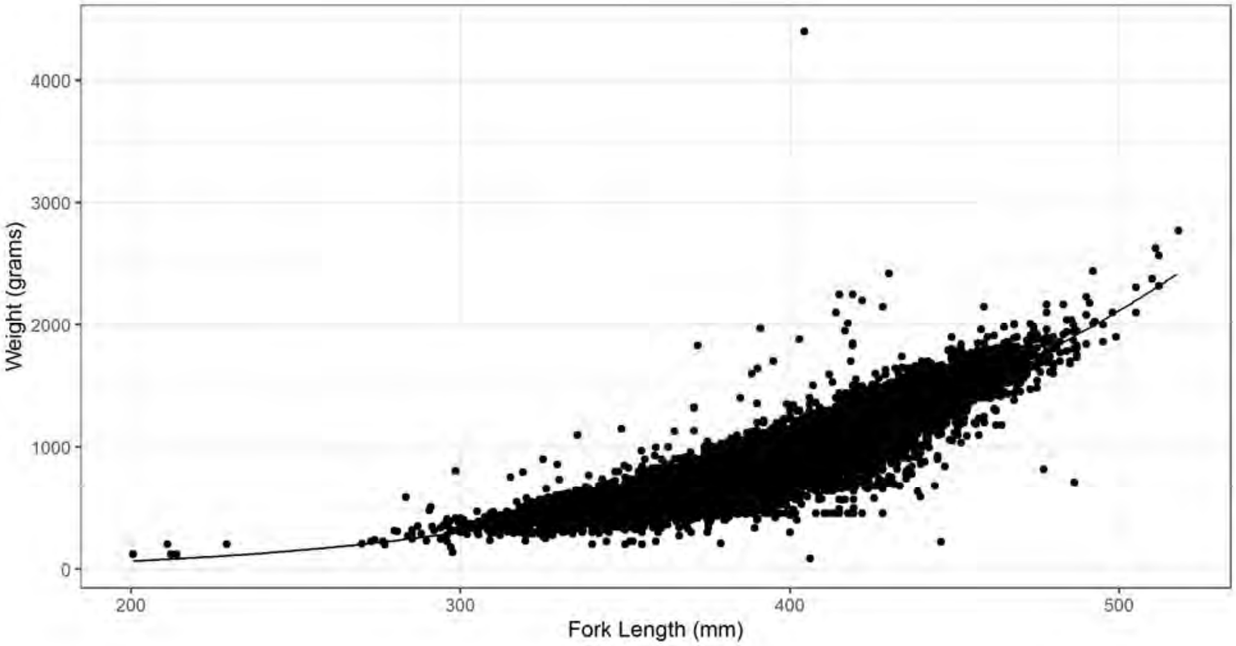


Figure 6. Predicted (line) and observed (circles) length-weight relationship of male American shad from the semelparous region.

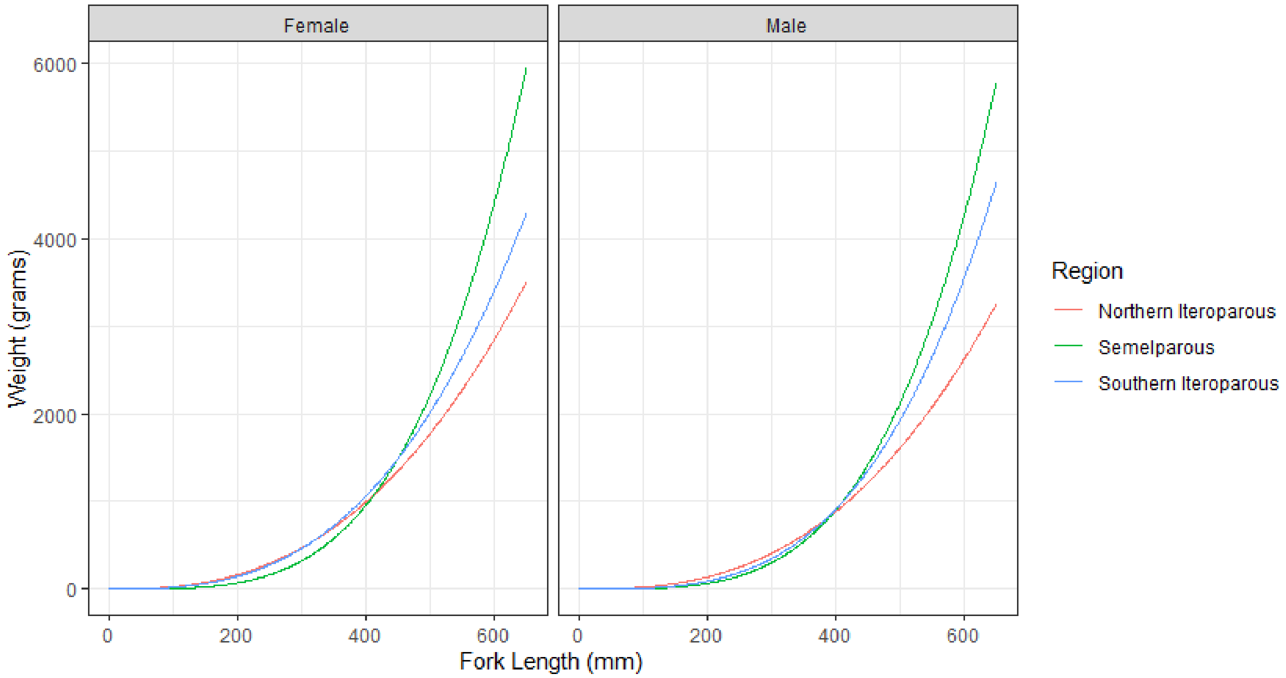


Figure 7. Predicted length-weight relationships of American shad by region and sex.

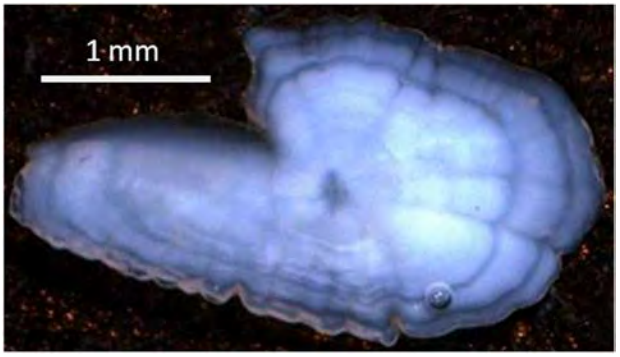


Figure 8. Distal view of an alewife sagittal otolith.

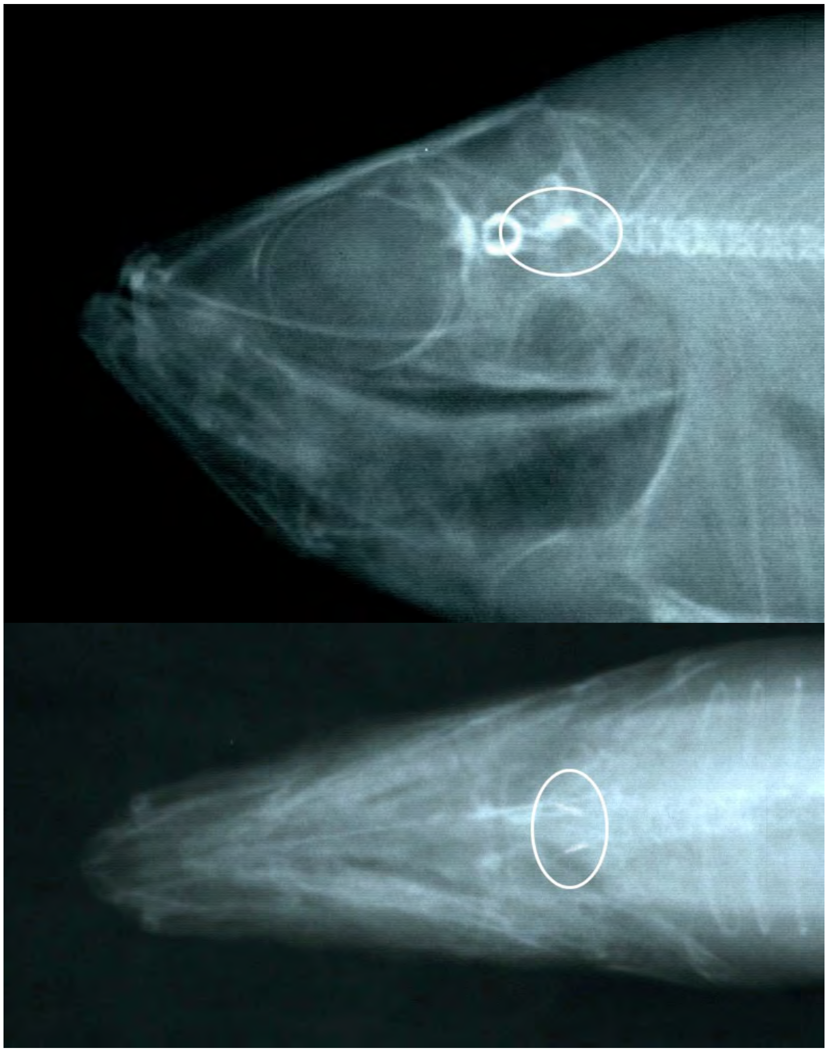


Figure 9. The lateral (top image) and ventral-dorsal (bottom image) views of sagittae in an alewife. Location is consistent among alosines.

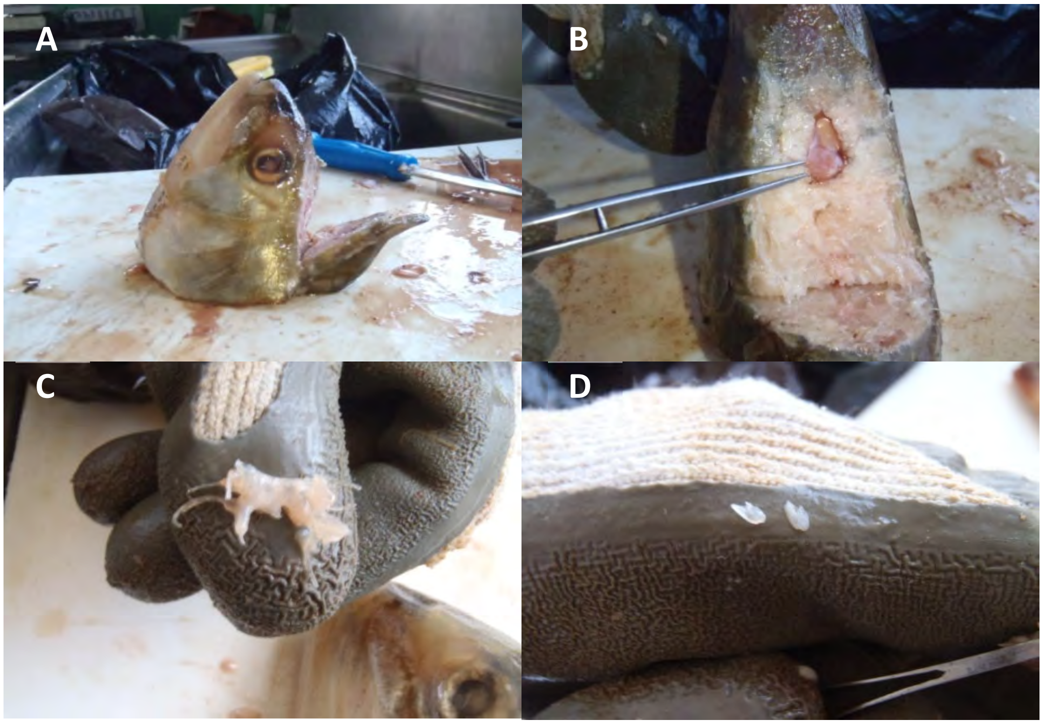


Figure 10. **A) Make a horizontally cut across cranium above eye to B) expose brain cavity and remove it carefully. C) Extract the sacculus from the brain cavity and D) carefully remove otoliths from within the membrane.**

Figure 11. **A blueback herring scale which is typical of the alosines.**

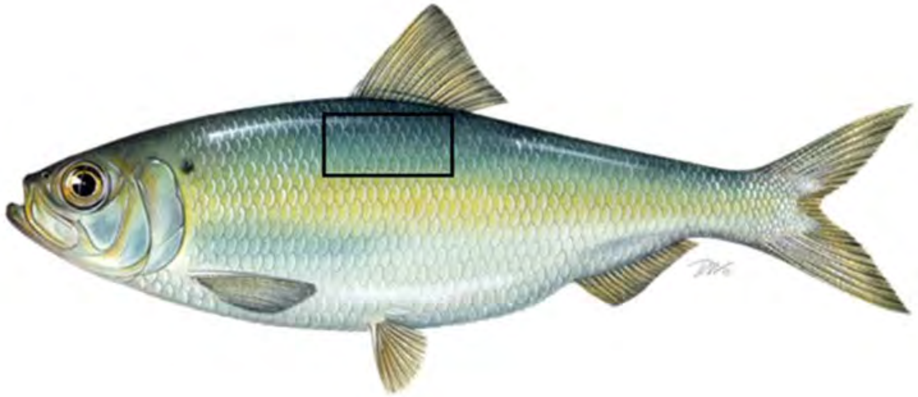


Figure 12. Scale collection area for alosines.

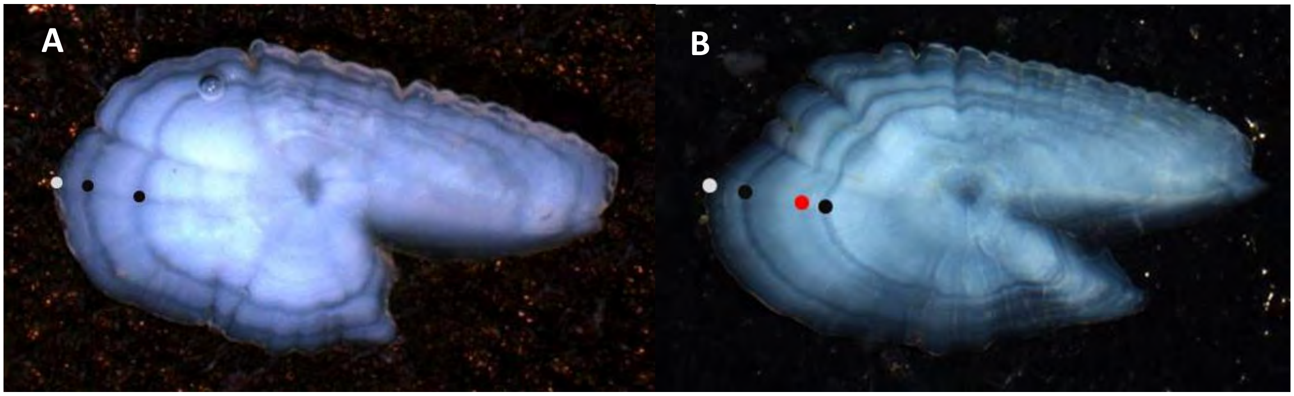


Figure 13. Whole blueback otoliths from A) an age-3 and B) an age-3 with a check mark or false annuli. Black dots mark the first and second annuli, the red dot marks the check, and the gray dot marks an annuli forming at the edge. Note: the growth between the first annulus and the check mark isn't as much as expected for it to be the second annulus and the check isn't continuously dark around the entire otolith.

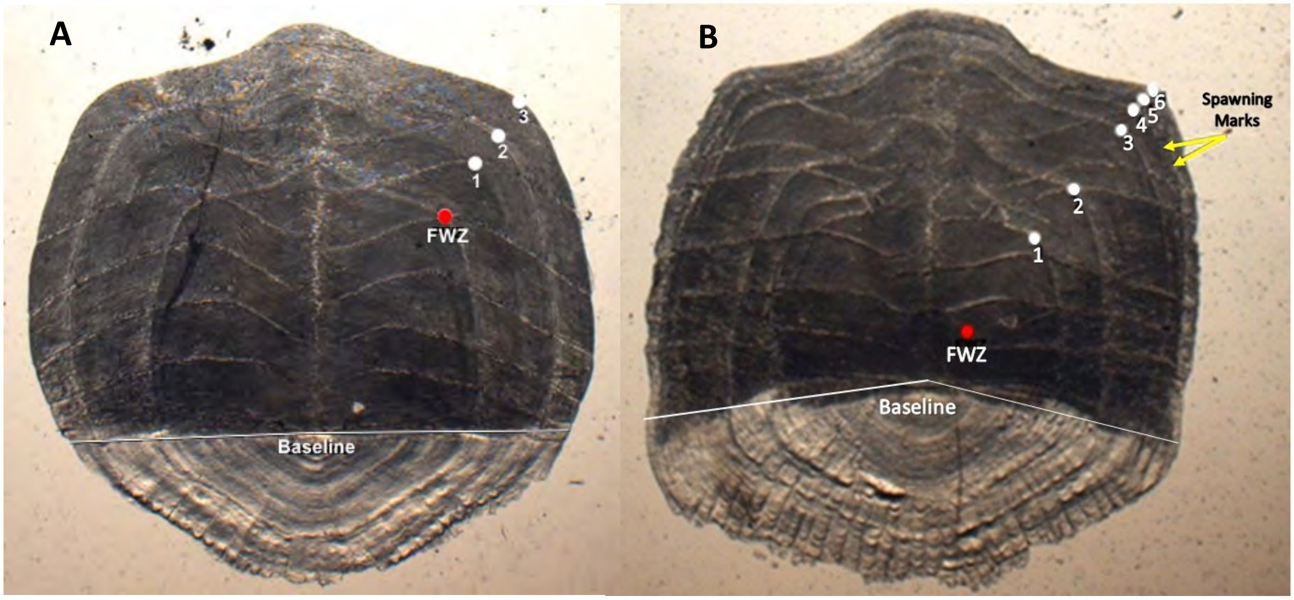
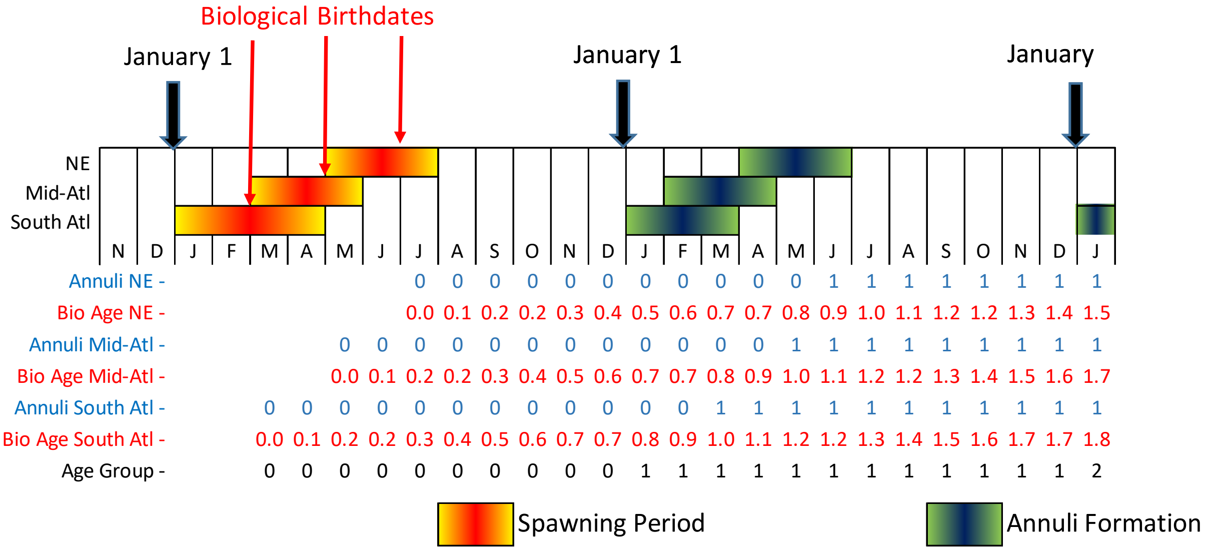


Figure 14. A) An age-3 alewife and B) an age-6 blueback with baseline, fresh water zone (FWZ in red), annuli (white), and spawning marks (yellow arrows) indicated. Note the straight baseline and large FWZ typical of alewife scales A) and angled baseline with narrow FWZ in blueback scales B).



	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J
Annuli NE -									0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
Bio Age NE -									0.0	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.1	1.2	1.2	1.3	1.4	1.5
Annuli Mid-Atl -							0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
Bio Age Mid-Atl -							0.0	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.1	1.2	1.2	1.3	1.4	1.5	1.6	1.7
Annuli South Atl -					0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Bio Age South Atl -					0.0	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.1	1.2	1.2	1.3	1.4	1.5	1.6	1.7	1.7	1.8
Age Group -					0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	2

Figure 15. Spawning periodicity and age assignment timeline for American shad from New England to Florida.

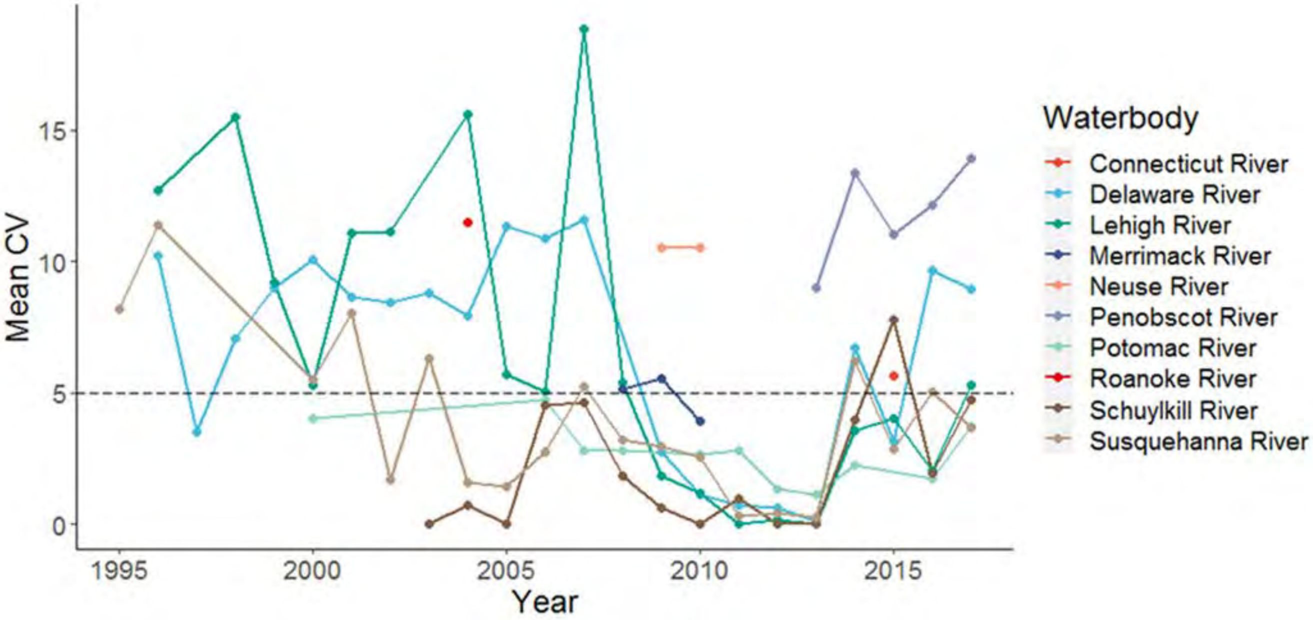


Figure 16. Mean CV of paired scale and otolith age estimates. The dashed black line indicates a target for precision at 5%.

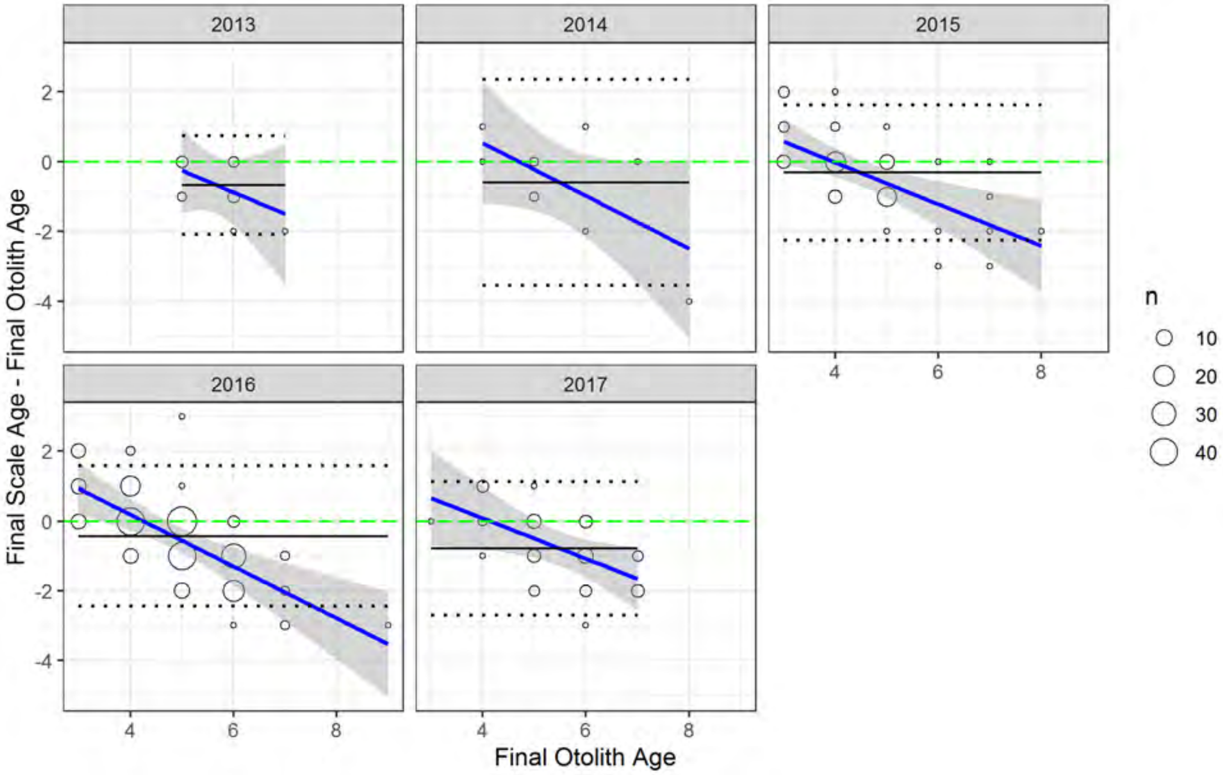


Figure 17. Bland-Altman plot of paired scale and otolith age estimate comparisons from the Penobscot River. The solid black line is the mean difference between age estimates across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between age estimates, the blue line is a linear smoother fit through the mean differences between age estimates at respective otolith ages on the x-axis, and the bubbles are the number of samples at the difference between ages.

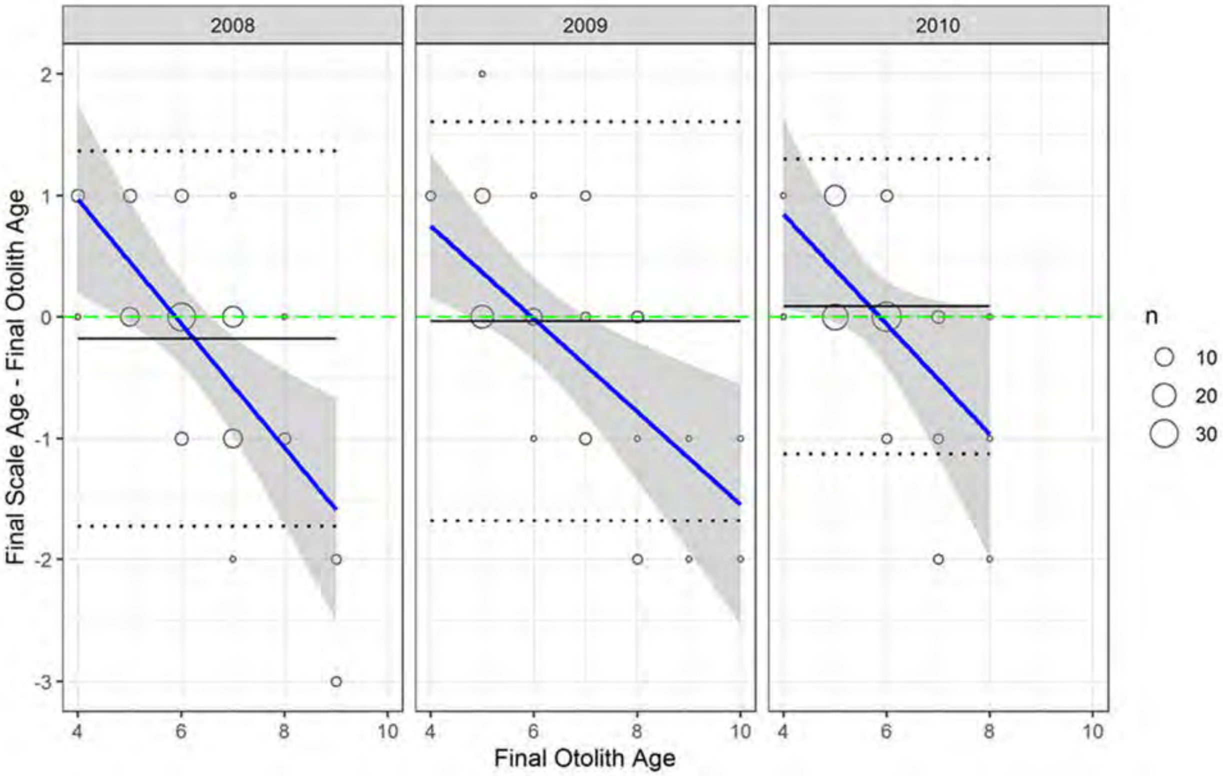


Figure 18. Bland-Altman plot of paired scale and otolith age estimate comparisons from the Merrimack River. The solid black line is the mean difference between age estimates across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between age estimates, the blue line is a linear smoother fit through the mean differences between age estimates at respective otolith ages on the x-axis, and the bubbles are the number of samples at the difference between ages.

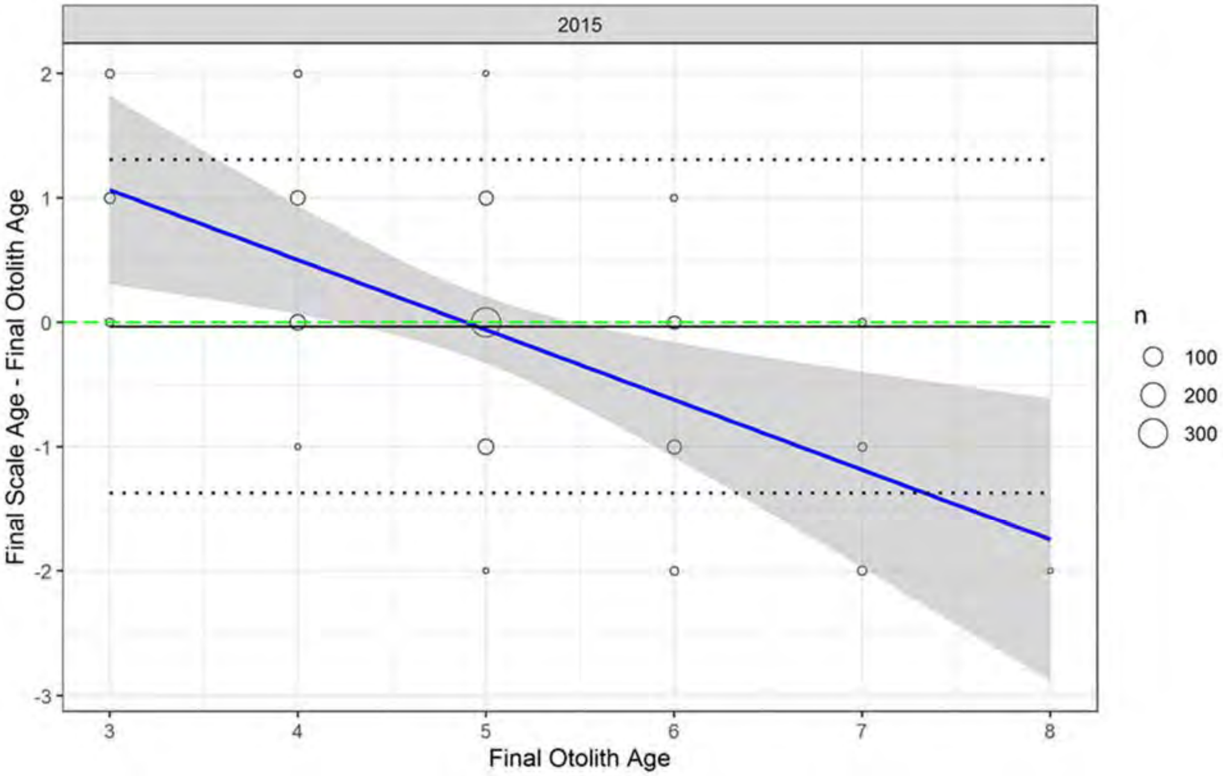


Figure 19. **Bland-Altman plot of paired scale and otolith age estimate comparisons from the Connecticut River. The solid black line is the mean difference between age estimates across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between age estimates, the blue line is a linear smoother fit through the mean differences between age estimates at respective otolith ages on the x-axis, and the bubbles are the number of samples at the difference between ages.**

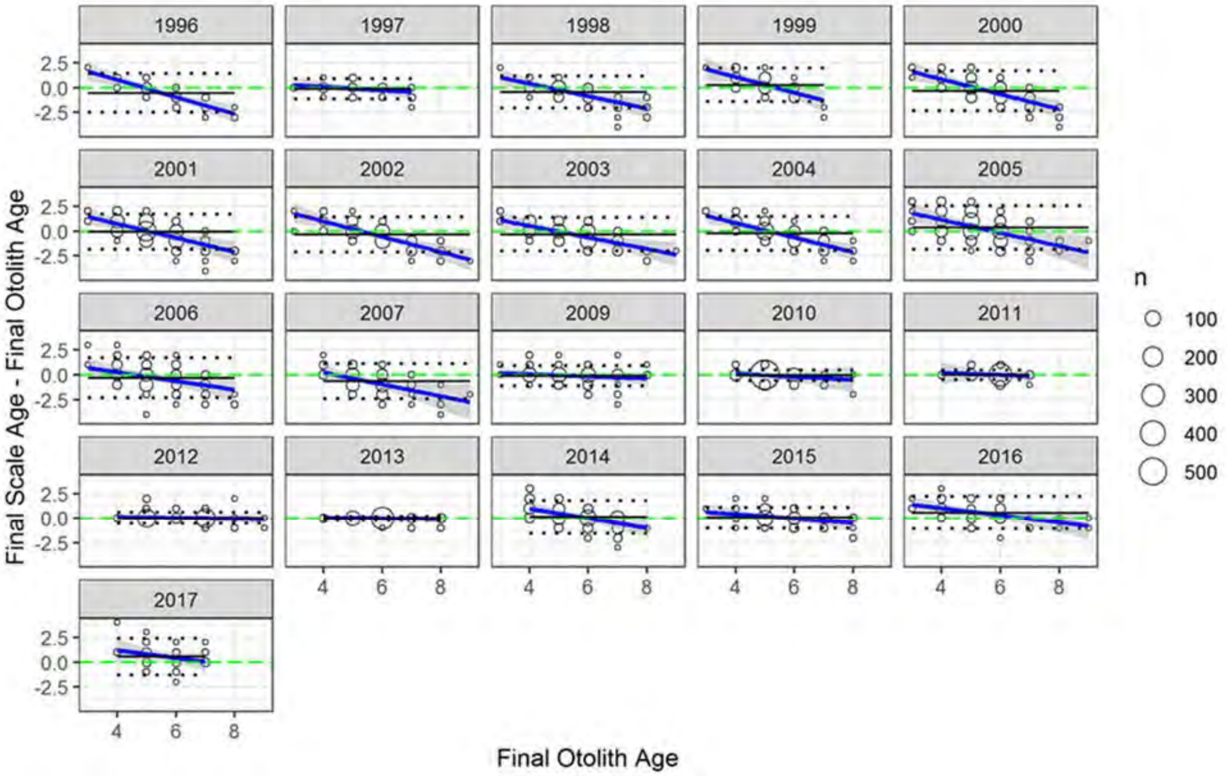


Figure 20. **Bland-Altman plot of paired scale and otolith age estimate comparisons from the Delaware River. The solid black line is the mean difference between age estimates across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between age estimates, the blue line is a linear smoother fit through the mean differences between age estimates at respective otolith ages on the x-axis, and the bubbles are the number of samples at the difference between ages.**

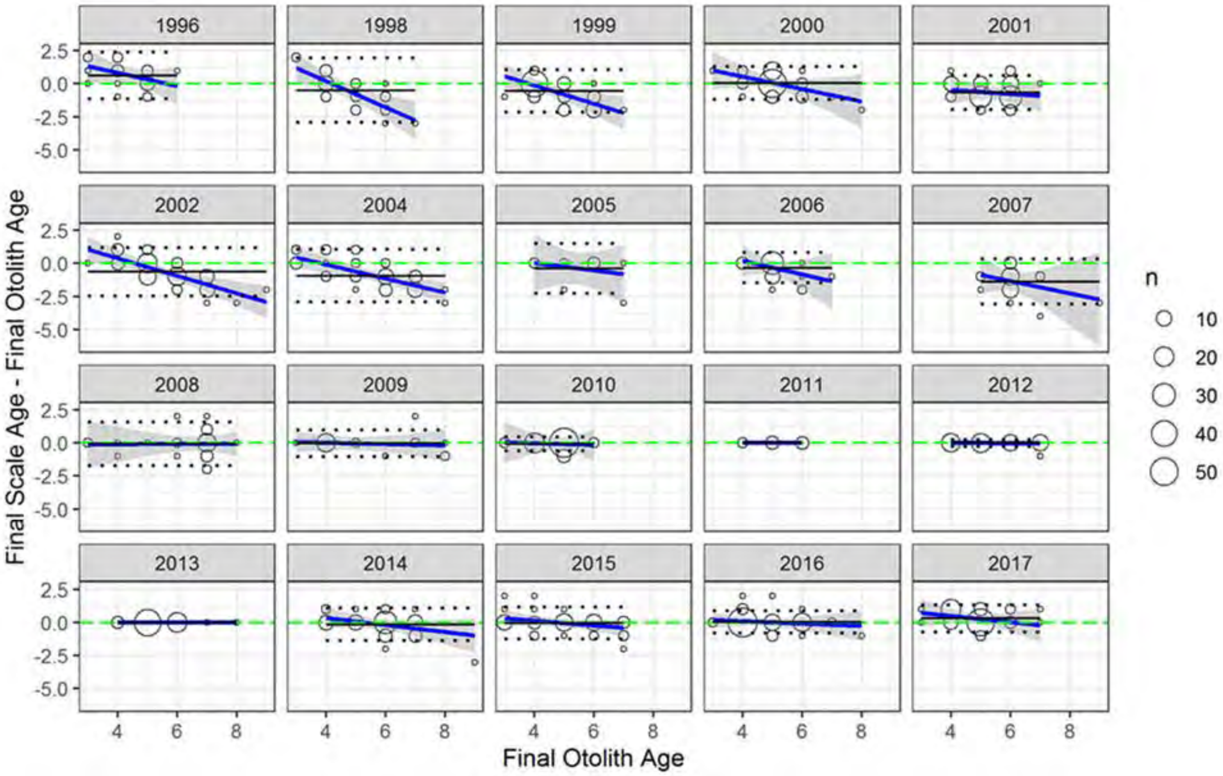


Figure 21. **Bland-Altman plot of paired scale and otolith age estimate comparisons from the Lehigh River. The solid black line is the mean difference between age estimates across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between age estimates, the blue line is a linear smoother fit through the mean differences between age estimates at respective otolith ages on the x-axis, and the bubbles are the number of samples at the difference between ages.**

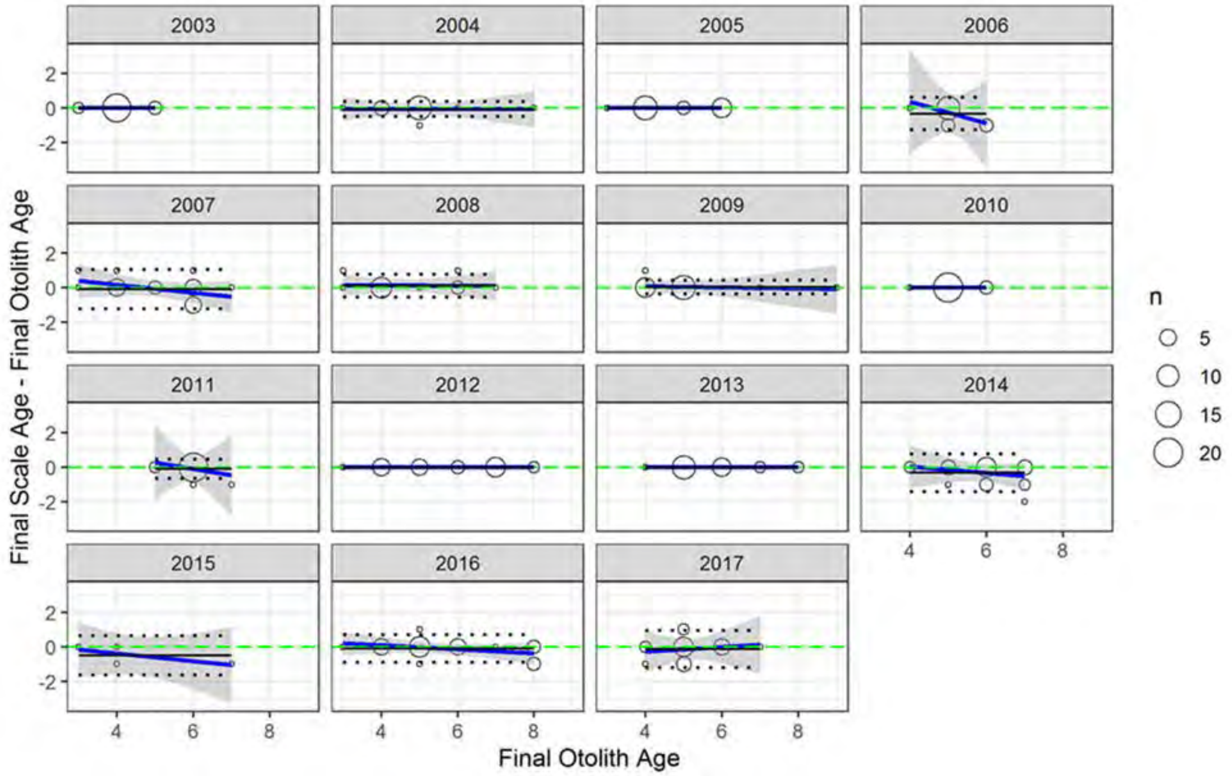


Figure 22. Bland-Altman plot of paired scale and otolith age estimate comparisons from the Schuylkill River. The solid black line is the mean difference between age estimates across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between age estimates, the blue line is a linear smoother fit through the mean differences between age estimates at respective otolith ages on the x-axis, and the bubbles are the number of samples at the difference between ages.

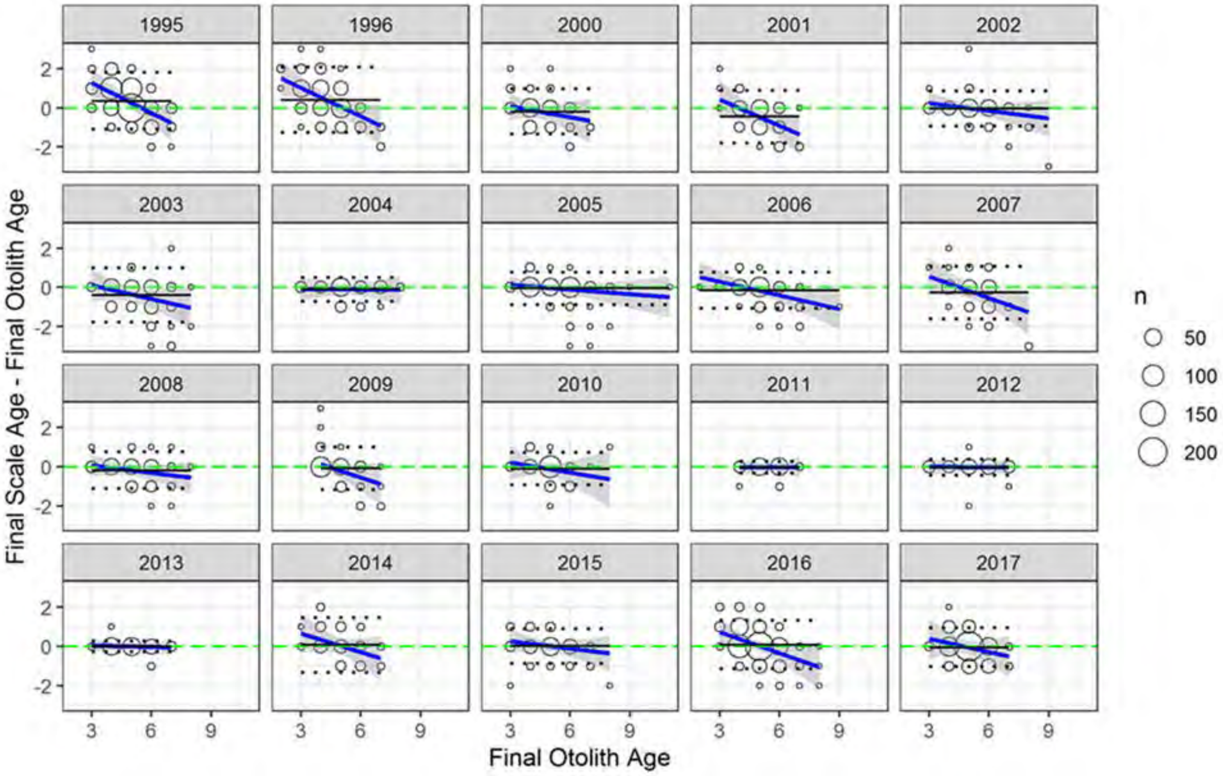


Figure 23. **Bland-Altman plot of paired scale and otolith age estimate comparisons from the Susquehanna River. The solid black line is the mean difference between age estimates across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between age estimates, the blue line is a linear smoother fit through the mean differences between age estimates at respective otolith ages on the x-axis, and the bubbles are the number of samples at the difference between ages.**

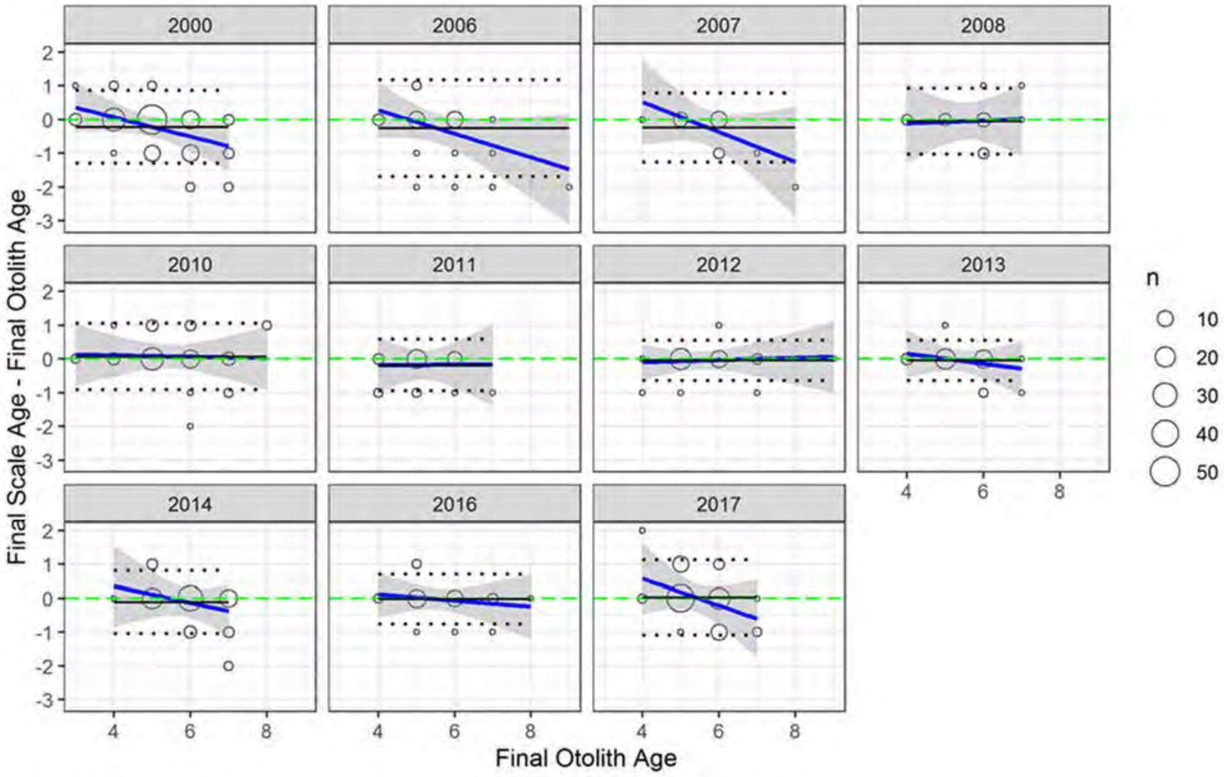


Figure 24. Bland-Altman plot of paired scale and otolith age estimate comparisons from the Potomac River. The solid black line is the mean difference between age estimates across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between age estimates, the blue line is a linear smoother fit through the mean differences between age estimates at respective otolith ages on the x-axis, and the bubbles are the number of samples at the difference between ages.

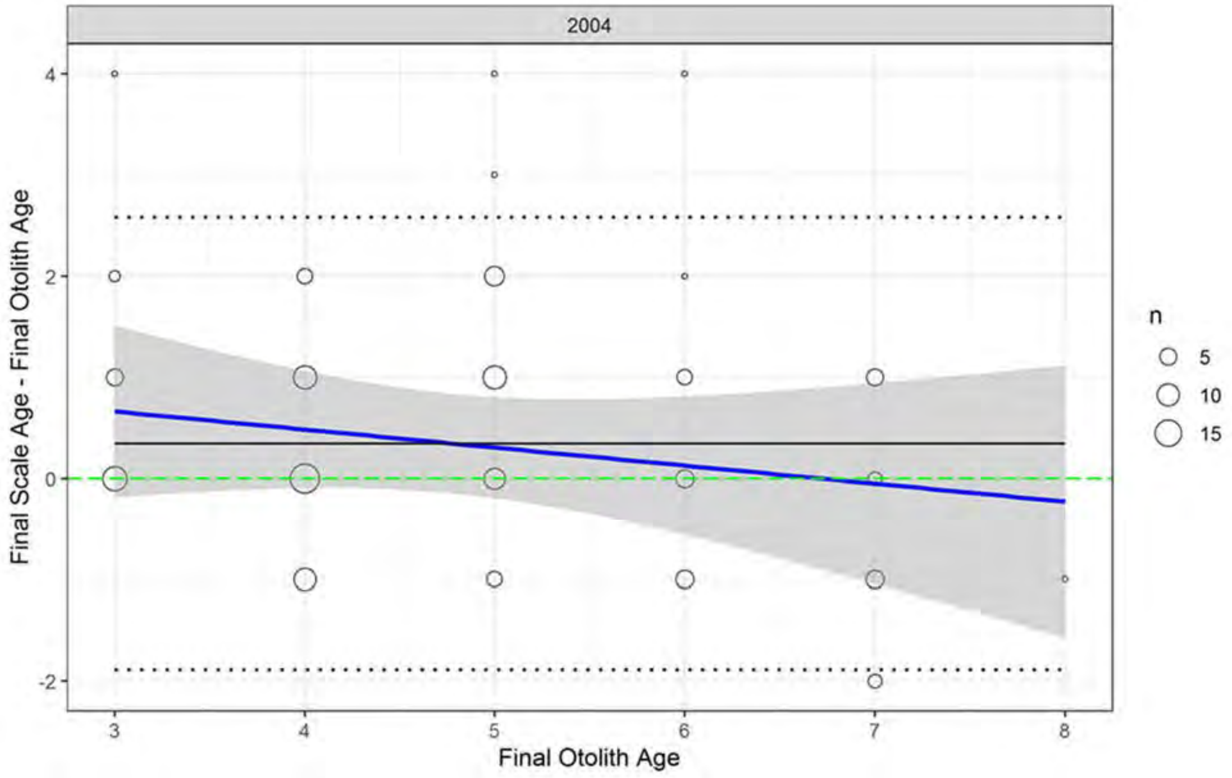


Figure 25. **Bland-Altman plot of paired scale and otolith age estimate comparisons from the Roanoke River. The solid black line is the mean difference between age estimates across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between age estimates, the blue line is a linear smoother fit through the mean differences between age estimates at respective otolith ages on the x-axis, and the bubbles are the number of samples at the difference between ages.**

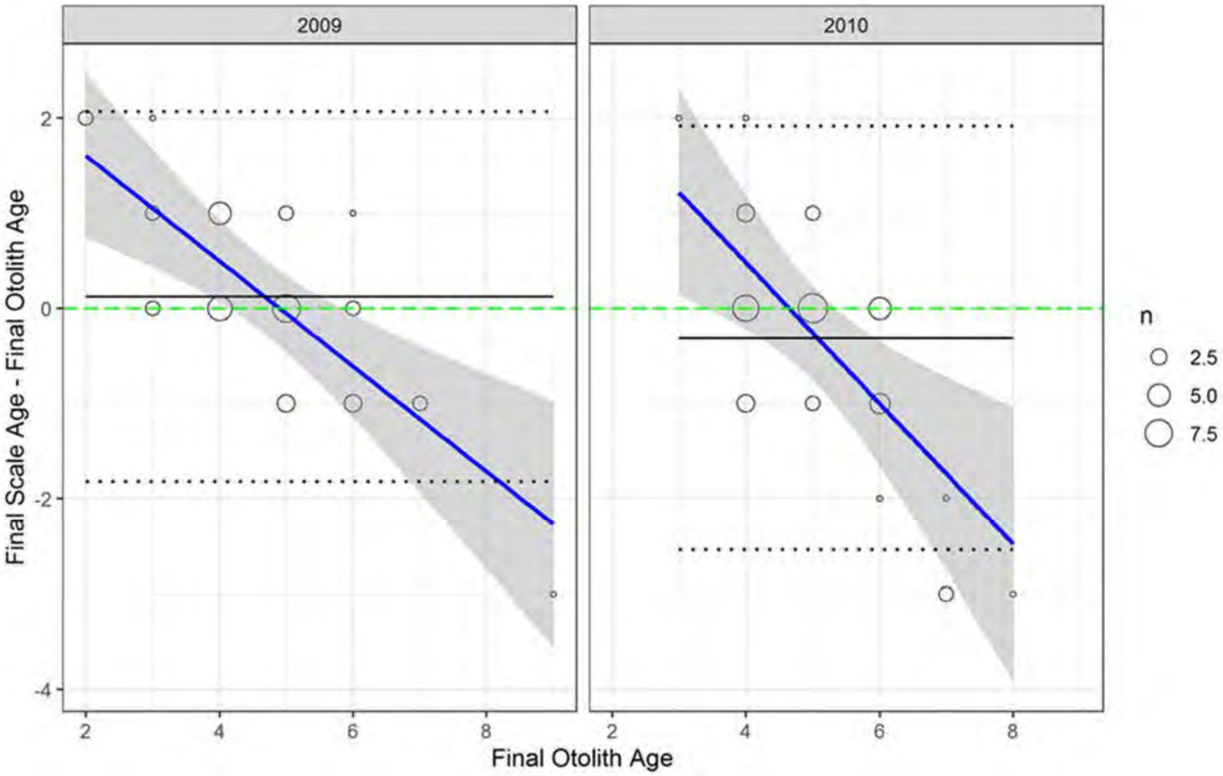


Figure 26. Bland-Altman plot of paired scale and otolith age estimate comparisons from the Neuse River. The solid black line is the mean difference between age estimates across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between age estimates, the blue line is a linear smoother fit through the mean differences between age estimates at respective otolith ages on the x-axis, and the bubbles are the number of samples at the difference between ages.

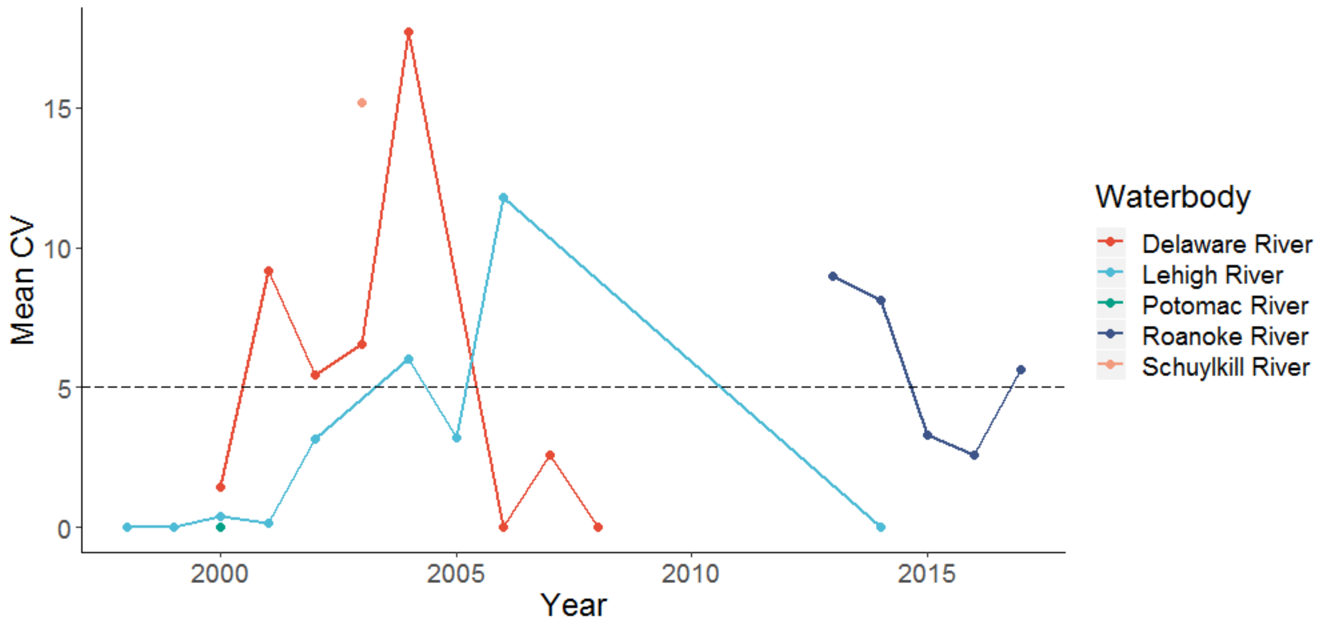


Figure 27. Mean CV of otolith age estimate and known age. The dashed black line indicates a target for precision at 5%.

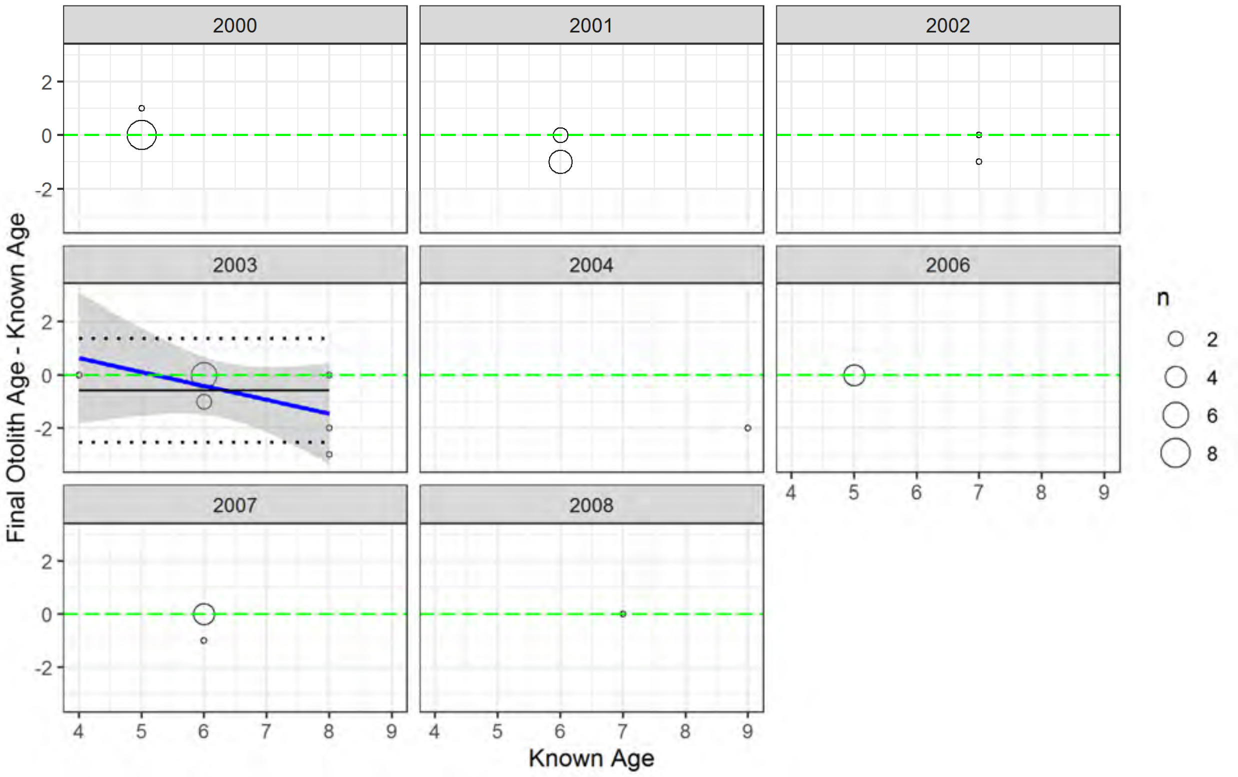


Figure 28. Bland-Altman plot of otolith age estimate and known age comparisons from the Delaware River. The solid black line is the mean difference between ages across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between ages, the blue line is a linear smoother fit through the mean differences between ages at respective known ages on the x-axis, and the bubbles are the number of samples at the difference between ages.

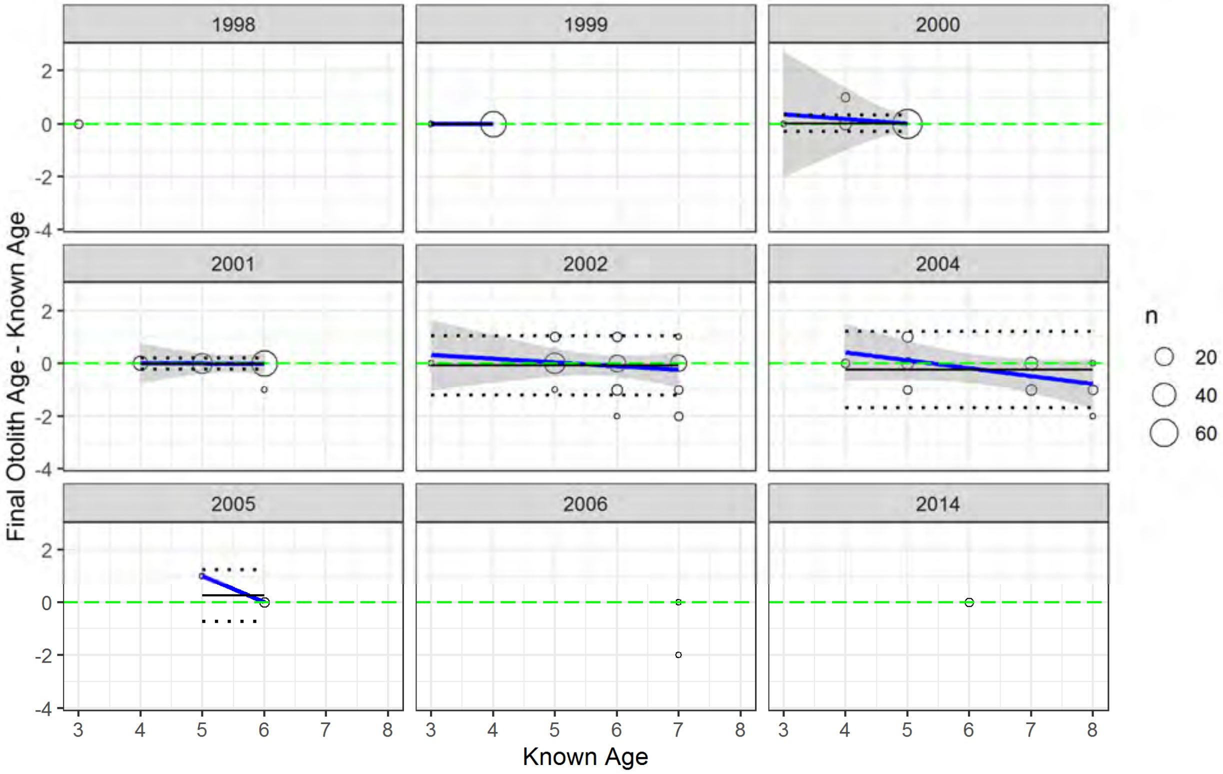


Figure 29. **Bland-Altman plot of otolith age estimate and known age comparisons from the Lehigh River. The solid black line is the mean difference between ages across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between ages, the blue line is a linear smoother fit through the mean differences between ages at respective known ages on the x-axis, and the bubbles are the number of samples at the difference between ages.**

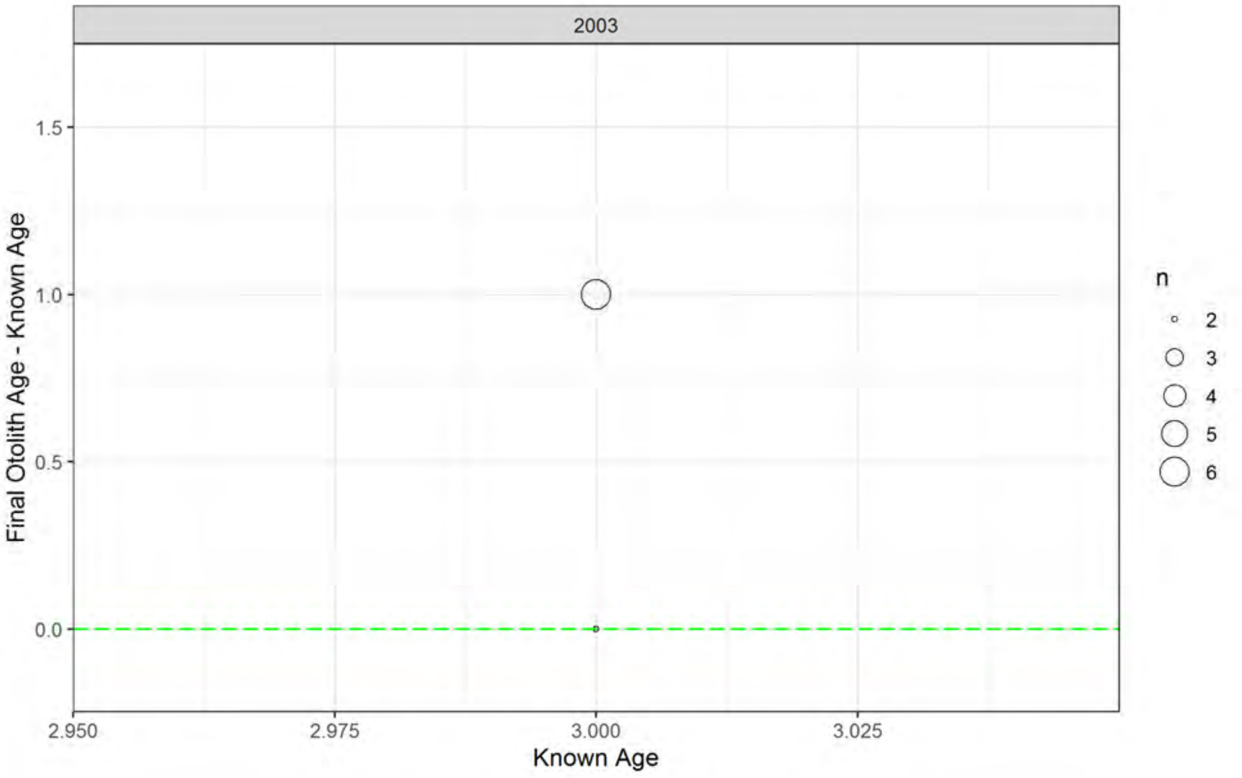


Figure 30. **Bland-Altman plot of otolith age estimate and known age comparisons from the Schuylkill River. The green line is reference for no difference between ages and the bubbles are the number of samples at the difference between ages.**

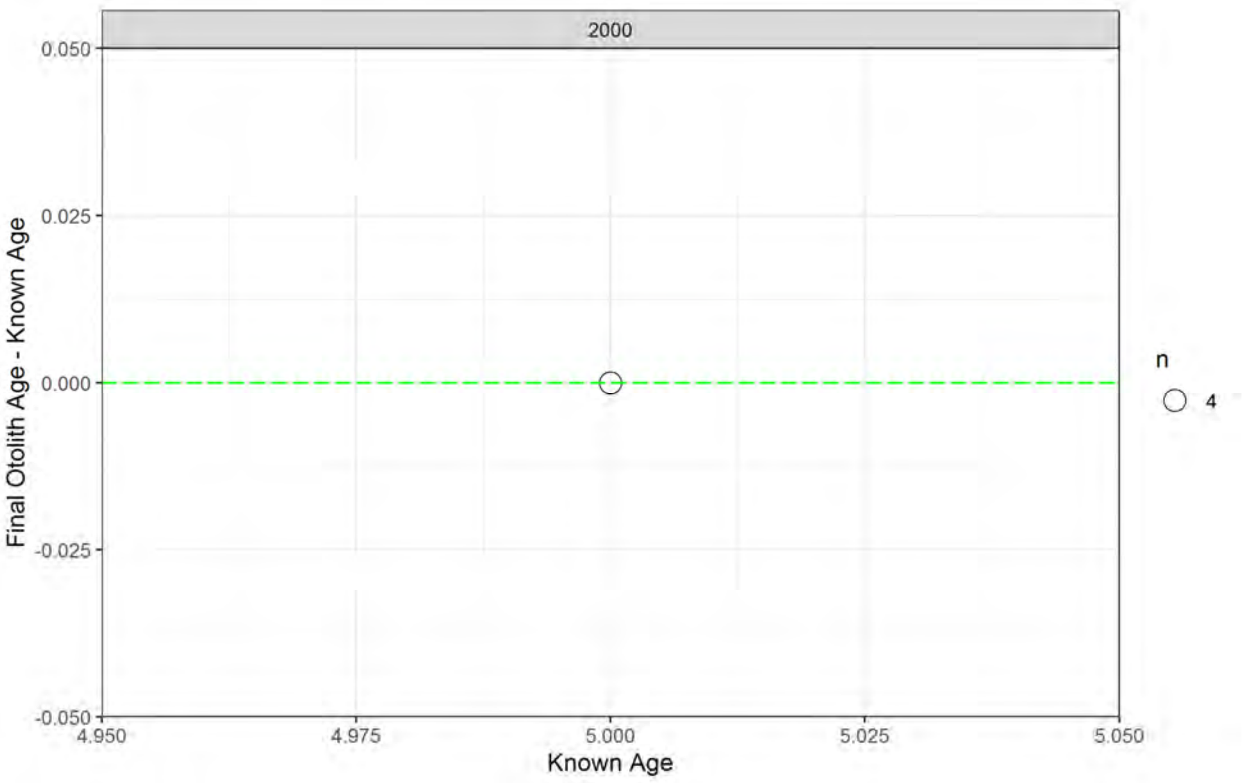


Figure 31. Bland-Altman plot of otolith age estimate and known age comparisons from the Potomac River. The green line is reference for no difference between ages and the bubbles are the number of samples at the difference between ages.

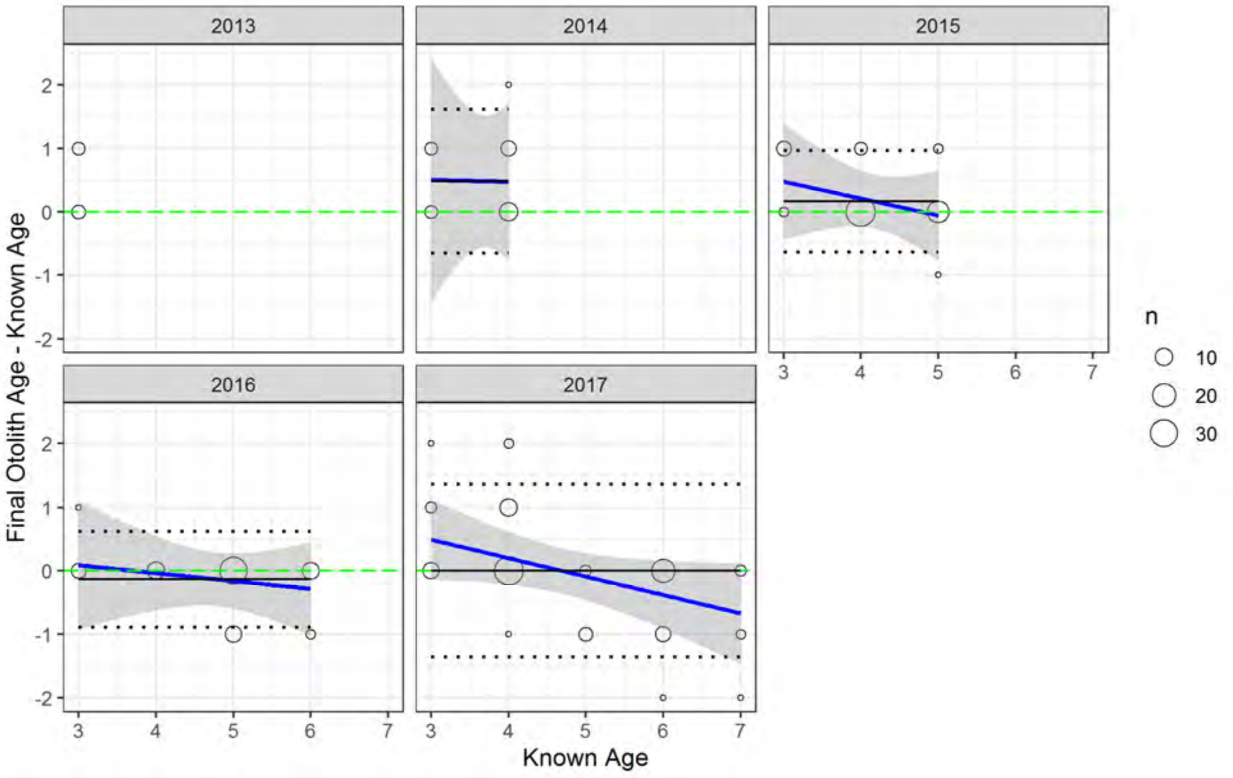


Figure 32. Bland-Altman plot of otolith age estimate and known age comparisons from the Roanoke River. The solid black line is the mean difference between ages across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between ages, the blue line is a linear smoother fit through the mean differences between ages at respective known ages on the x-axis, and the bubbles are the number of samples at the difference between ages.

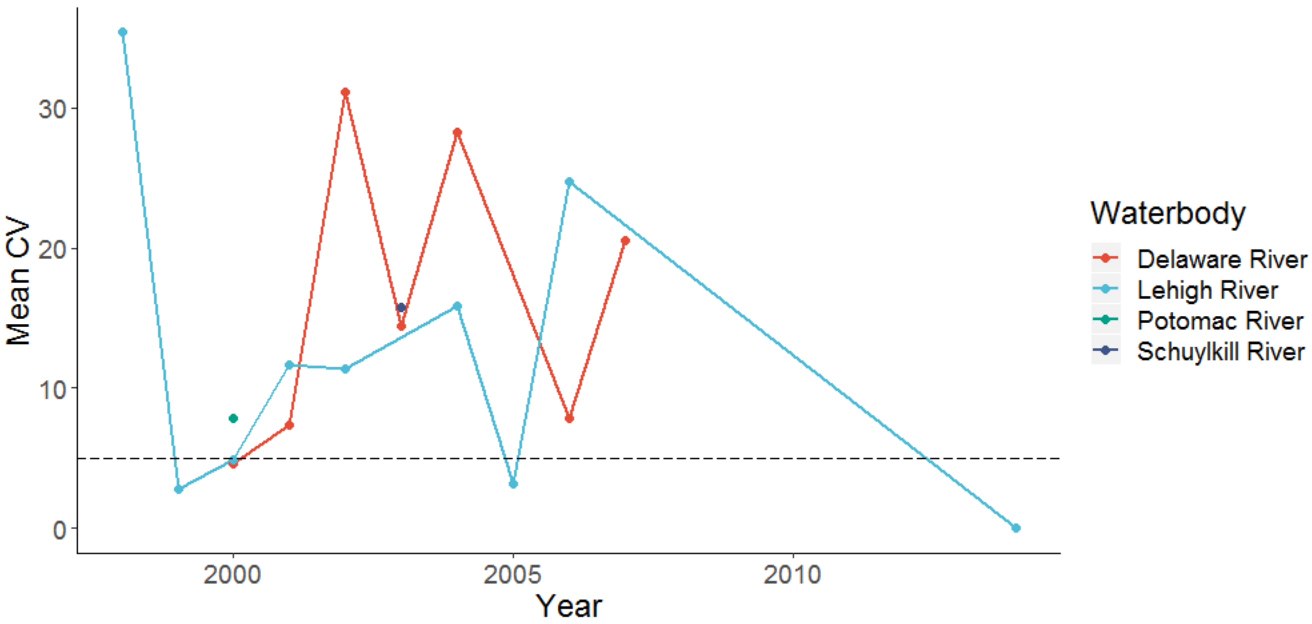


Figure 33. Mean CV of scale age estimate and known age. The dashed black line indicates a target for precision at 5%.

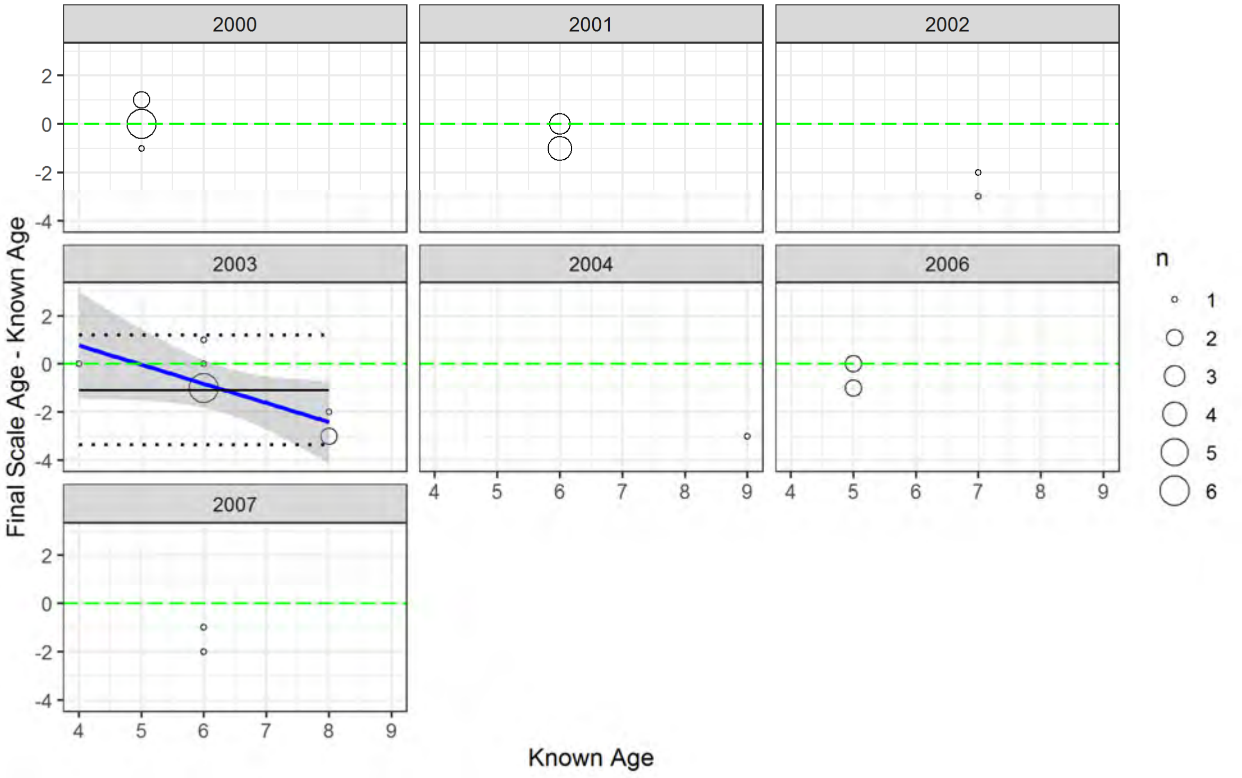


Figure 34. Bland-Altman plot of scale age estimate and known age comparisons from the Delaware River. The solid black line is the mean difference between ages across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between ages, the blue line is a linear smoother fit through the mean differences between ages at respective known ages on the x-axis, and the bubbles are the number of samples at the difference between ages.

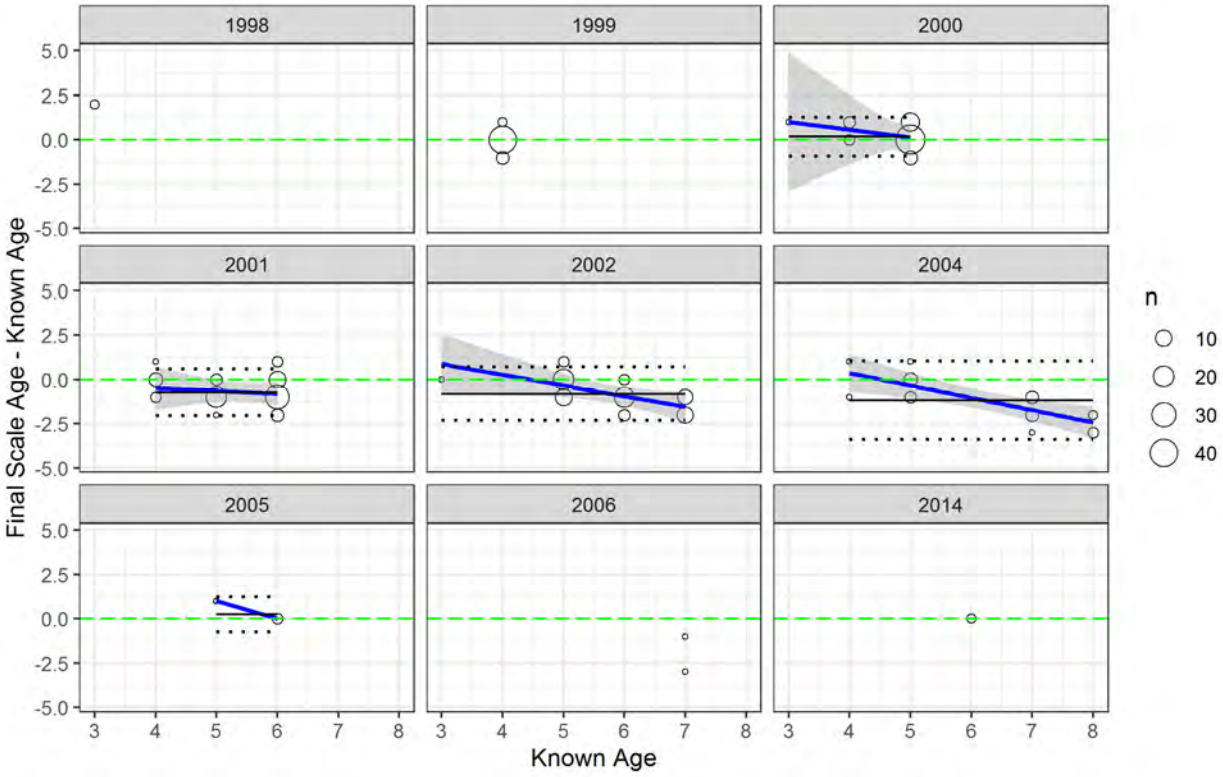


Figure 35. Bland-Altman plot of scale age estimate and known age comparisons from the Lehigh River. The solid black line is the mean difference between ages across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between ages, the blue line is a linear smoother fit through the mean differences between ages at respective known ages on the x-axis, and the bubbles are the number of samples at the difference between ages.

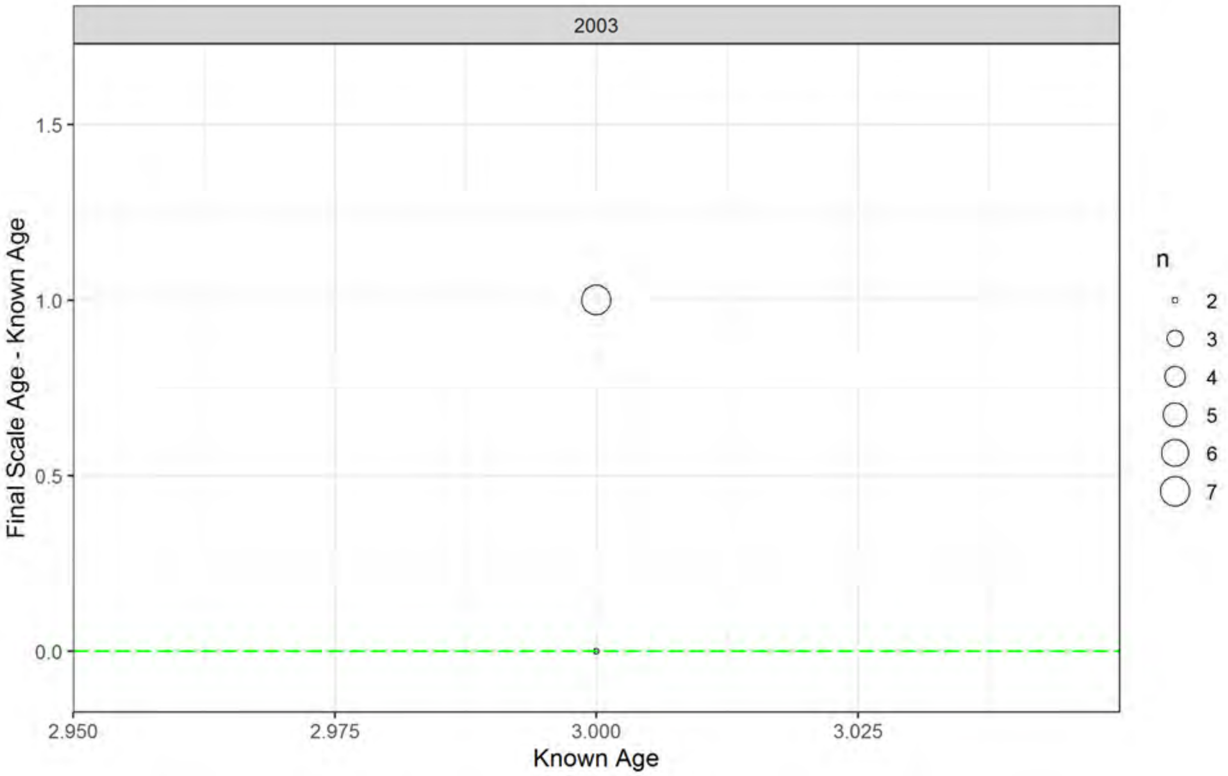


Figure 36. Bland-Altman plot of scale age estimate and known age comparisons from the Schuylkill River. The green line is reference for no difference between ages and the bubbles are the number of samples at the difference between ages.

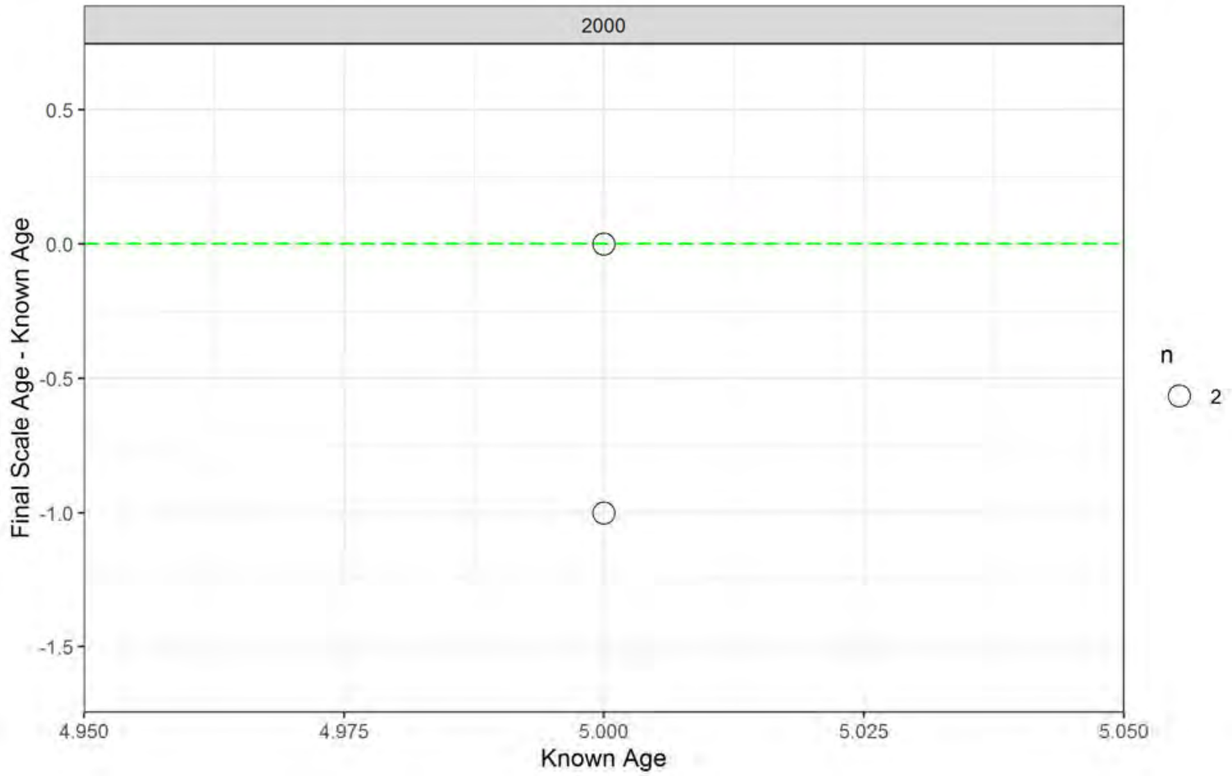


Figure 37. Bland-Altman plot of scale age estimate and known age comparisons from the Potomac River. The green line is reference for no difference between ages and the bubbles are the number of samples at the difference between ages.

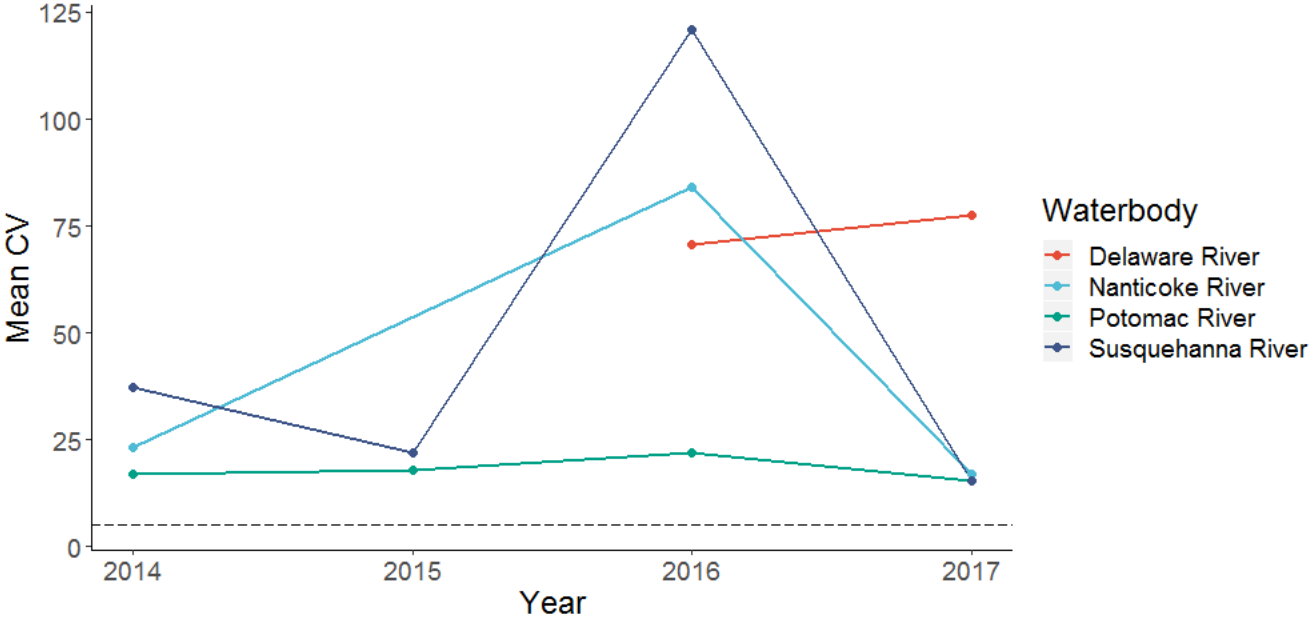


Figure 38. Mean CV of spawn mark estimates from two readers. The dashed black line indicates a target for precision at 5%.

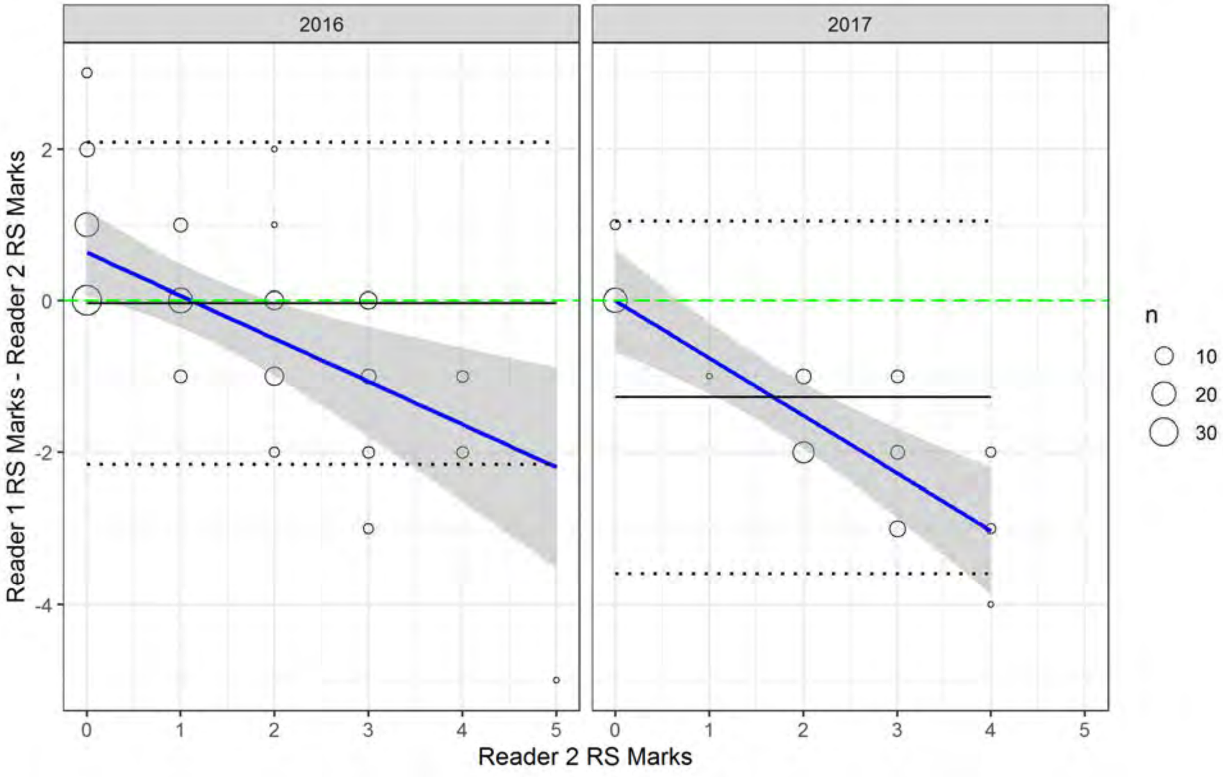


Figure 39. Bland-Altman plot of comparisons of spawn mark estimates from two readers from the Delaware River. The solid black line is the mean difference between estimates across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between estimates, the blue line is a linear smoother fit through the mean differences between estimates at respective spawn mark counts from reader 2 on the x-axis, and the bubbles are the number of samples at the difference between estimates.

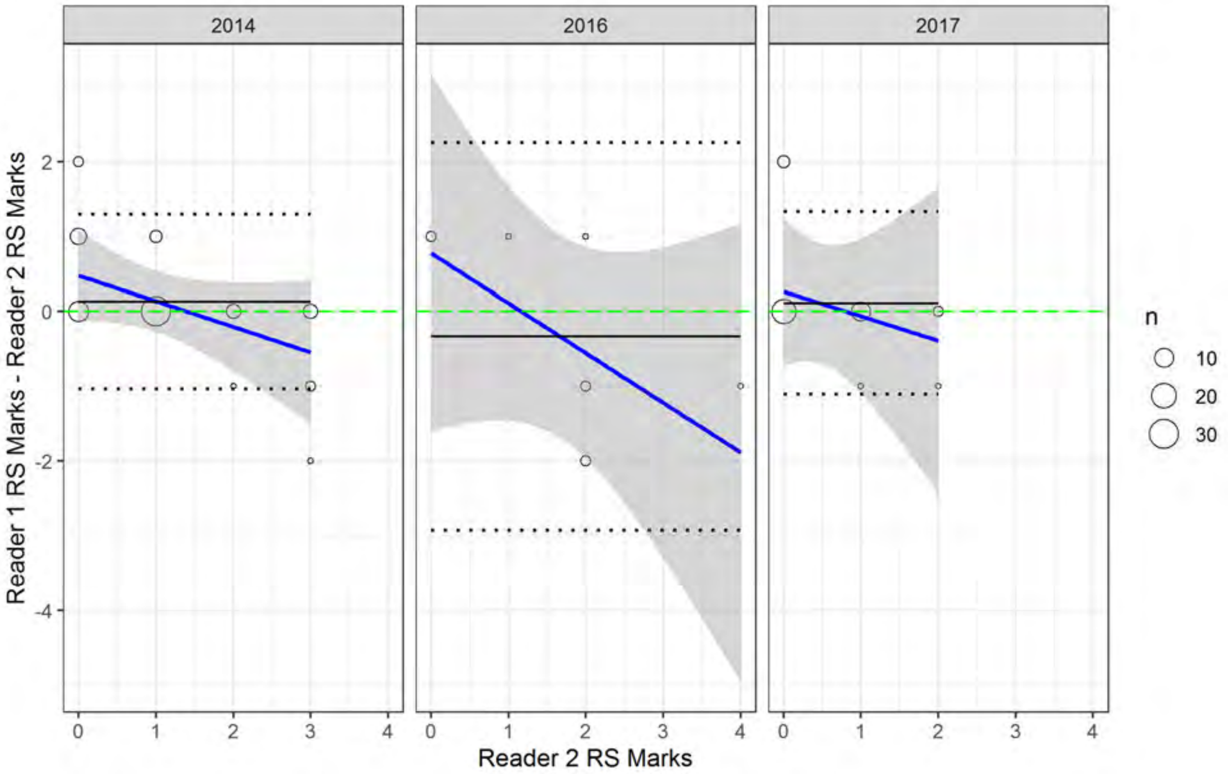


Figure 40. **Bland-Altman plot of comparisons of spawn mark estimates from two readers from the Nanticoke River. The solid black line is the mean difference between estimates across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between estimates, the blue line is a linear smoother fit through the mean differences between estimates at respective spawn mark counts from reader 2 on the x-axis, and the bubbles are the number of samples at the difference between estimates.**

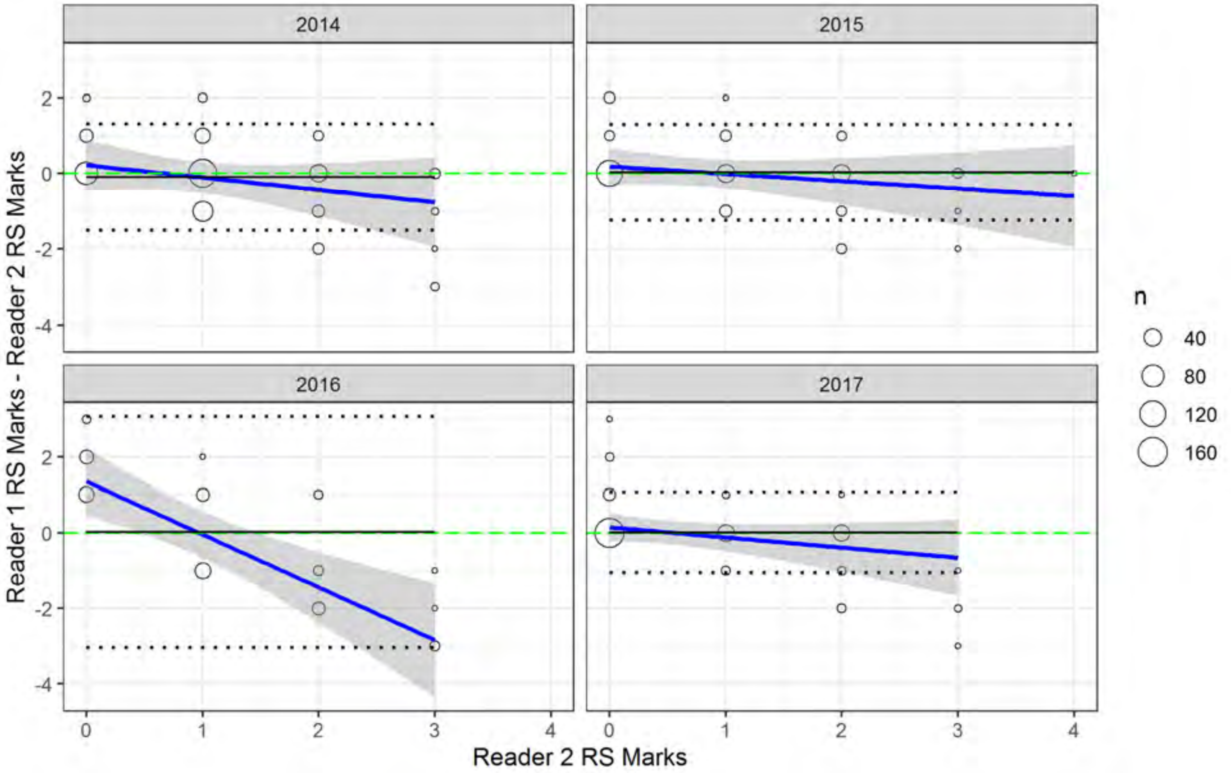


Figure 41. **Bland-Altman plot of comparisons of spawn mark estimates from two readers from the Susquehanna River. The solid black line is the mean difference between estimates across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between estimates, the blue line is a linear smoother fit through the mean differences between estimates at respective spawn mark counts from reader 2 on the x-axis, and the bubbles are the number of samples at the difference between estimates.**

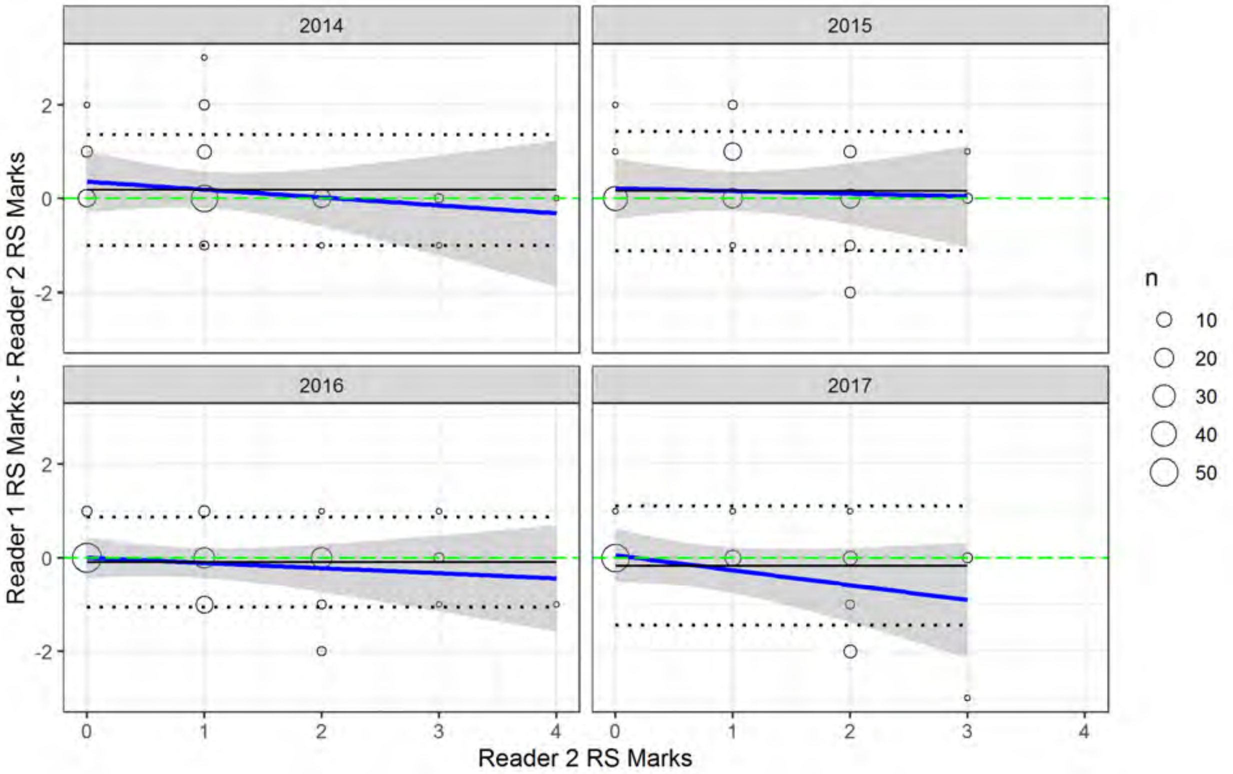


Figure 42. **Bland-Altman plot of comparisons of spawn mark estimates from two readers from the Potomac River. The solid black line is the mean difference between estimates across all samples, the black dashed lines are 95% confidence intervals around the mean difference across all samples, the green line is reference for no difference between estimates, the blue line is a linear smoother fit through the mean differences between estimates at respective spawn mark counts from reader 2 on the x-axis, and the bubbles are the number of samples at the difference between estimates.**

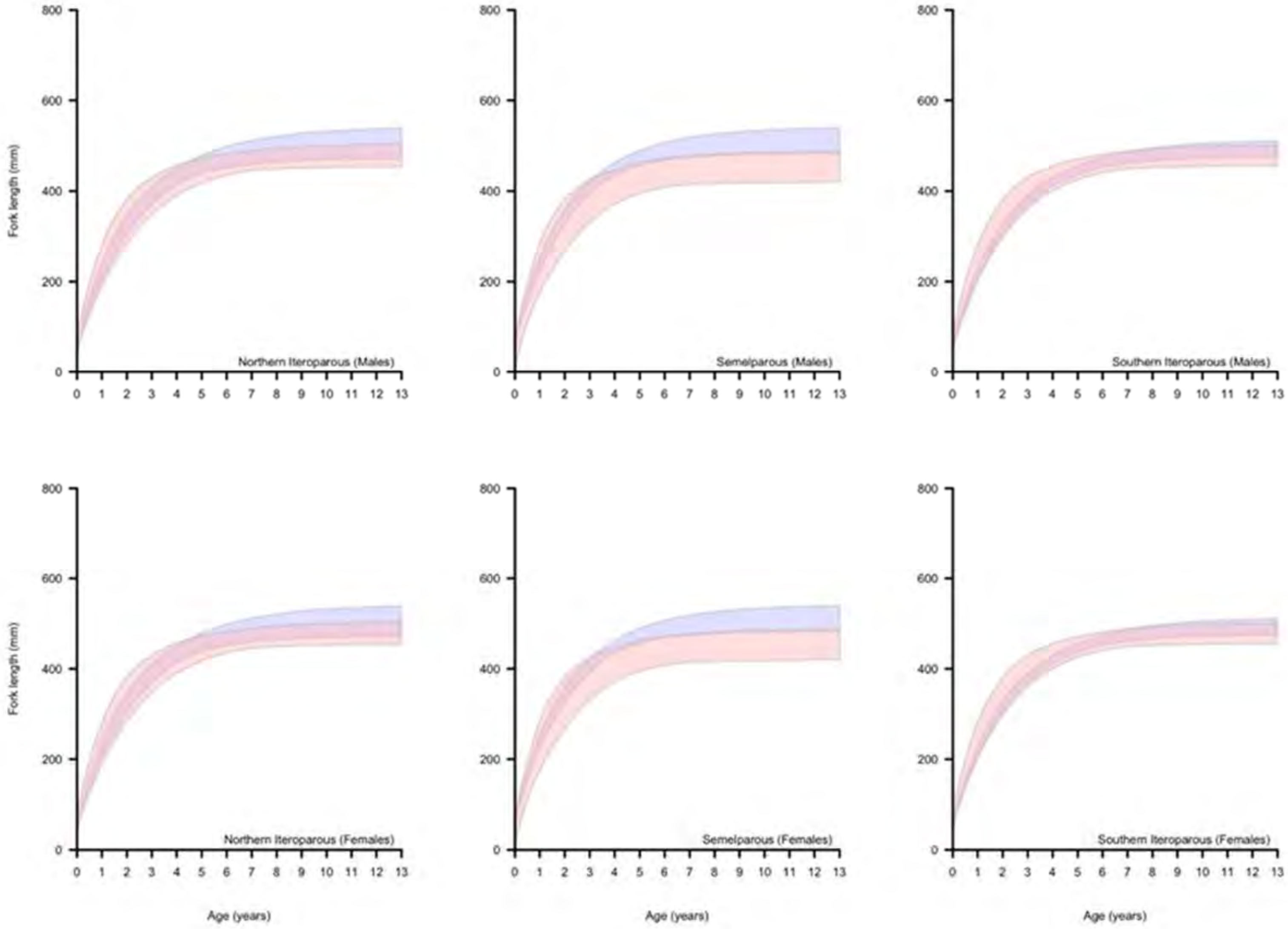


Figure 43. Differences in growth due to otolith-based (red) ageing approaches compared to scale-based (blue) approaches for males and females in each region.

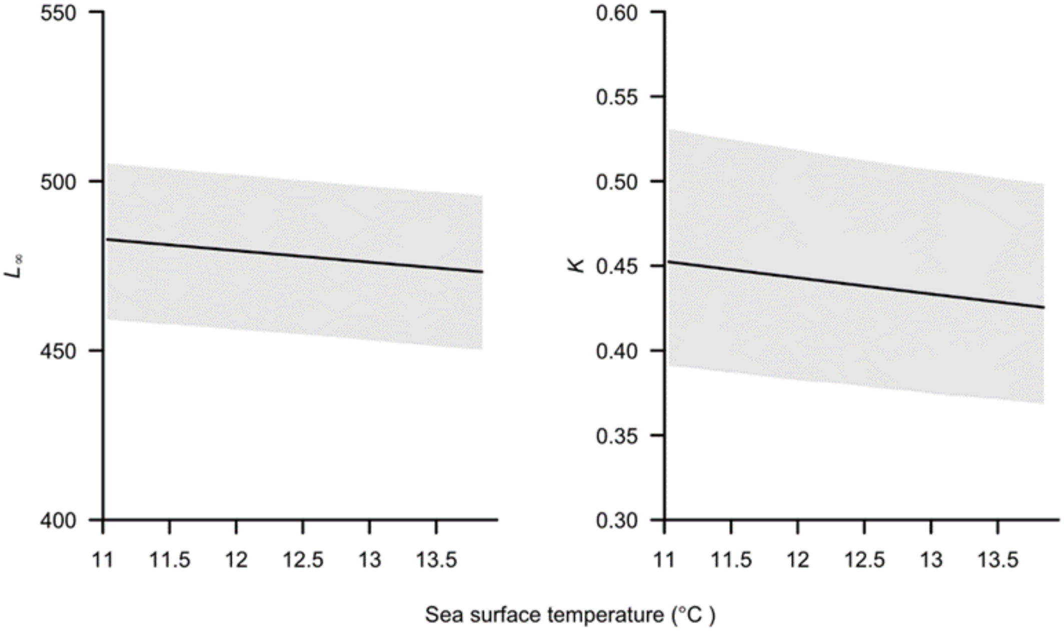


Figure 44. Observed effects on von Bertalanffy growth parameters from rising sea surface temperatures during the 1981-2017 time-frame. The black solid line represents the mean and the light gray represents 95% credible intervals.

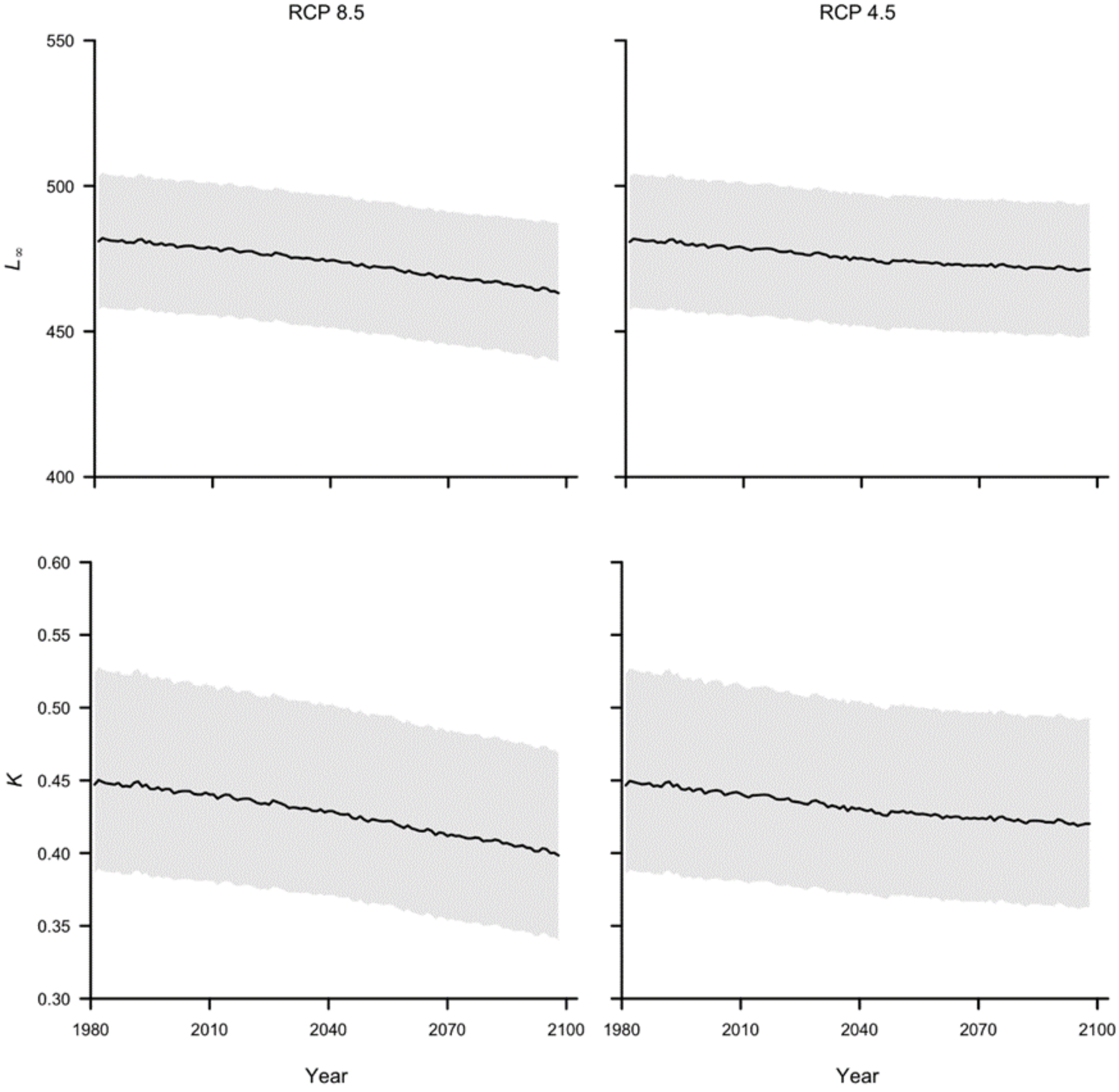


Figure 45. **Projected temperature effects on von Bertalanffy growth parameters for RCP 4.5 and RCP 8.5 climate scenarios from 1981-2099. The black solid line represents the mean and the light gray represents 95% credible intervals.**

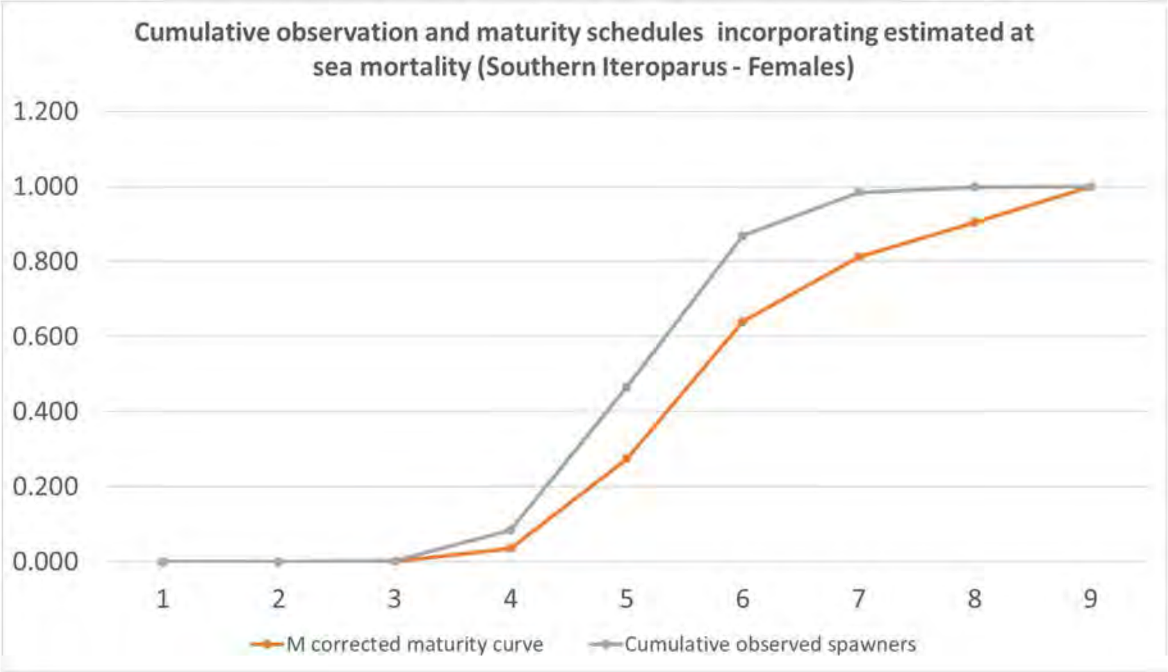


Figure 46. Result of mortality correction approach with respect to a cumulative curve for observed southern iteroparous female spawners-at-age.

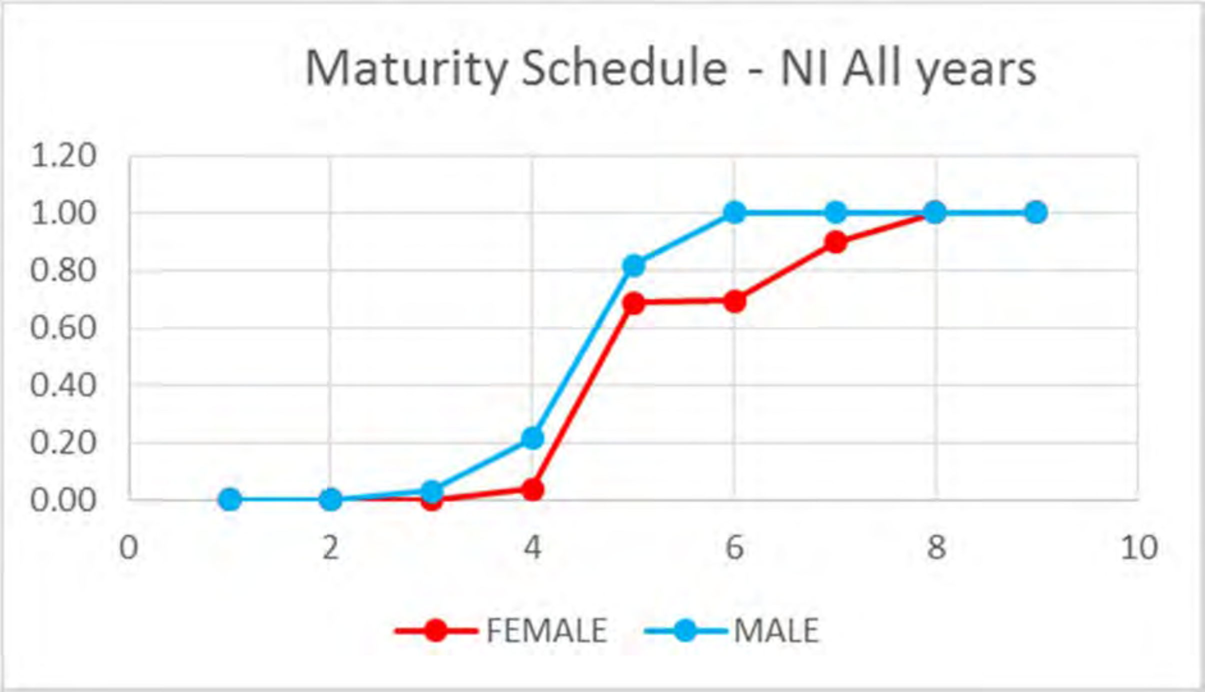


Figure 47. Maturity estimates of northern iteroparous fish with the mortality correction approach.

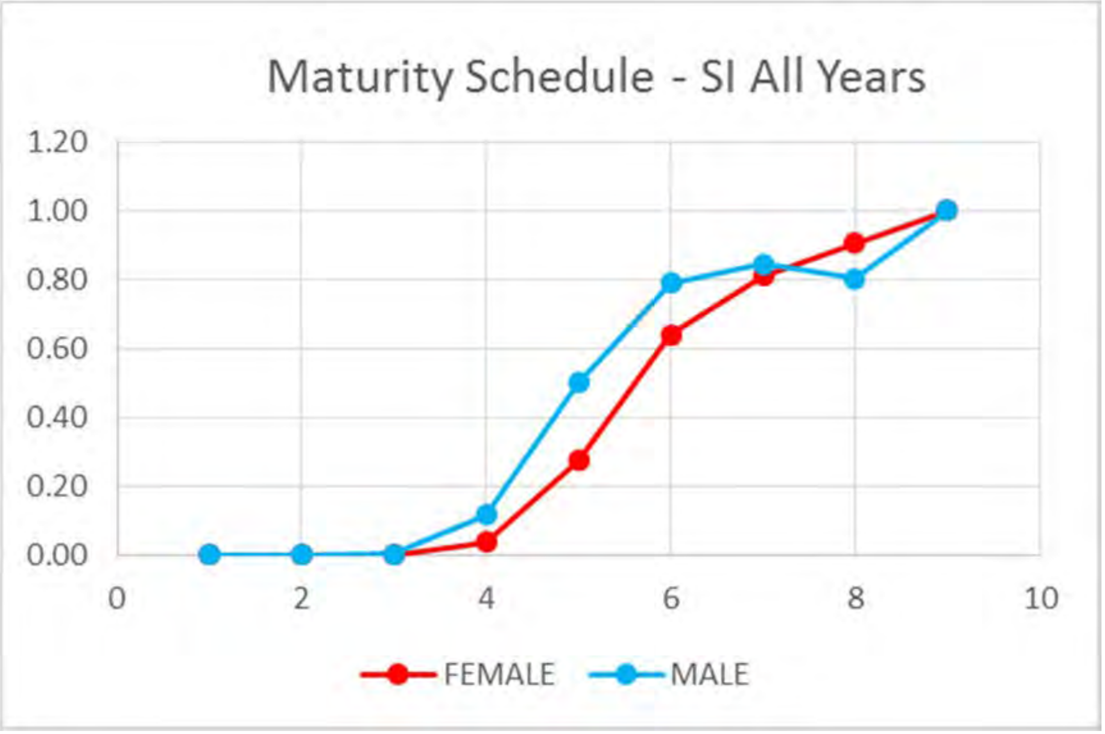


Figure 48. Maturity estimates of southern iteroparous fish with the mortality correction approach.

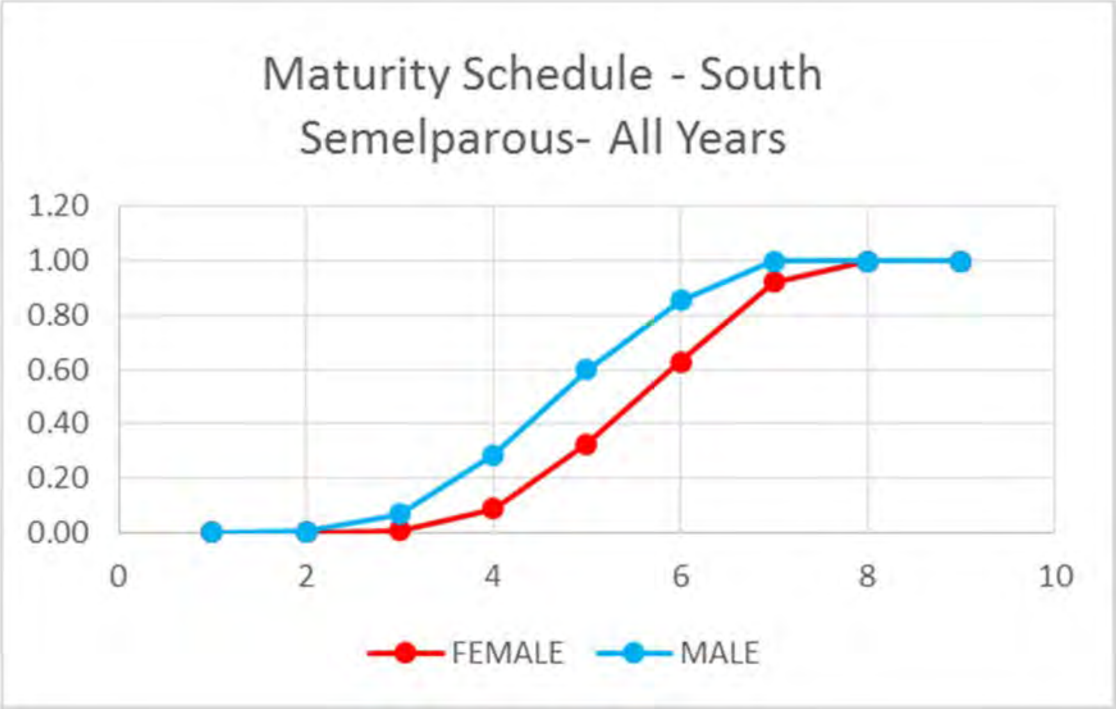


Figure 49. Maturity estimates of semelparous fish with the mortality correction approach.

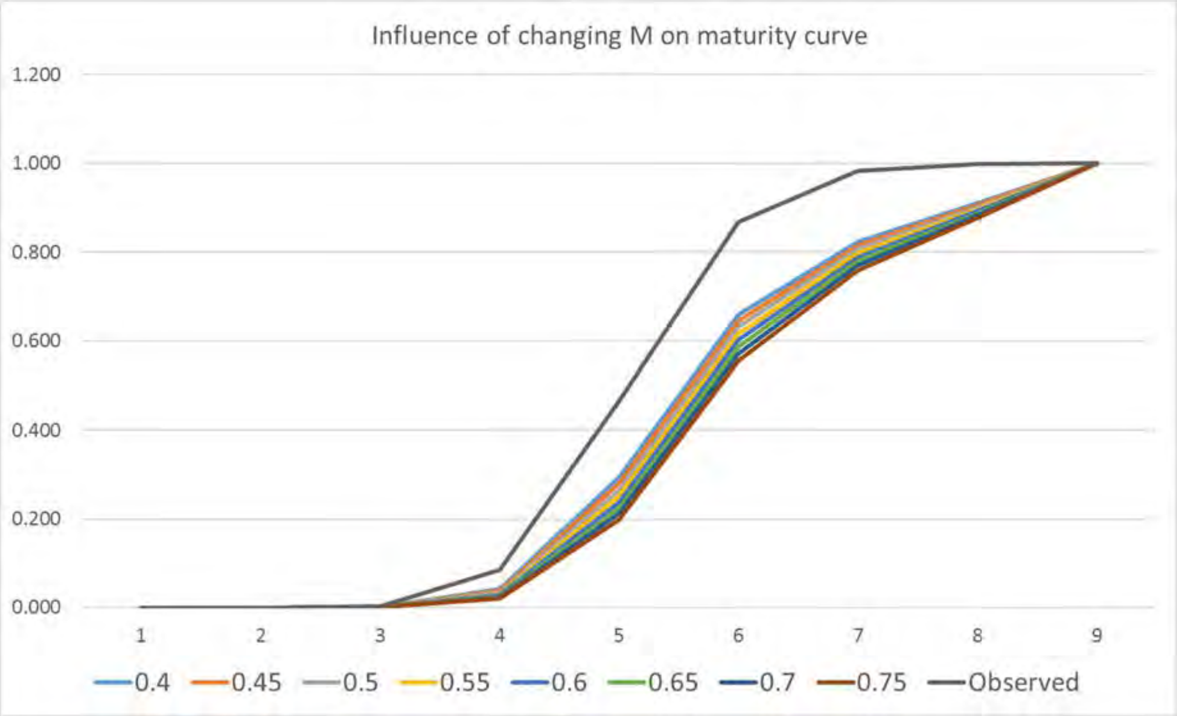


Figure 50. **Results of a sensitivity analysis of the corrected maturity curve based on incorporation of at sea mortality (*M*). The observed data is presented for the southern iteroparous females as a reference. The corrected curves are based on scenarios where *M* varied over an inclusive range for American shad (Table 10) from 0.4 to 0.75. Increasing *M* shifted the curve to the right but resulted in small shifts in cumulative maturity.**

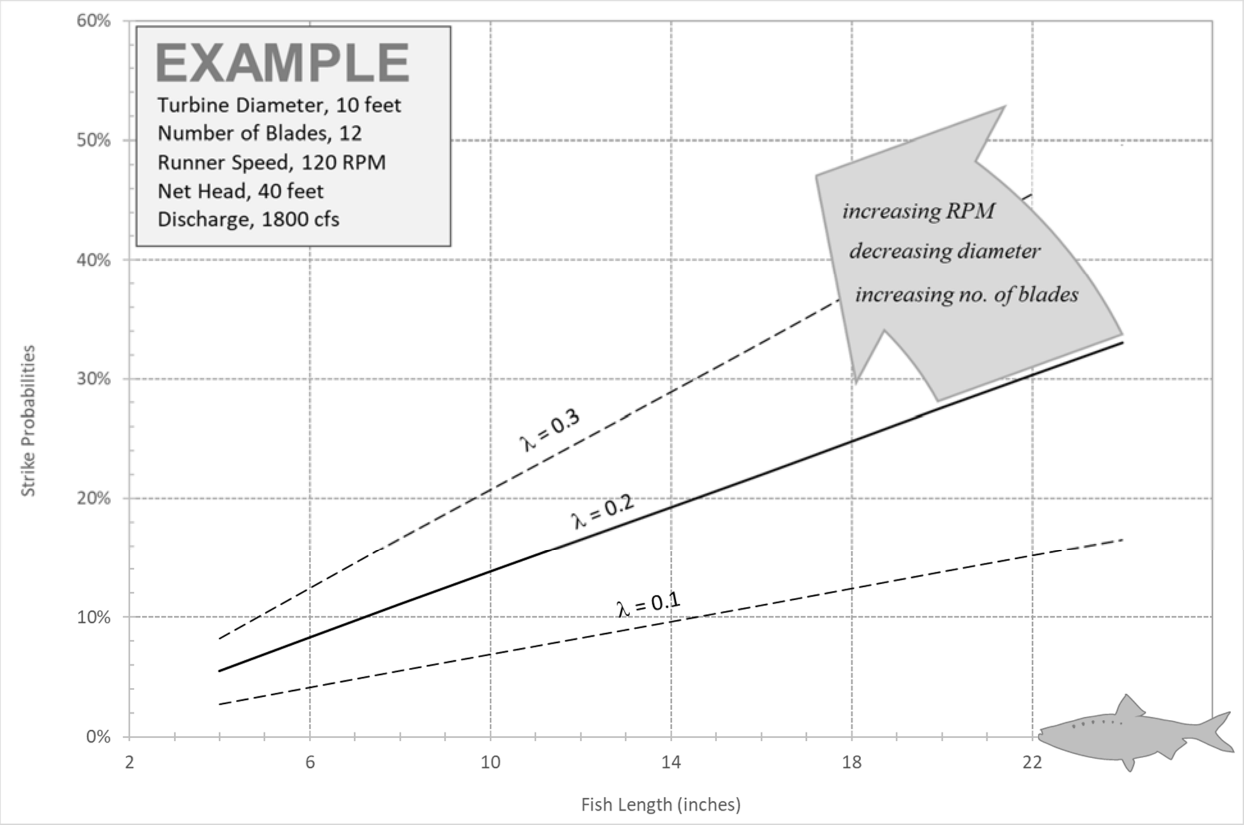


Figure 51. Blade strike probabilities for an example turbine in relation to selected Lambda and responses to increases in turbine RPM, fish length, decreases in turbine diameter, and increases in number of turbine blades.

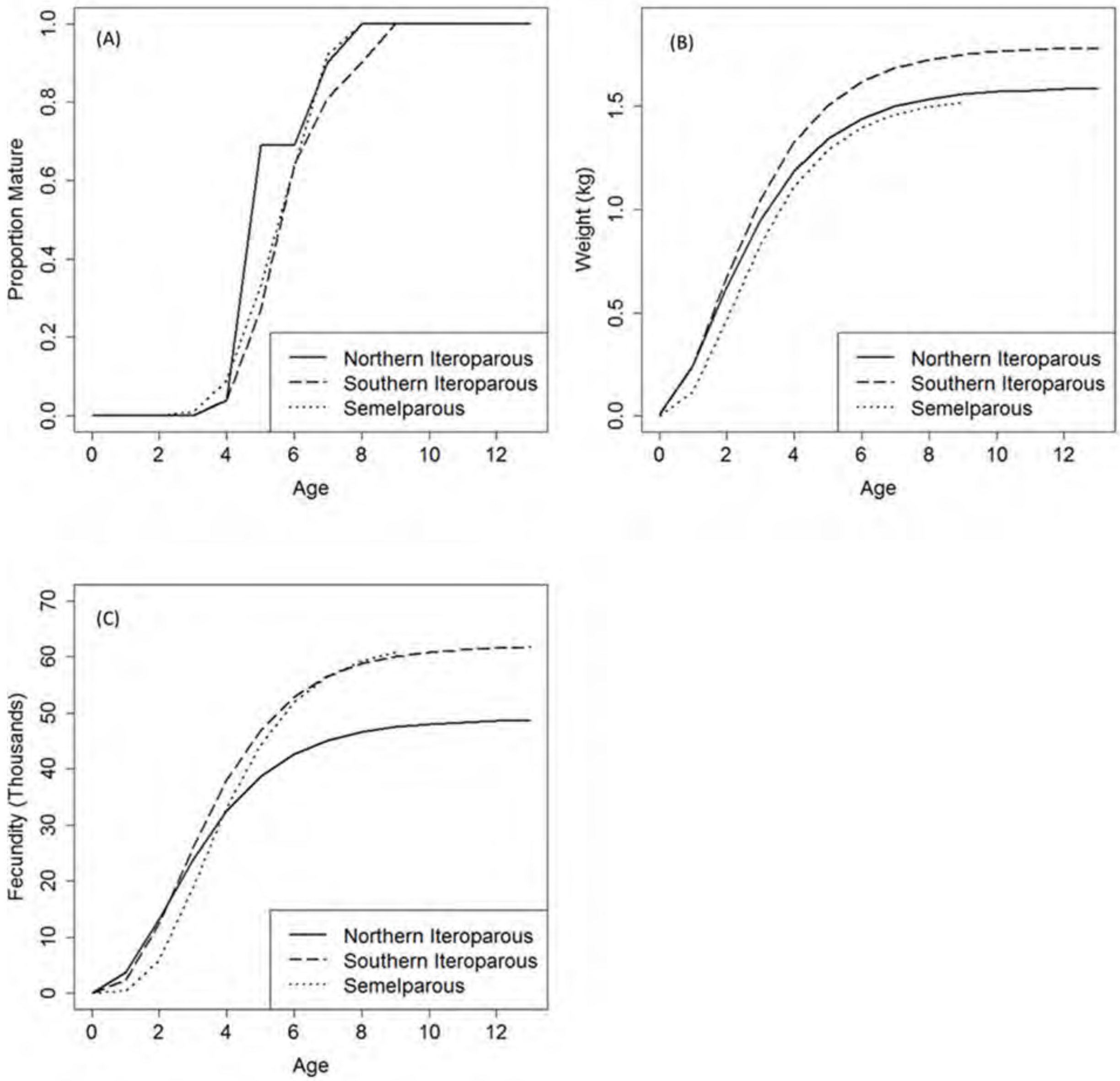


Figure 52. Regional life history data used as inputs to the Thompson Bell spawning stock biomass per-recruit and egg per-recruit models. Inputs include (A) Proportion mature-at-age (B) weight-at-age, and (C) fecundity-at-age.

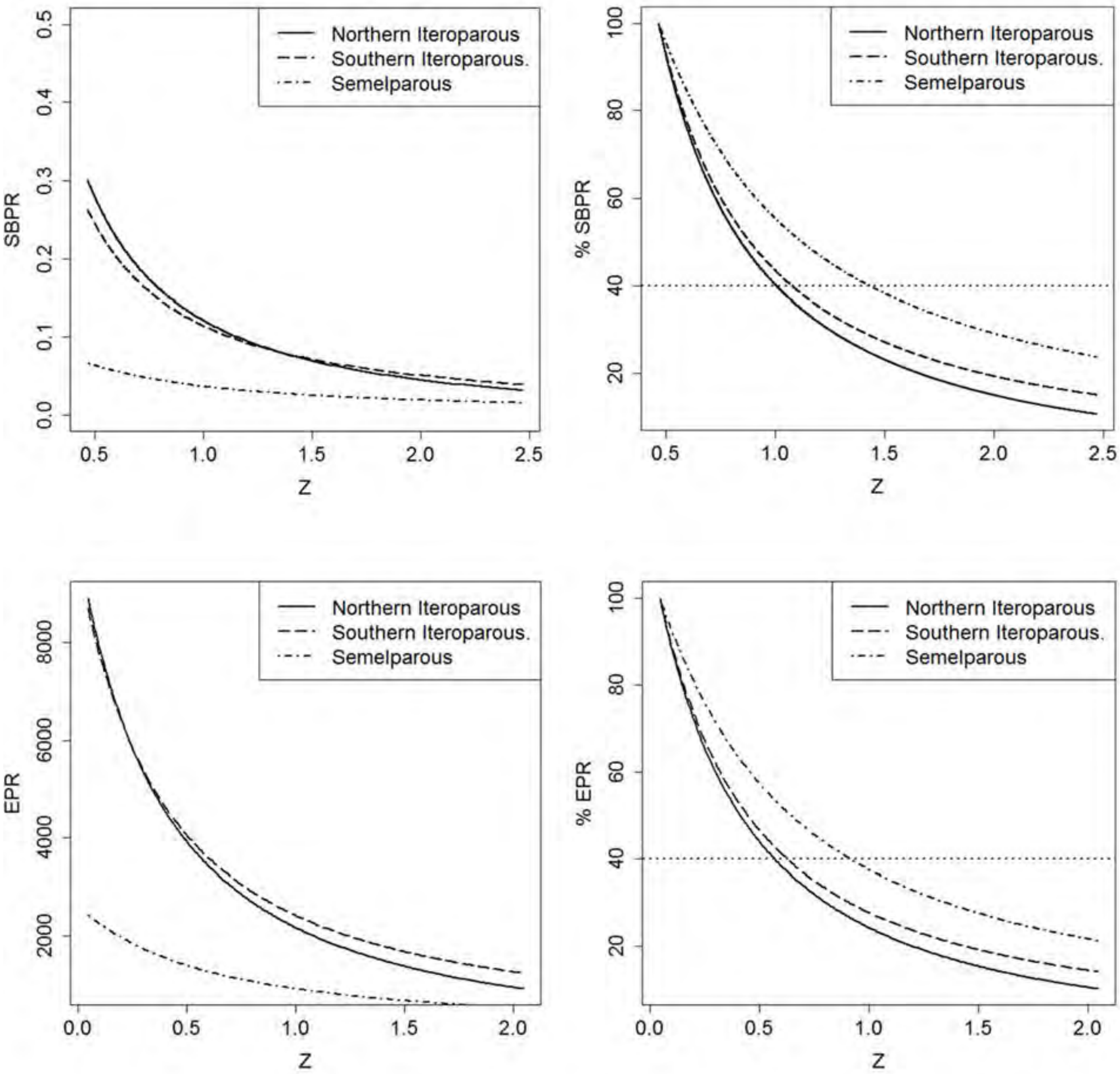


Figure 53. Spawning stock biomass per-recruit (top) and egg per-recruit (bottom) values at *Z* for regional American shad metapopulations. Right panels correspond to the percent of maximum per-recruit values at *Z*. Dotted horizontal line corresponds to 40% of maximum per-recruit values. Regional $Z_{40\%}$ reference points correspond to the intersection of the dashed line and regional curves.

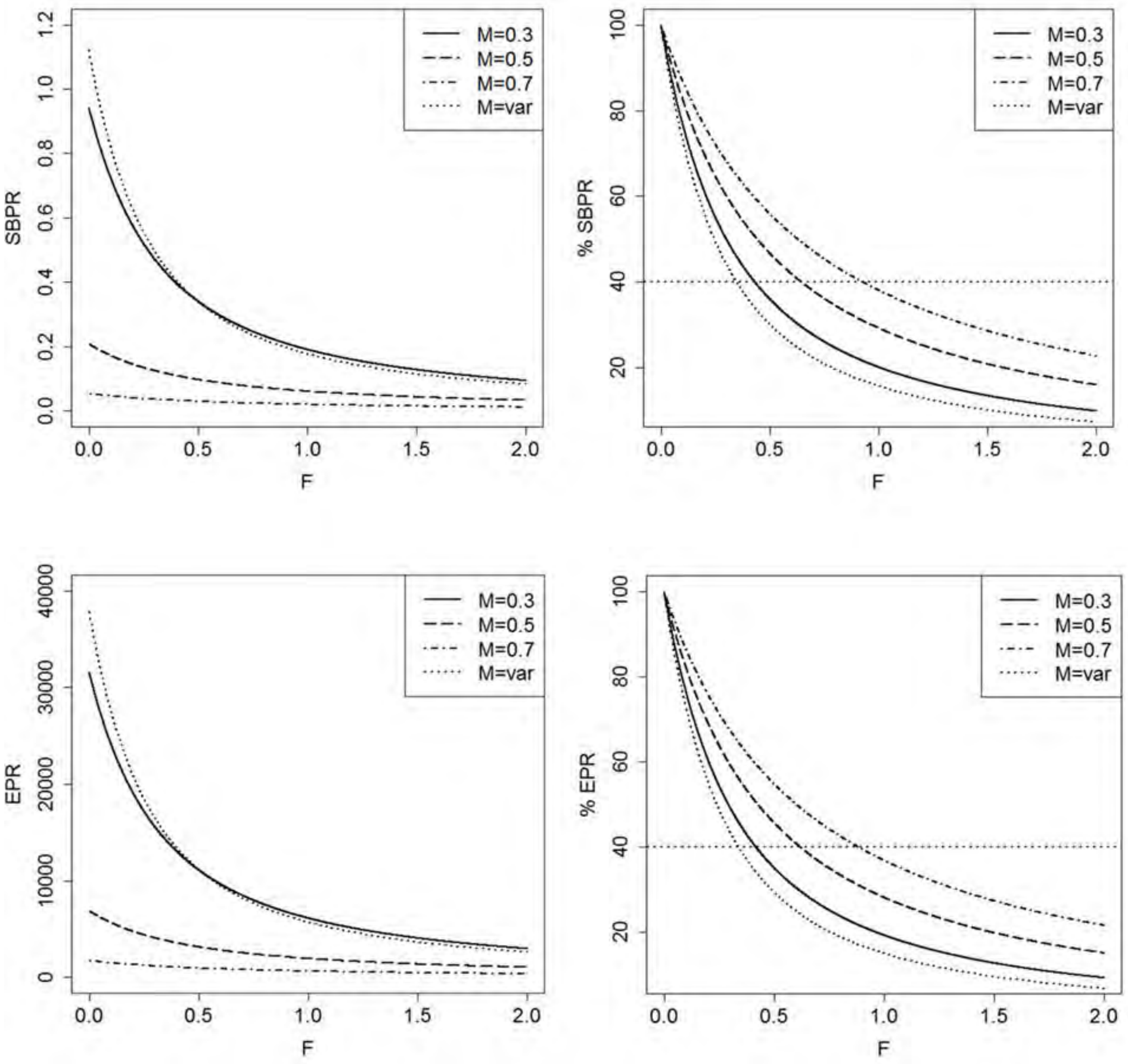


Figure 54. Sensitivity of spawning stock biomass per-recruit (top) and egg per-recruit (bottom) to variation in *M*, with Southern iteroparous regional data inputs held constant. Right panels correspond to percent of maximum per-recruit values at *F*. Dotted horizontal line corresponds to 40% of maximum per-recruit values. $F_{40\%}$ at different values of *M* corresponds to the intersection of the dashed line and respective curves.

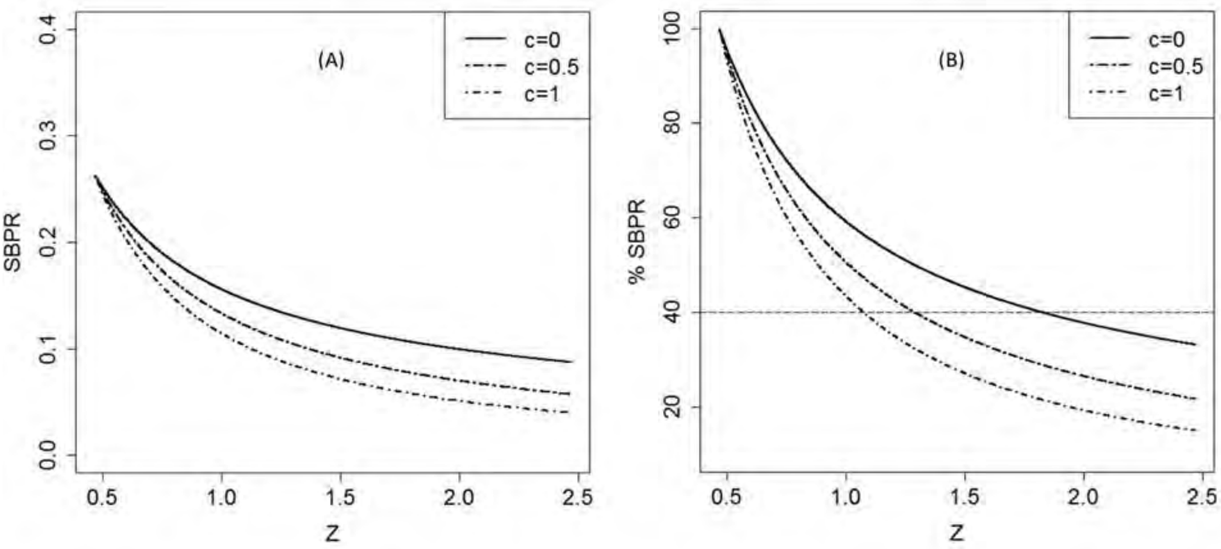


Figure 55. Sensitivity of spawning stock biomass per-recruit to model parameter c (proportion of *F* occurring prior to spawning), with model parameter d (proportion of *M* occurring prior to spawning) held constant to d = 1. Spawning stock biomass per-recruit values at 0.001 increments of *Z* (left) and percent of maximum per-recruit values at *Z* (right). Dotted horizontal line corresponds to 40% of maximum spawning stock biomass per-recruit. $Z_{40\%}$ at different values of c corresponds to the intersection of the dotted line and respective curves.

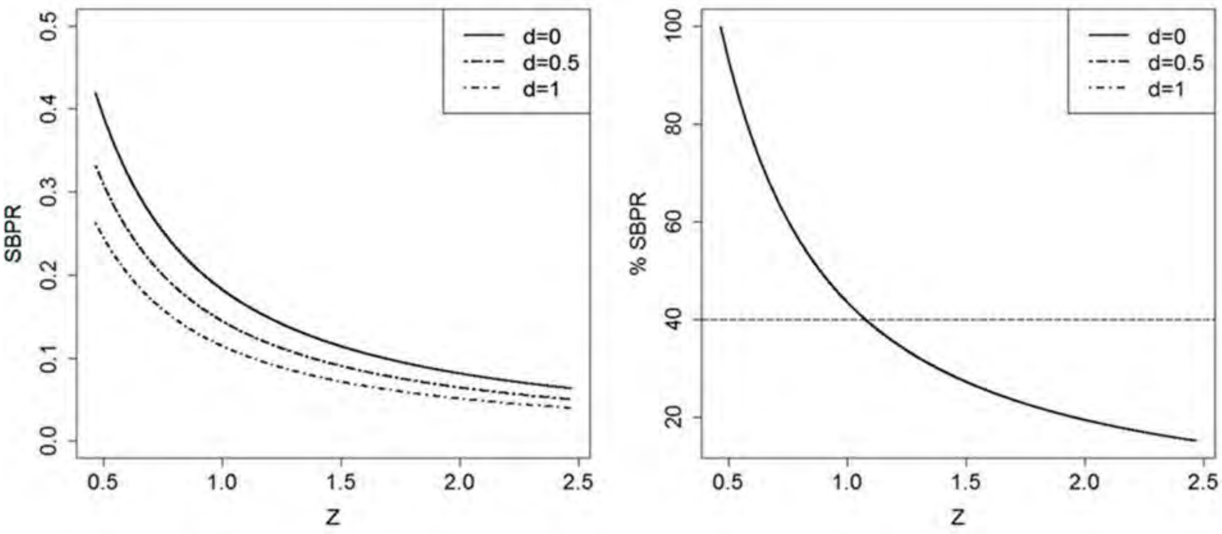


Figure 56. Sensitivity of spawning stock biomass per-recruit to model parameter d (proportion of *M* occurring prior to spawning), with model parameter c (proportion of *F* occurring prior to spawning) held constant to c = 1. Spawning stock biomass per-recruit values at *Z* (left) and percent of maximum per-recruit values at *Z* (right). Dotted horizontal line corresponds to 40% of maximum spawning stock biomass per-recruit. $Z_{40\%}$ at different values of c corresponds to the intersection of the dotted line and respective curves. Note: All curves in the right panel overlap.

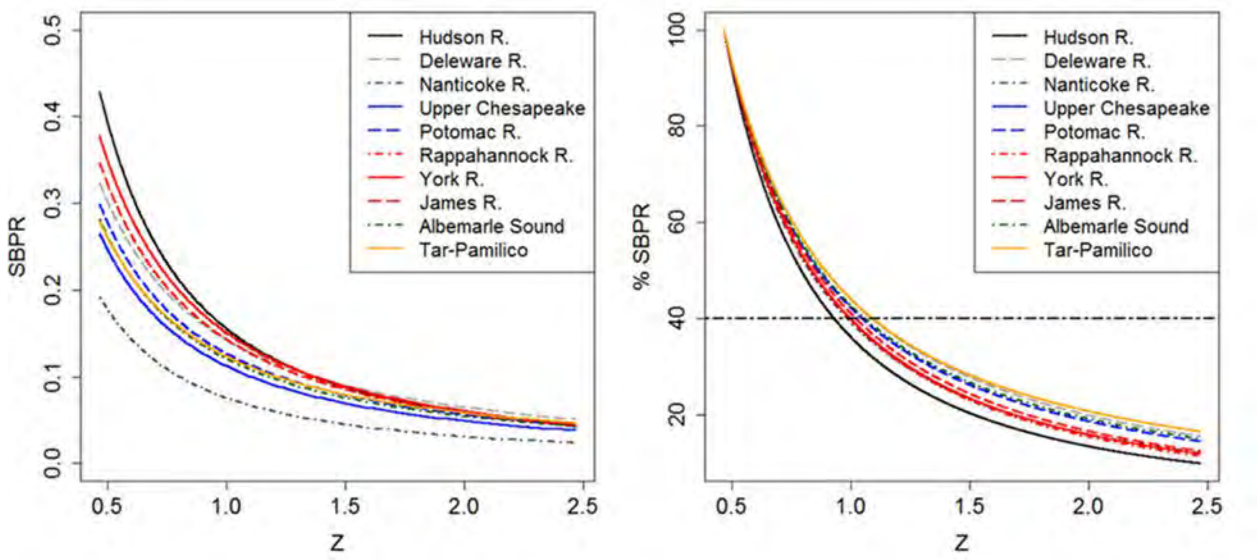


Figure 57. Sensitivity of spawning stock biomass per-recruit to river-specific inputs (maturity-at-age and weight-at-age), with *M* held constant at *M* = 0.47. Spawning stock biomass per-recruit values *Z* (left) and percent of maximum per-recruit values *Z* (right). Dotted horizontal line corresponds to 40% of maximum spawning stock biomass-per-recruit. River specific $Z_{40\%}$ values corresponds to the intersection of the dotted line and river specific curves.

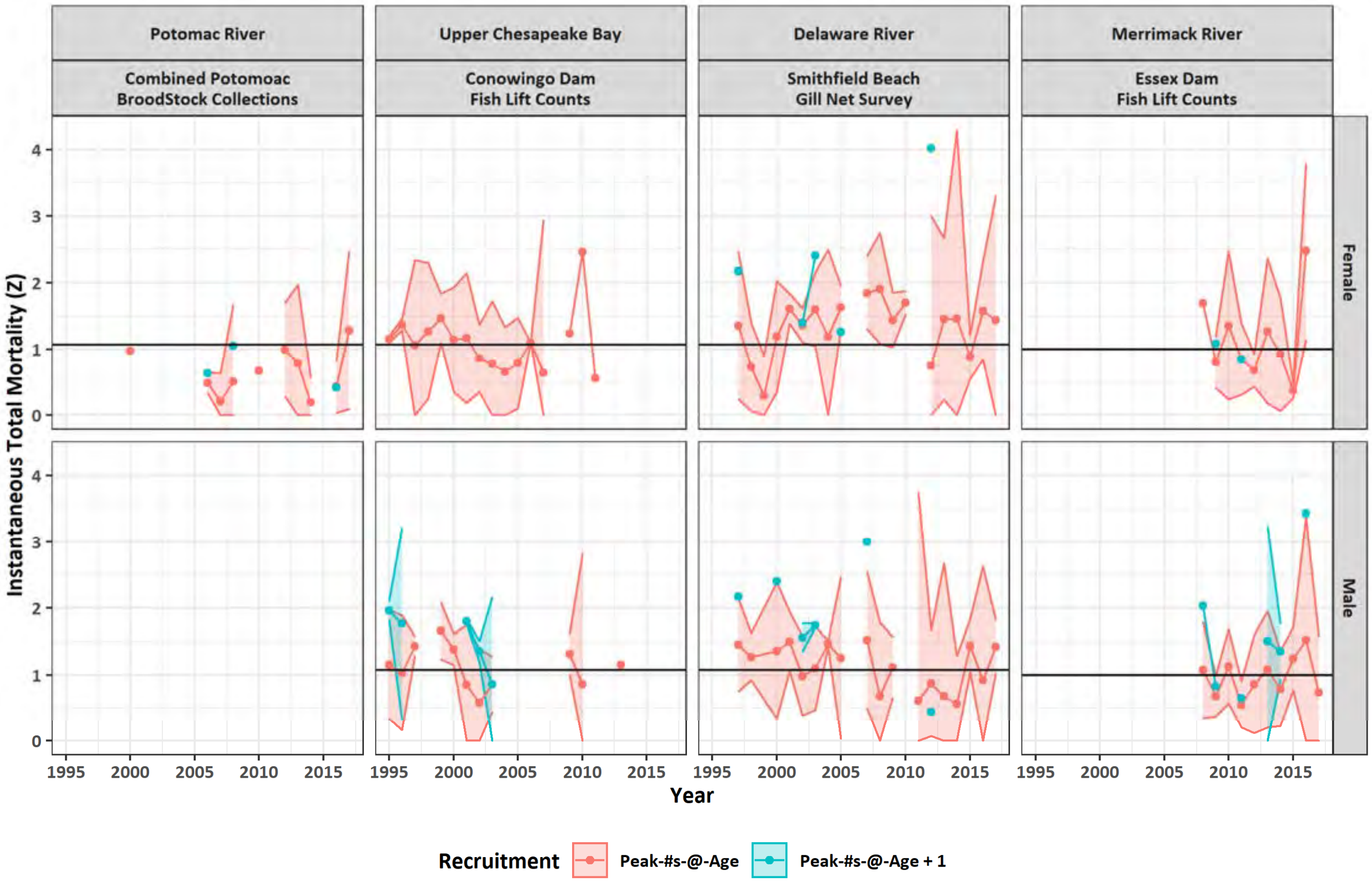


Figure 58. Instantaneous total mortality (*Z*) estimates from weighted linear regression by sex, system, and full recruitment definition (peak age and peak age plus one) using otolith-based data sets and annual age compositions (e.g., cross-sectional or synthetic cohort analysis). Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

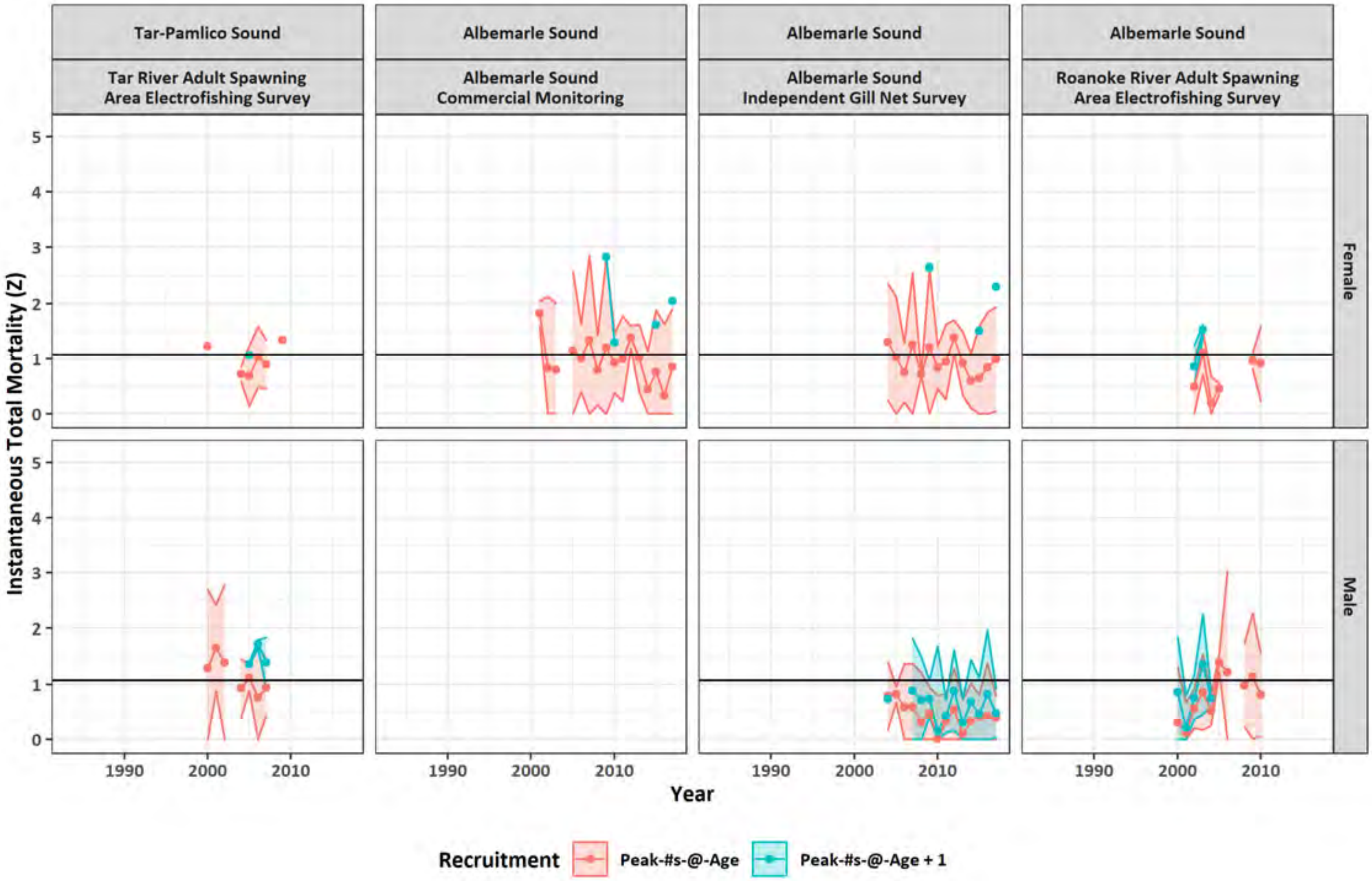


Figure 59. Instantaneous total mortality (*Z*) estimates from weighted linear regression by sex, system (Tar-Pamlico Sound and Albemarle Sound), and full recruitment definition (peak age and peak age plus one) using scale-based data sets and annual age compositions (e.g., cross-sectional or synthetic cohort analysis). Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

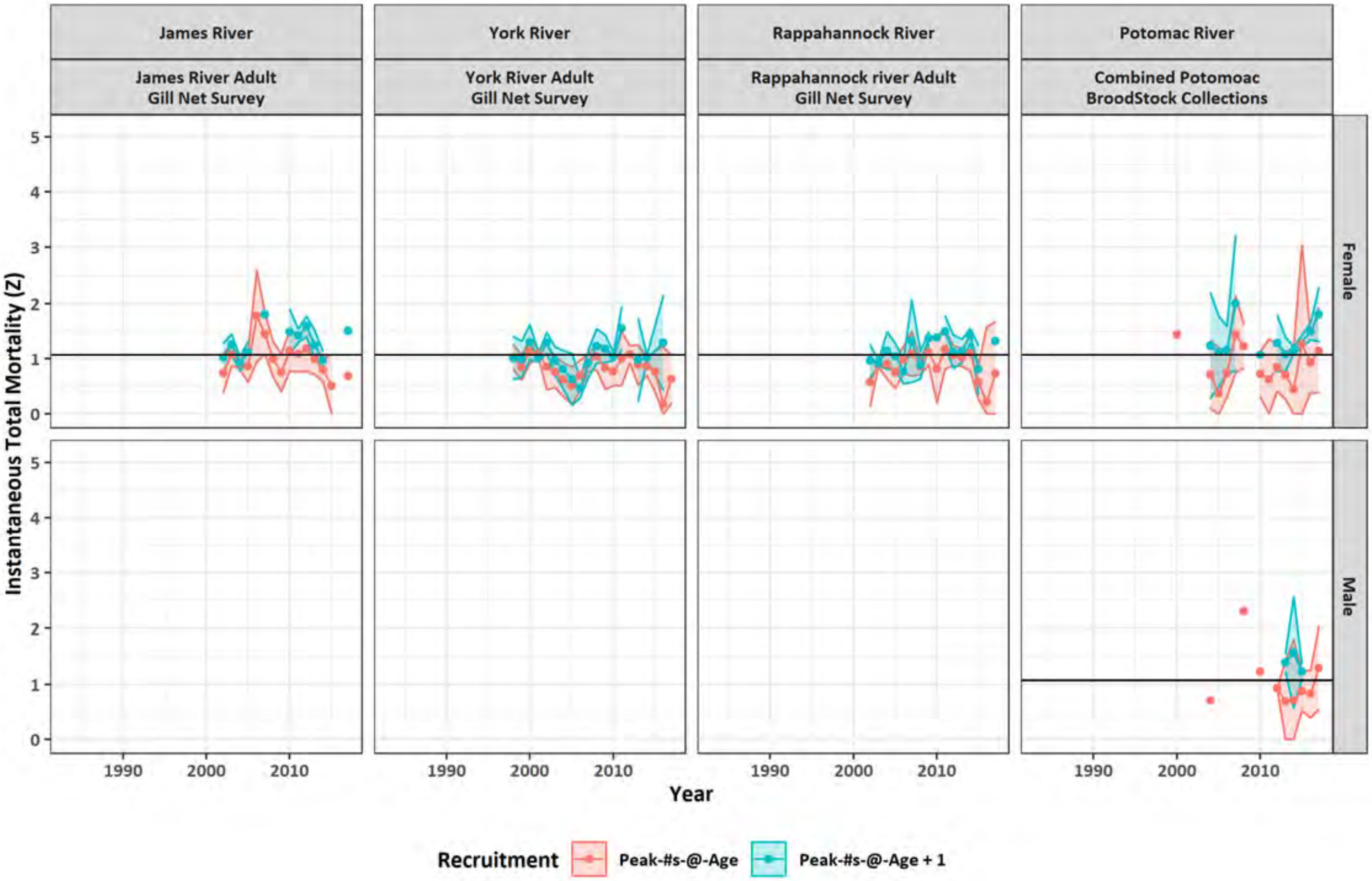


Figure 60. Instantaneous total mortality (*Z*) estimates from weighted linear regression by sex, system (James, York, Rappahannock and Potomac Rivers), and full recruitment definition (peak age and peak age plus one) using scale-based data sets and annual age compositions (e.g., cross-sectional or synthetic cohort analysis). Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

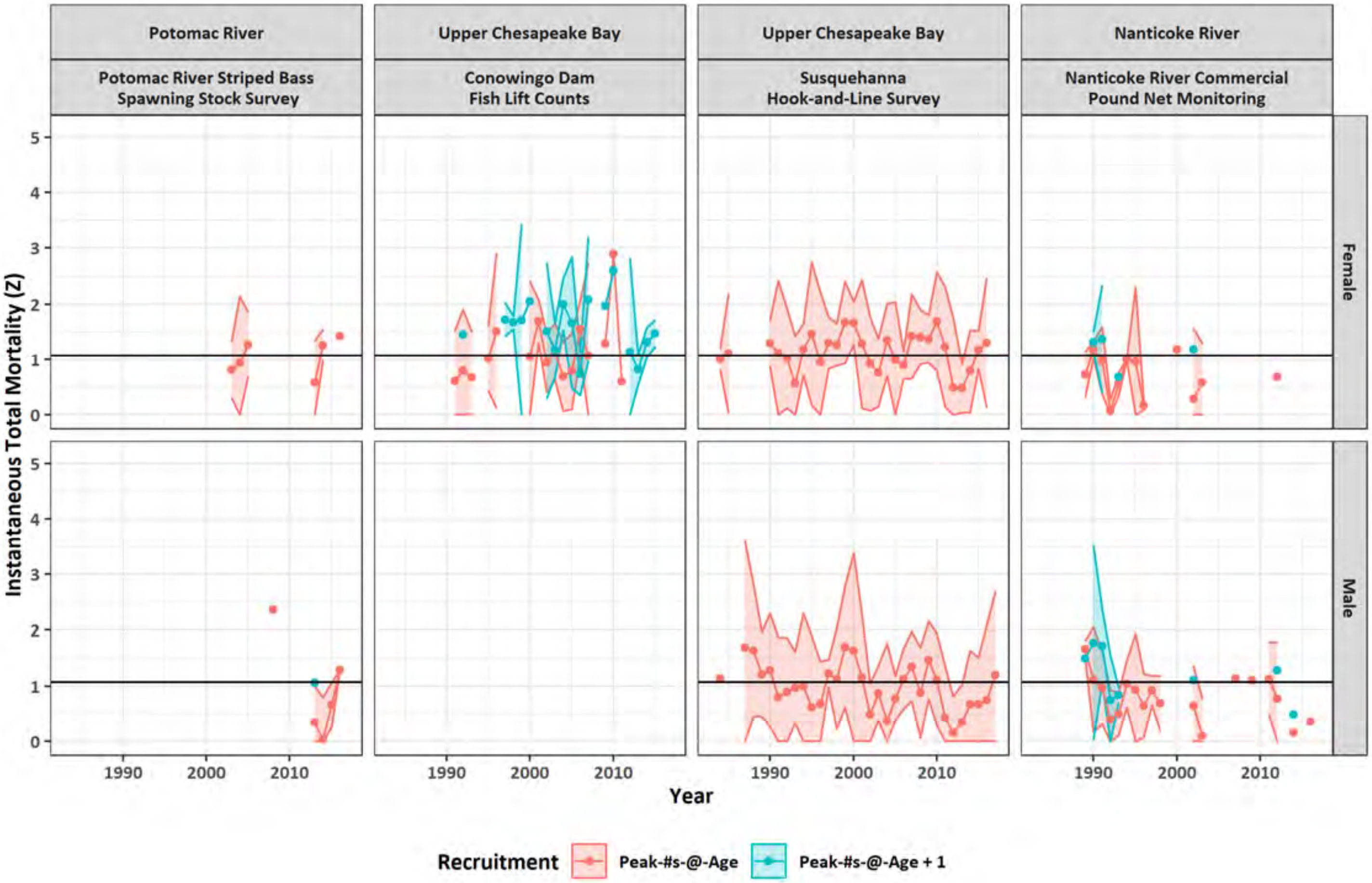


Figure 61. Instantaneous total mortality (*Z*) estimates from weighted linear regression by sex, system (Potomac River, Upper Chesapeake Bay and Nanticoke River), and full recruitment definition (peak age and peak age plus one) using scale-based data sets and annual age compositions (e.g., cross-sectional or synthetic cohort analysis). Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

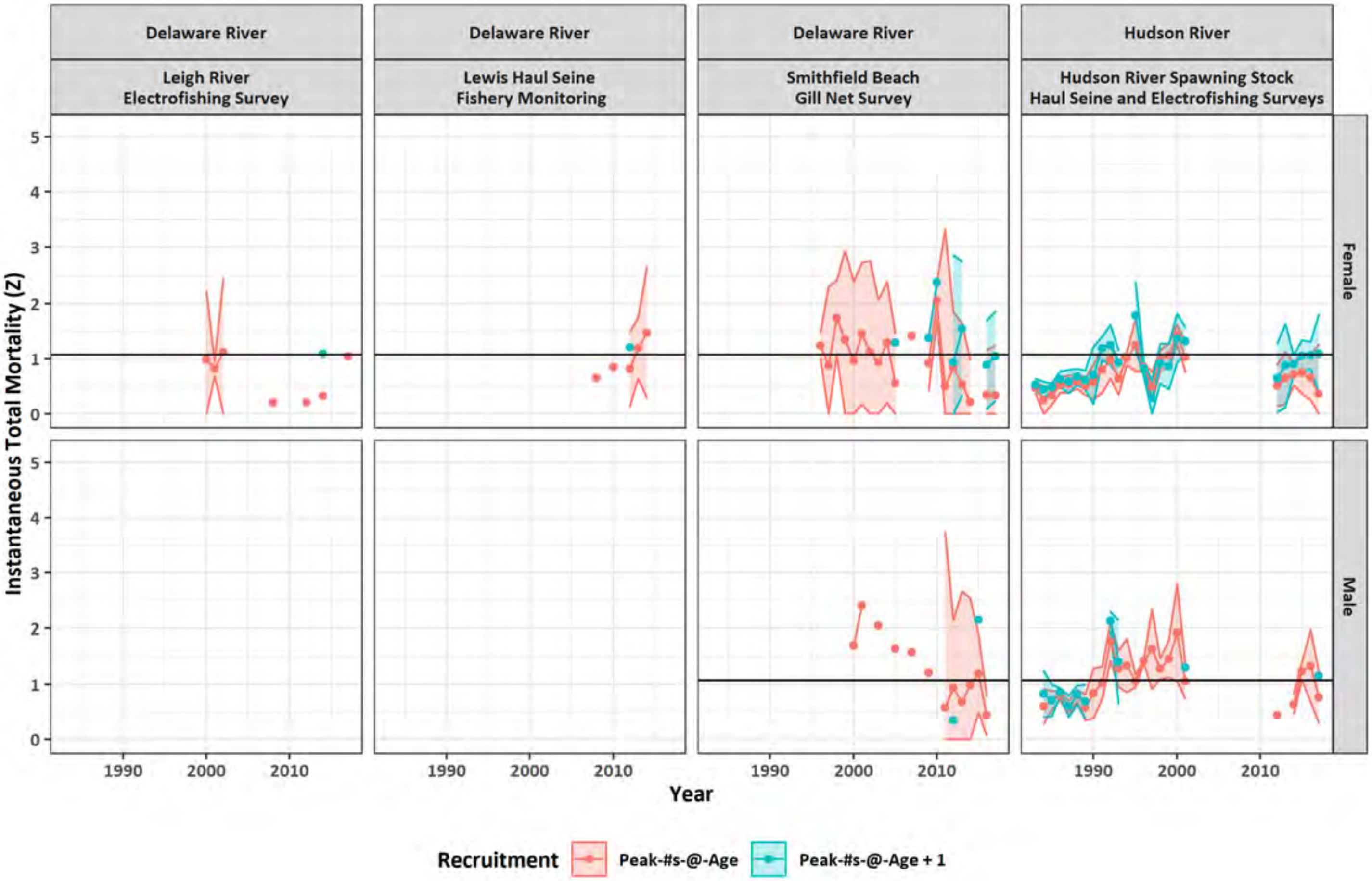


Figure 62. Instantaneous total mortality (*Z*) estimates from weighted linear regression by sex, system (Delaware and Hudson Rivers), and full recruitment definition (peak age and peak age plus one) using scale-based data sets and annual age compositions (e.g., cross-sectional or synthetic cohort analysis). Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

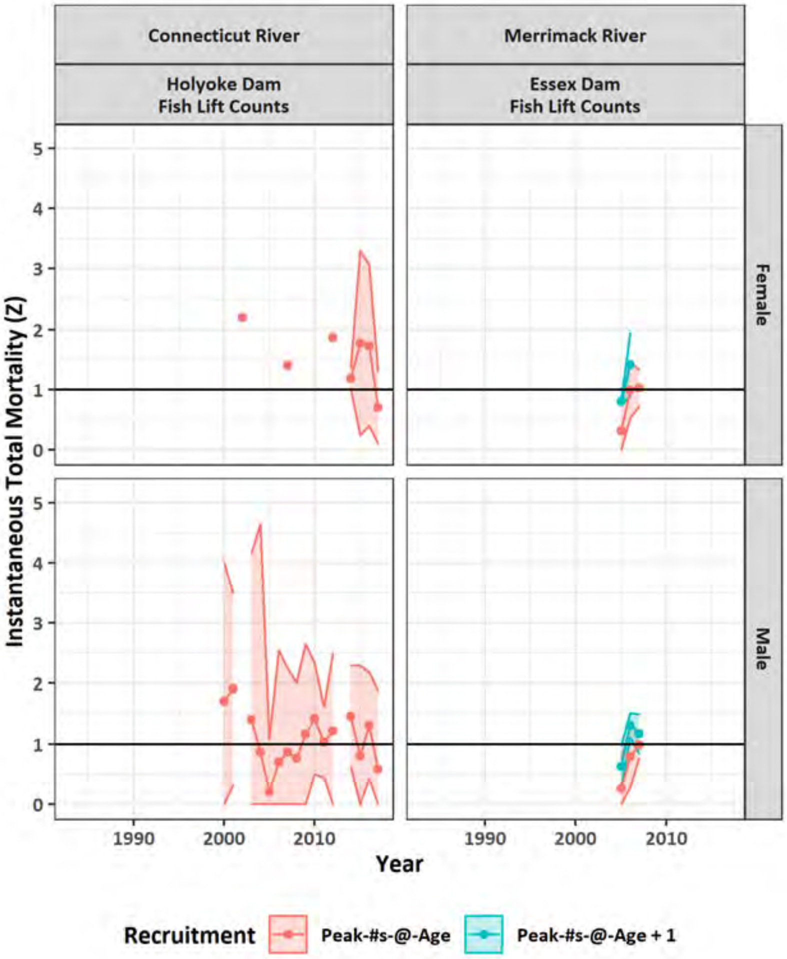


Figure 63. Instantaneous total mortality (*Z)* estimates from weighted linear regression by sex, system (Connecticut and Merrimack Rivers), and full recruitment definition (peak age and peak age plus one) using scale-based data sets and annual age compositions (e.g., cross-sectional or synthetic cohort analysis). Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

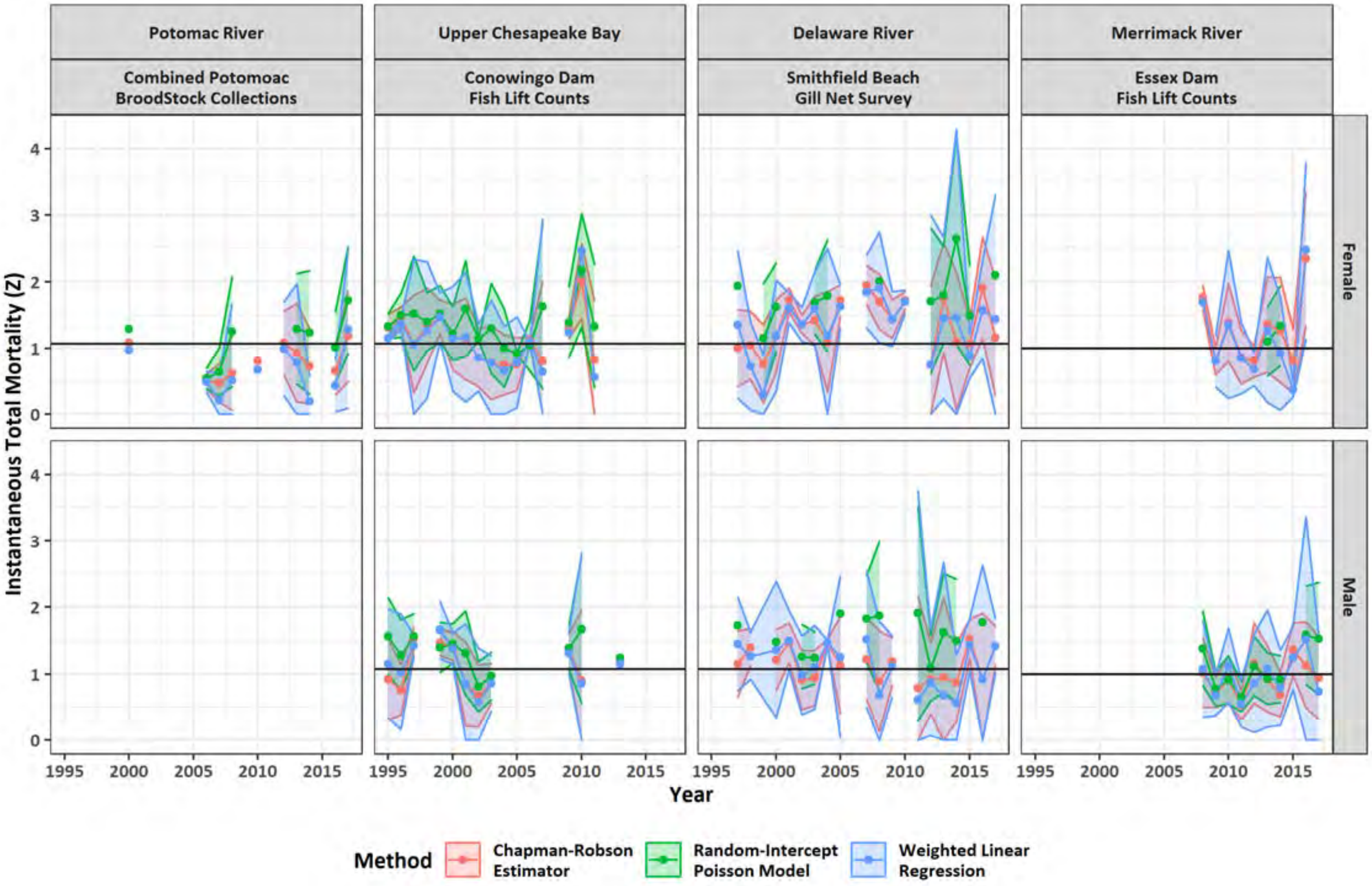


Figure 64. Instantaneous total mortality (*Z*) estimates by sex, system, monitoring program, and estimation method using full recruitment definition of peak age, otolith-based data sets, and annual age compositions (e.g., cross-sectional or synthetic cohort analysis). Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

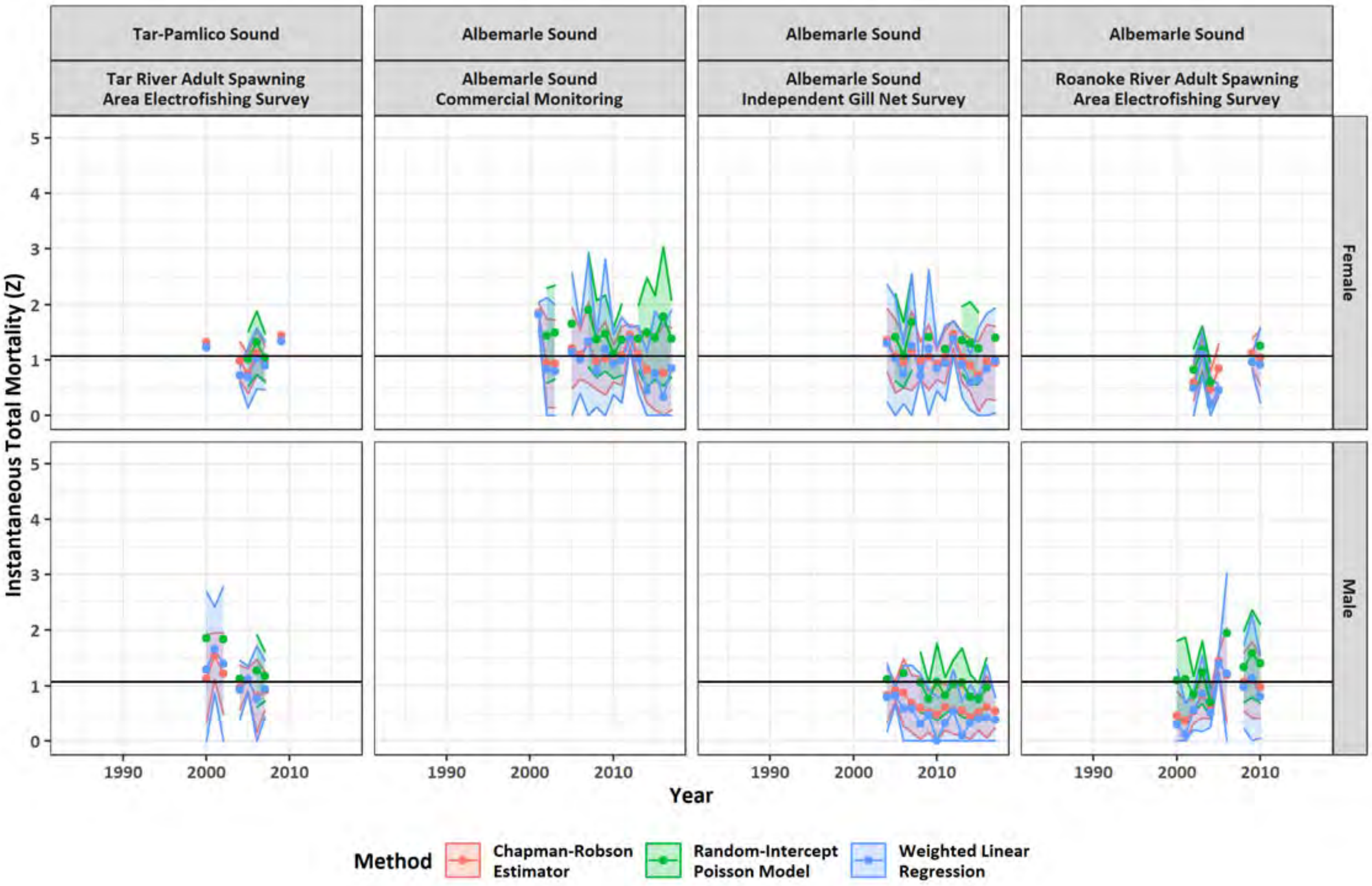


Figure 65. Instantaneous total mortality (Z) estimates by sex, system (Tar-Pamlico Sound & Albemarle Sound), monitoring program, and estimation method using full recruitment definition of peak age, scale-based data sets, and annual age compositions (e.g., cross-sectional or synthetic cohort analysis). Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

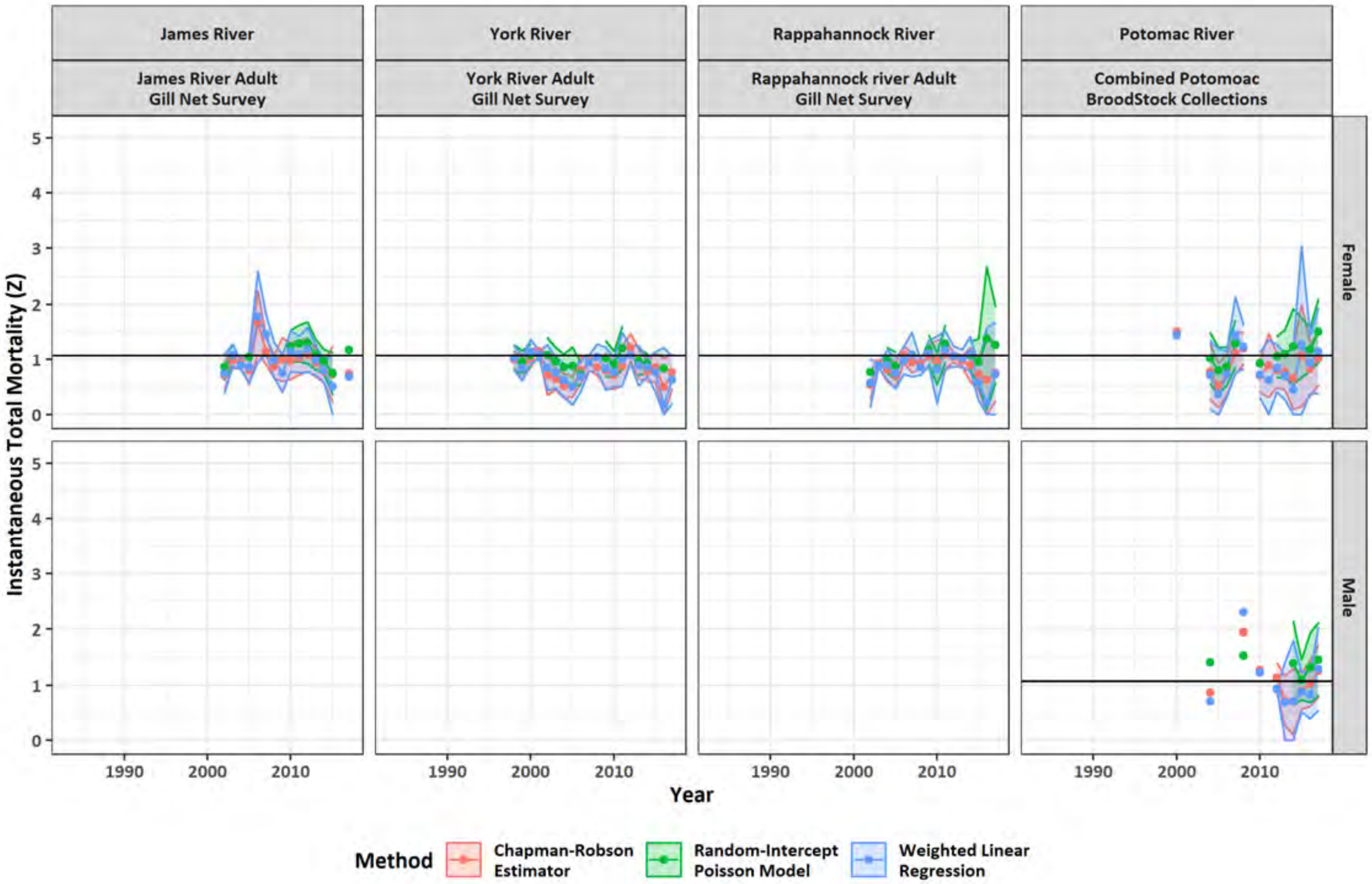


Figure 66. **Instantaneous total mortality (*Z*) estimates by sex, system (James, York, Rappahannock and Potomac Rivers), monitoring program, and estimation method using full recruitment definition of peak age, scale-based data sets, and annual age compositions (e.g., cross-sectional or synthetic cohort analysis). Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP**

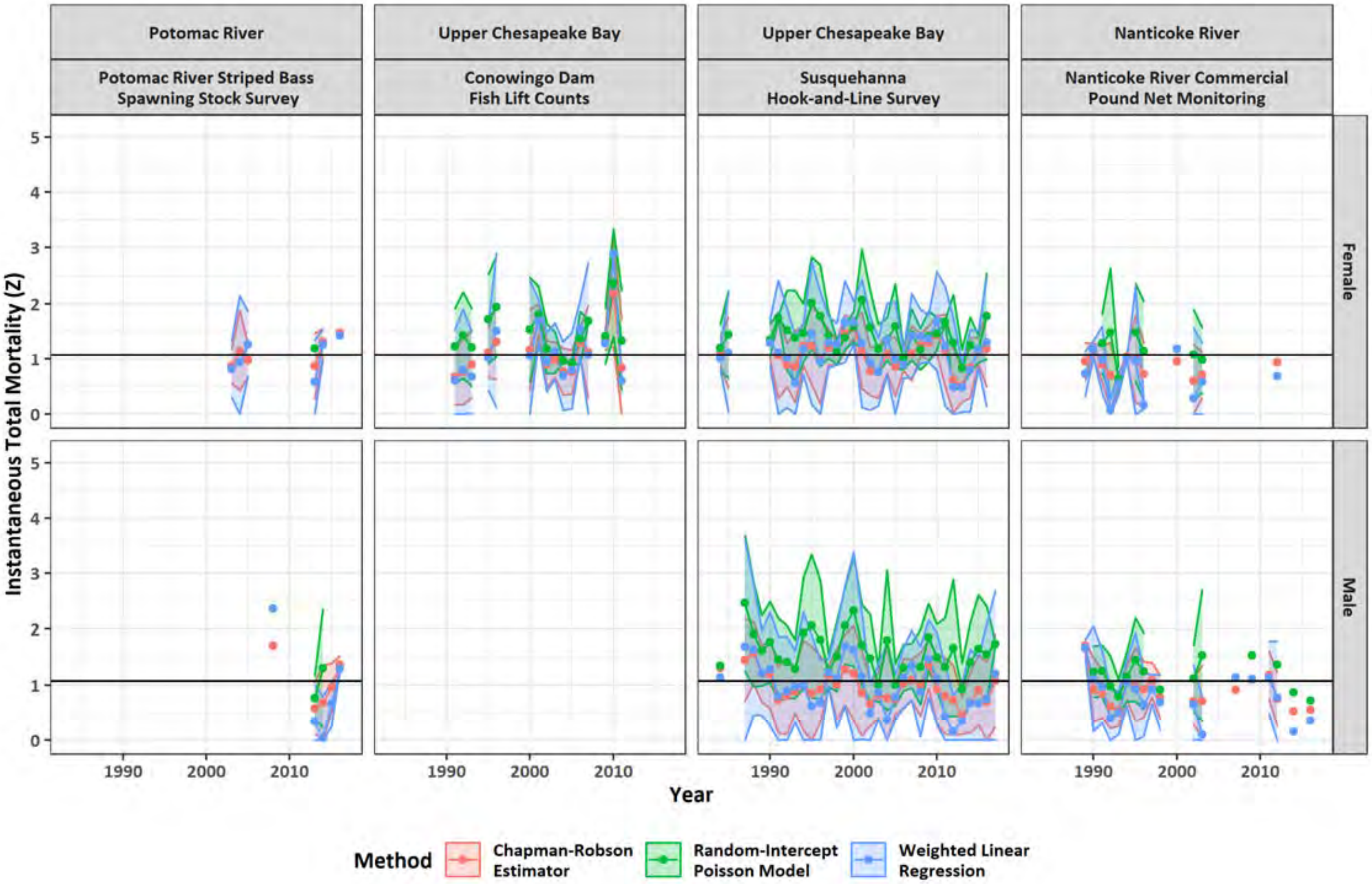


Figure 67. Instantaneous total mortality (*Z*) estimates by sex, system (Potomac River, Upper Chesapeake Bay and Nanticoke River), monitoring program, and estimation method using full recruitment definition of peak age, scale-based data sets, and annual age compositions (e.g., cross-sectional or synthetic cohort analysis). Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

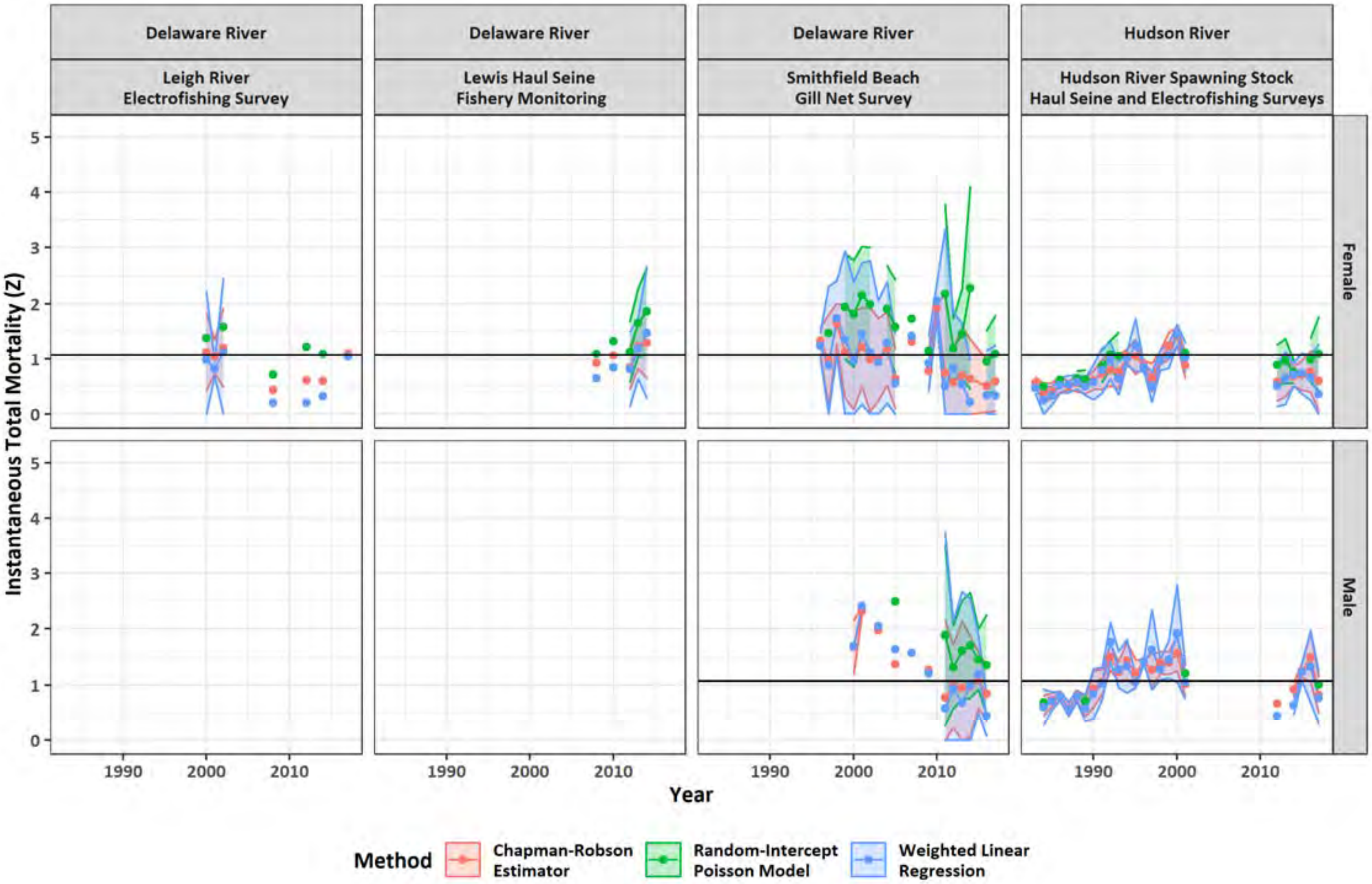


Figure 68. Instantaneous total mortality (*Z*) estimates by sex, system (Delaware and Hudson Rivers), monitoring program, and estimation method using full recruitment definition of peak age, scale-based data sets, and annual age compositions (e.g., cross-sectional or synthetic cohort analysis). Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

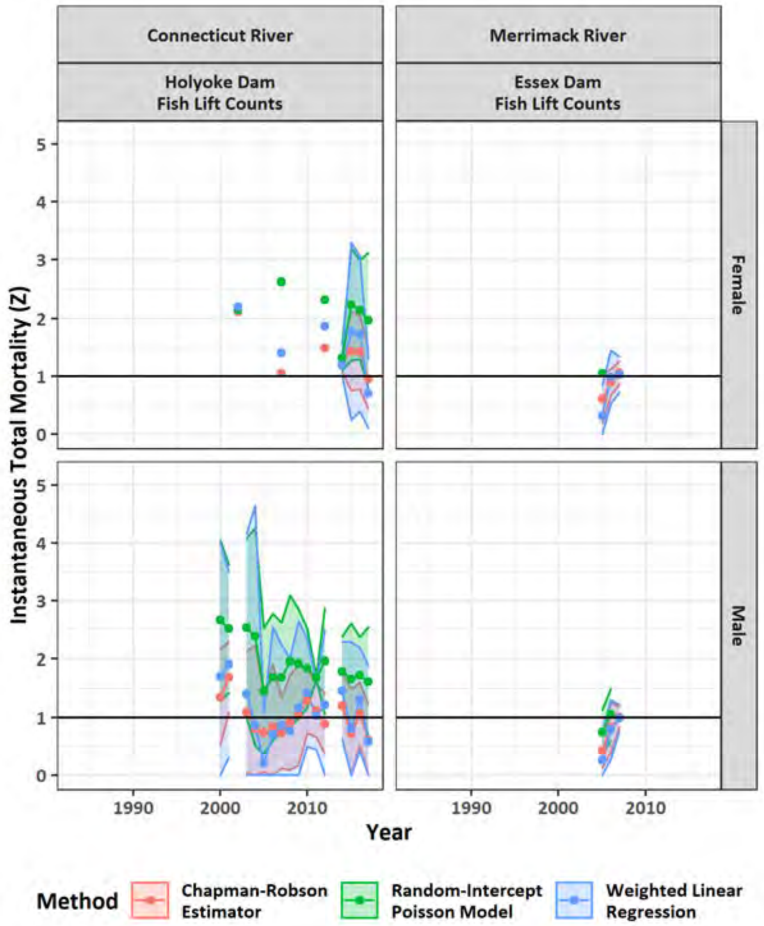


Figure 69. Instantaneous total mortality (*Z*) estimates by sex, system (Connecticut and Merrimack Rivers), monitoring program, and estimation method using full recruitment definition of peak age, scale-based data sets, and annual age compositions (e.g., cross-sectional or synthetic cohort analysis). Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

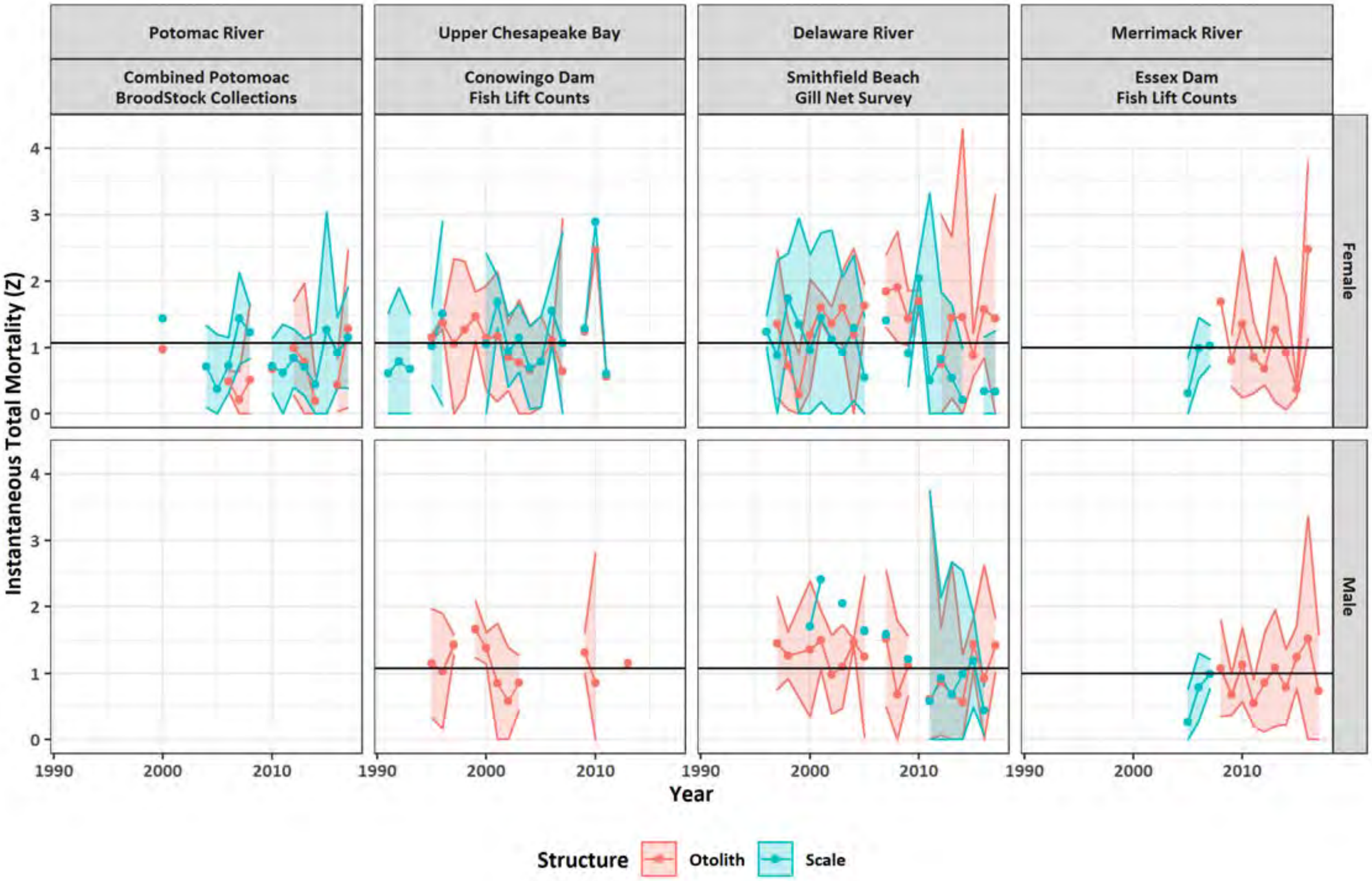


Figure 70. Instantaneous total mortality (*Z*) estimates from weighted linear regression by sex, system, and monitoring program where data were available from both age structures using full recruitment definition of peak age and annual age compositions (e.g., cross-sectional or synthetic cohort analysis). Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

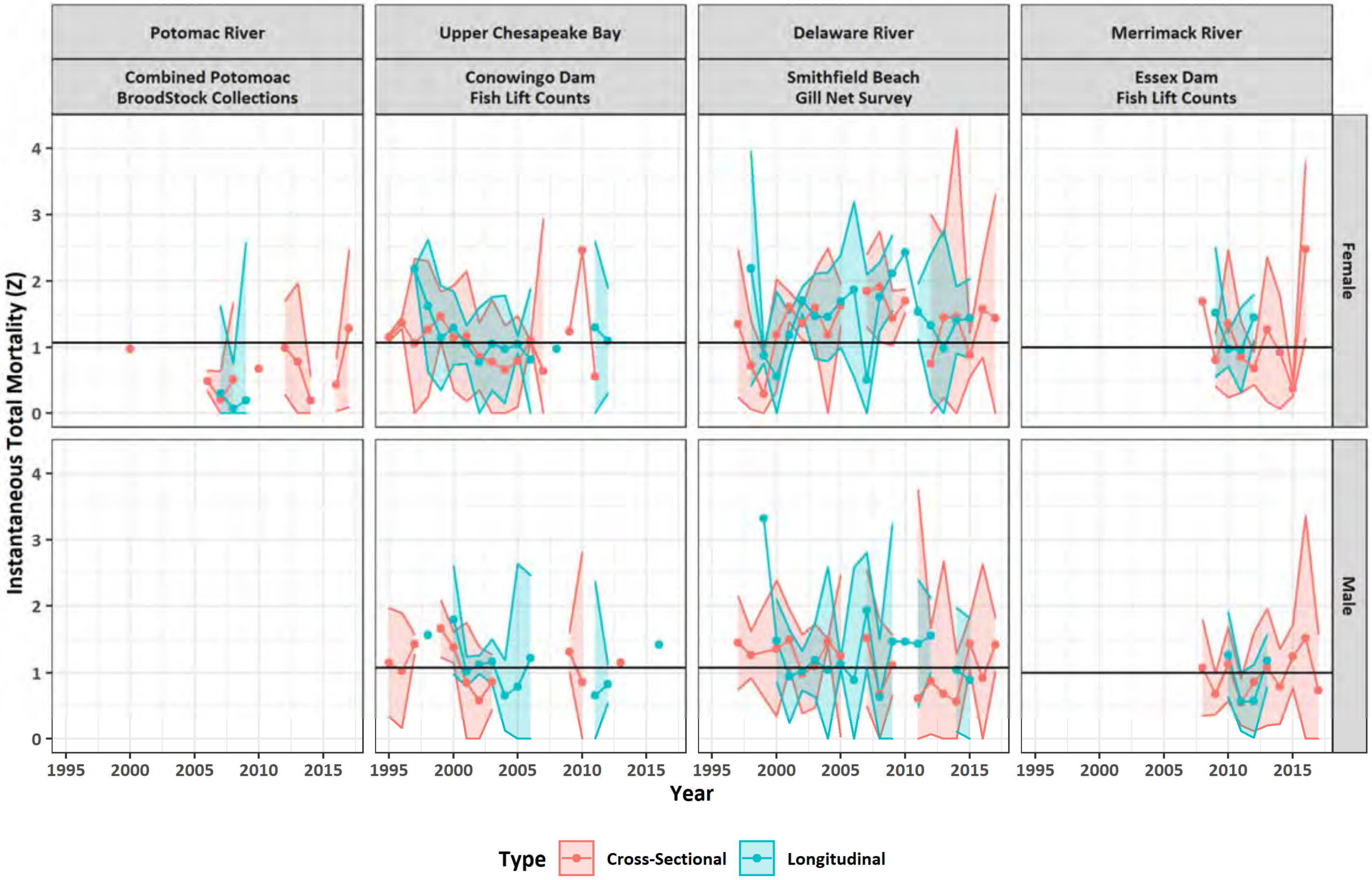


Figure 71. Instantaneous total mortality (*Z*) estimates via weighted linear regression by sex, system, monitoring program, and cohort type using full recruitment definition of peak age, otolith-based data sets, and annual age compositions. Seven years are added to longitudinal cohort year classes to select the comparison year. For example, the *Z* estimated from the 2000 year class is compared to the 2007 synthetic cohort *Z* estimate. Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

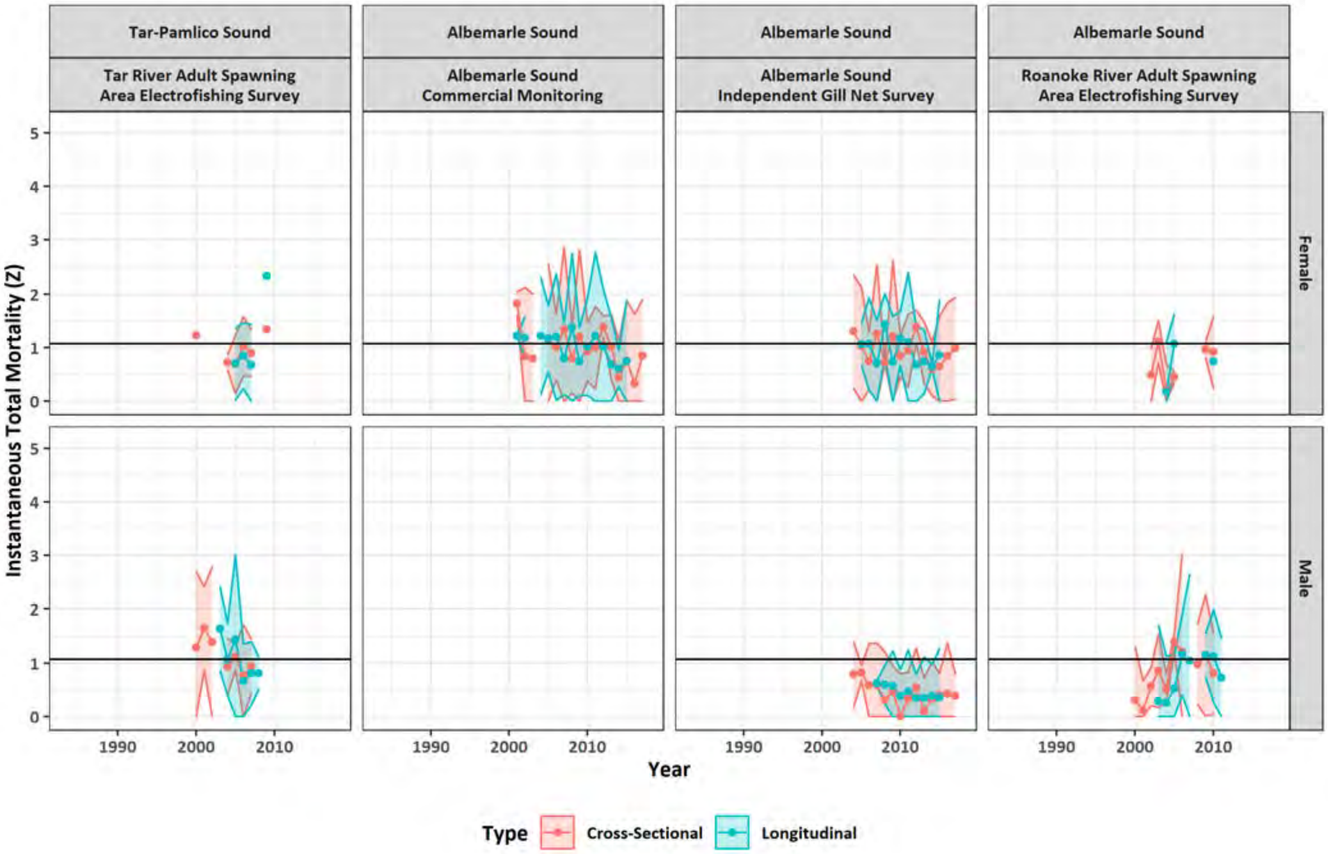


Figure 72. Instantaneous total mortality (*Z*) estimates via weighted linear regression by sex, system (Tar-Pamlico and Albemarle Sounds), monitoring program, and cohort type using full recruitment definition of peak age, scale-based data sets, and annual age compositions. Seven years are added to longitudinal cohort year classes to select the comparison year. For example, the *Z* estimated from the 2000 year class is compared to the 2007 synthetic cohort *Z* estimate. Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

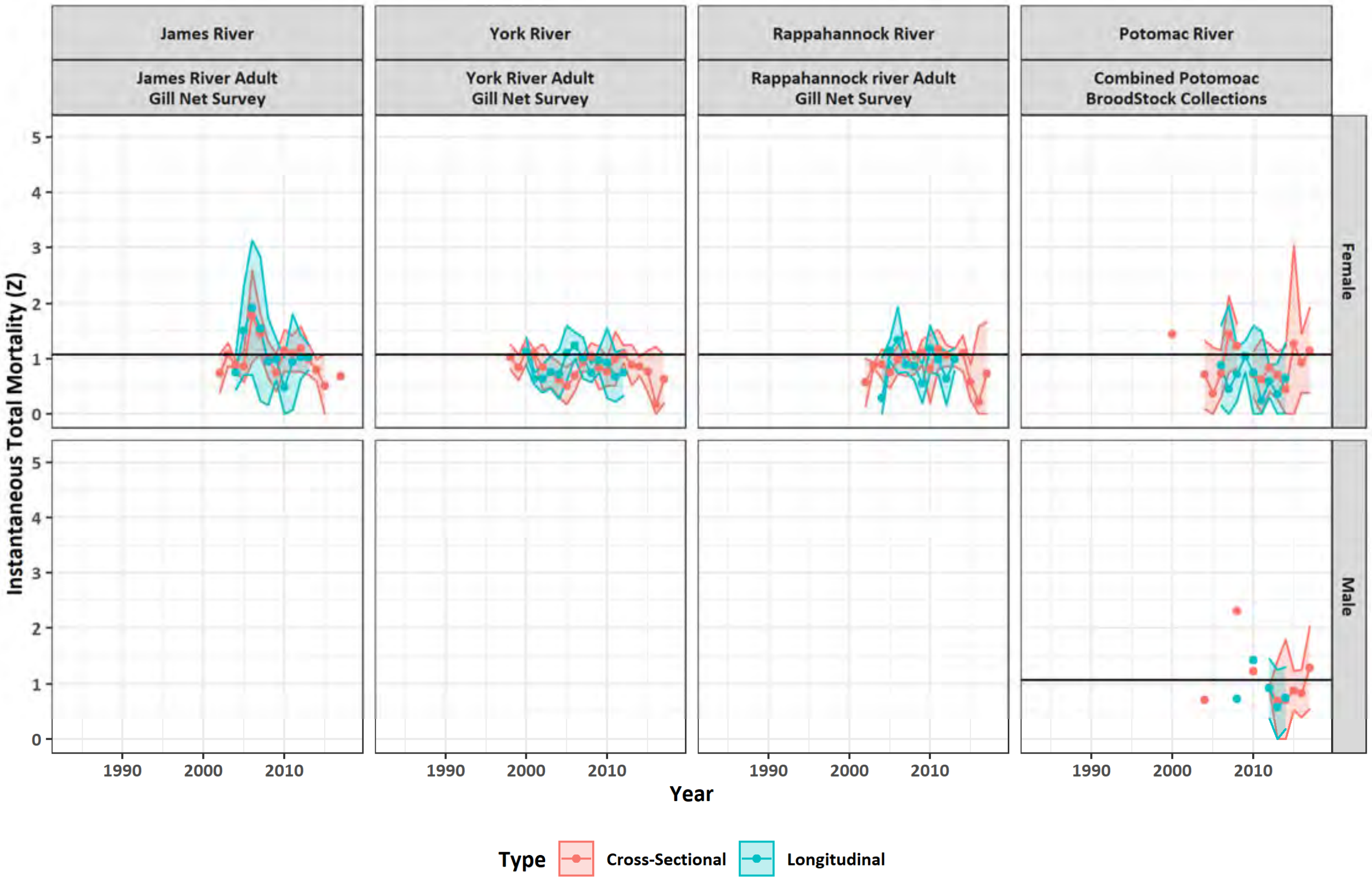


Figure 73. Instantaneous total mortality (*Z*) estimates via weighted linear regression by sex, system (James, York, Rappahannock, and Potomac Rivers), monitoring program, and cohort type using full recruitment definition of peak age, scale-based data sets, and annual age compositions. Seven years are added to longitudinal cohort year classes to select the comparison year. For example, the *Z* estimated from the 2000 year class is compared to the 2007 synthetic cohort *Z* estimate. Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

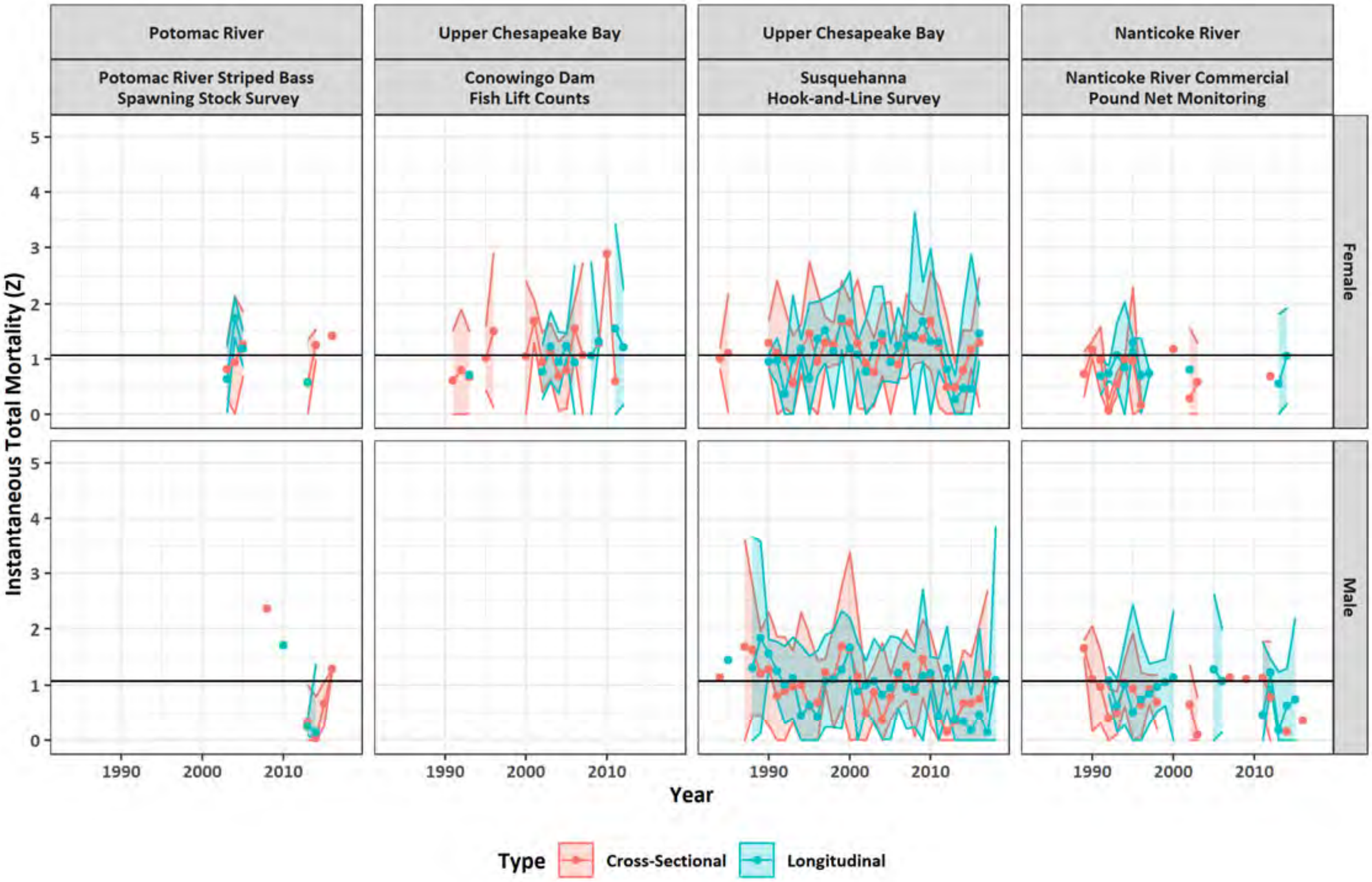


Figure 74. Instantaneous total mortality (*Z*) estimates via weighted linear regression by sex, system (Potomac River, Upper Chesapeake Bay, and Nanticoke River), monitoring program, and cohort type using full recruitment definition of peak age, scale-based data sets, and annual age compositions. Seven years are added to longitudinal cohort year classes to select the comparison year. For example, the *Z* estimated from the 2000 year class is compared to the 2007 synthetic cohort *Z* estimate. Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

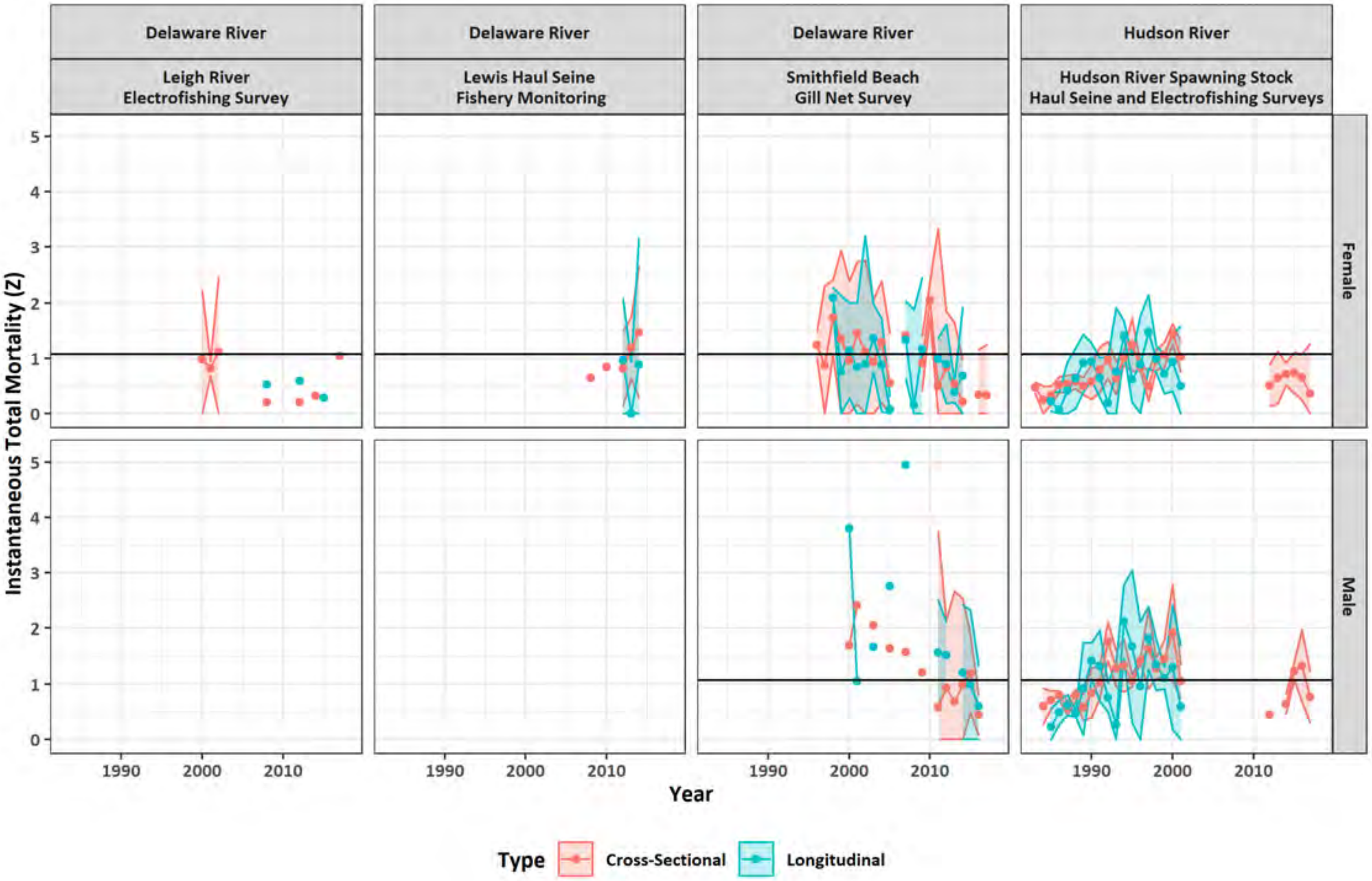


Figure 75. Instantaneous total mortality (*Z*) estimates via weighted linear regression by sex, system (Delaware and Hudson Rivers), monitoring program, and cohort type using full recruitment definition of peak age, scale-based data sets, and annual age compositions. Seven years are added to longitudinal cohort year classes to select the comparison year. For example, the *Z* estimated from the 2000 year class is compared to the 2007 synthetic cohort *Z* estimate. Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

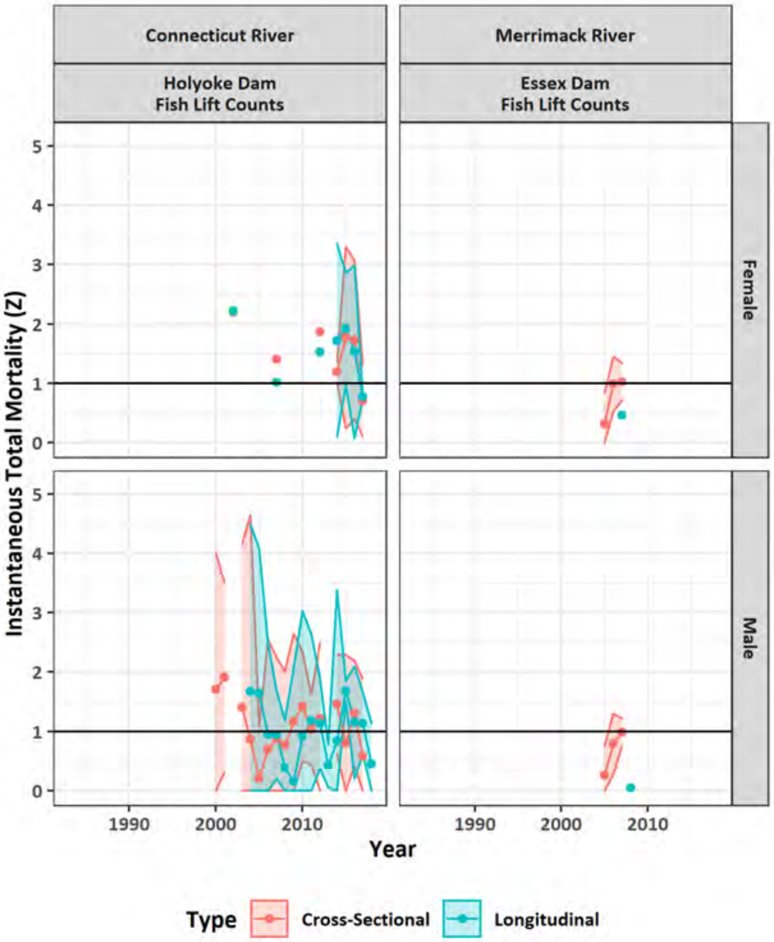


Figure 76. Instantaneous total mortality (*Z*) estimates via weighted linear regression by sex, system (Connecticut and Merrimack Rivers), monitoring program, and cohort type using full recruitment definition of peak age, scale-based data sets, and annual age compositions. Seven years are added to longitudinal cohort year classes to select the comparison year. For example, the *Z* estimated from the 2000 year class is compared to the 2007 synthetic cohort *Z* estimate. Shaded regions represent 95% confidence intervals with lower confidence intervals <0 censored to 0. Solid black line represents the region specific $Z_{40\%}$ BRP.

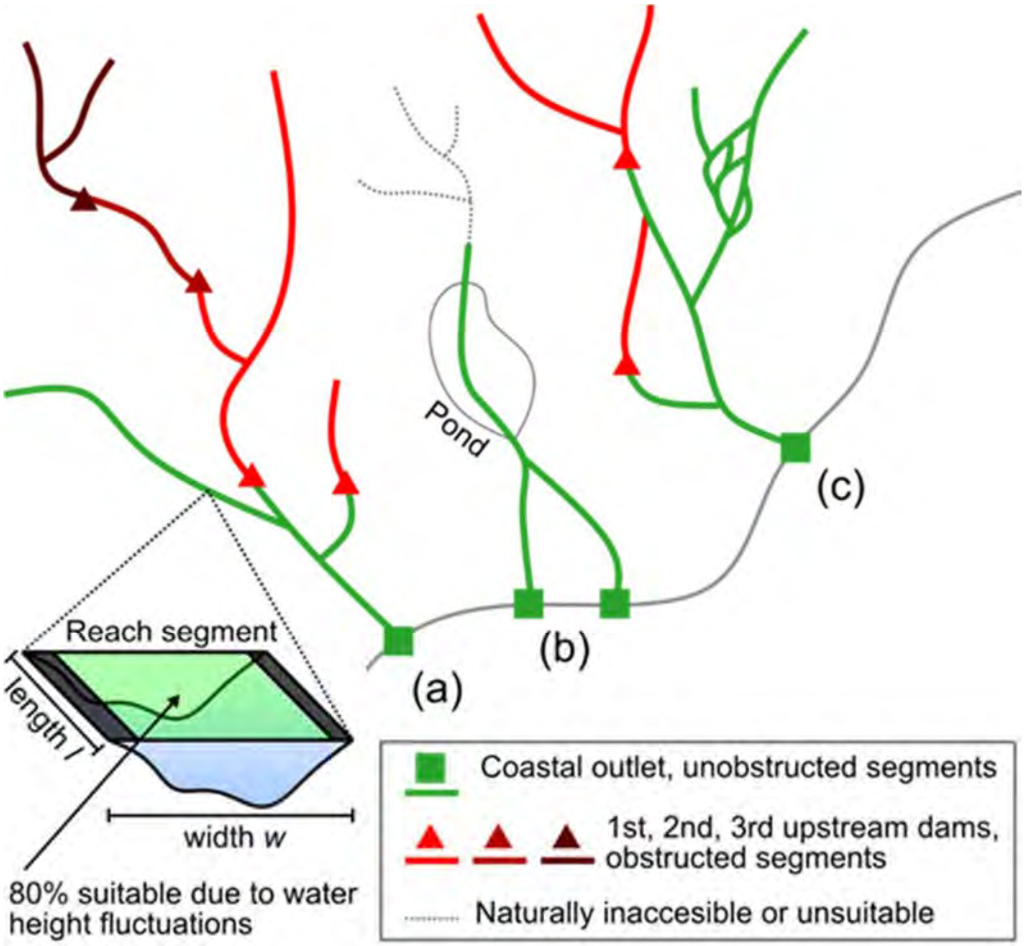


Figure 77. Example of the approach to habitat area calculation. (a) Habitat is calculated for all reach segments. Habitat groups that occur between point features (for example, habitat between a coastal outlet point and the first upstream dams in that river, habitat between a dam and other dams immediately upstream) was summed. (b) Rivers that bifurcate along the coast are summed as a single habitat group due to their upstream connection. Reach segments that are deemed inaccessible or unsuitable by experts are excluded from the habitat calculation, in addition to pond and lake areas. (c) Downstream bifurcations were included in habitat group calculations. Dams located on a bifurcation obstruct habitat only to the end of the bifurcation when other dominant flow paths are unobstructed.

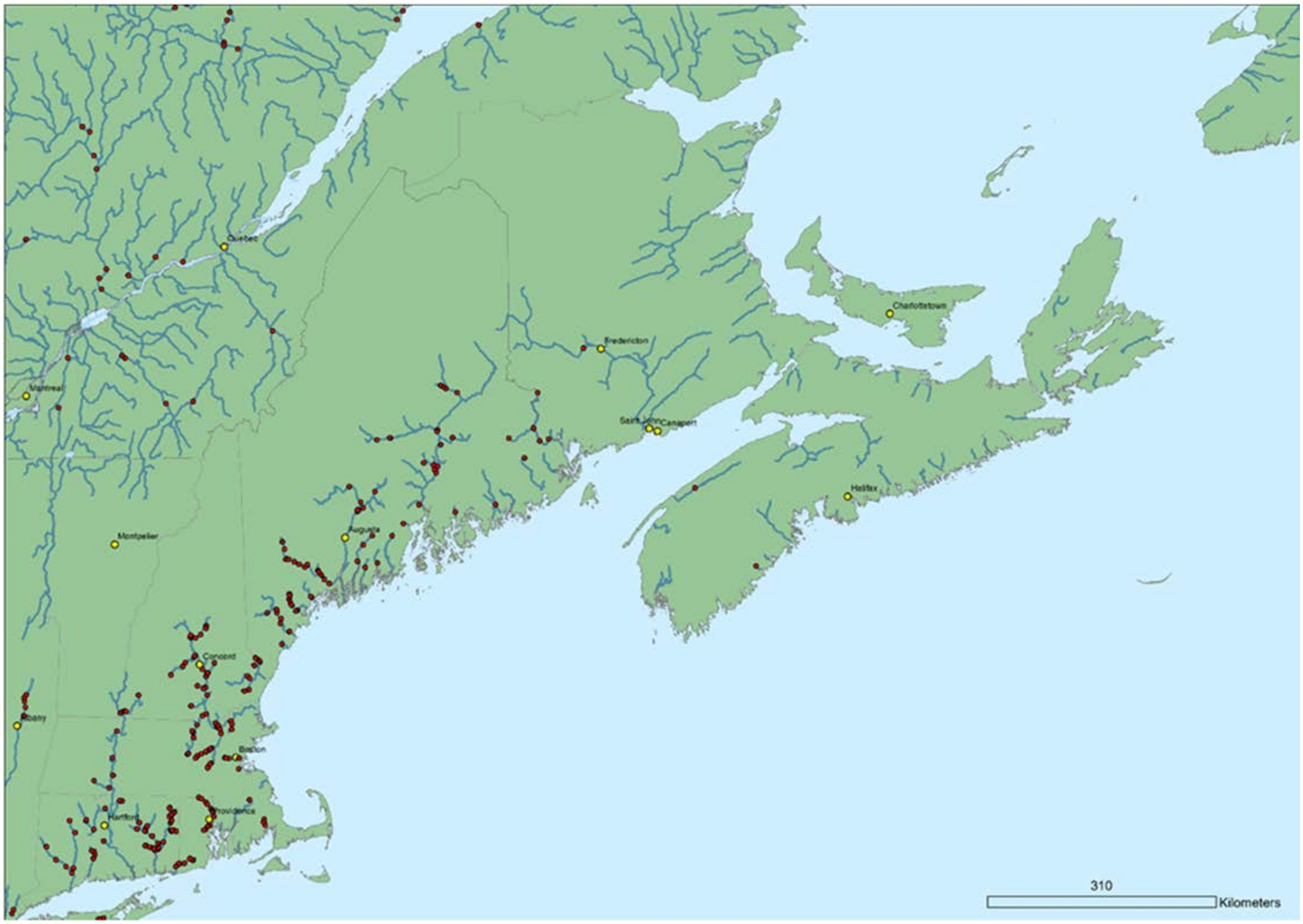


Figure 78. Modeled northern iteroparous habitat with dams indicated by red points.

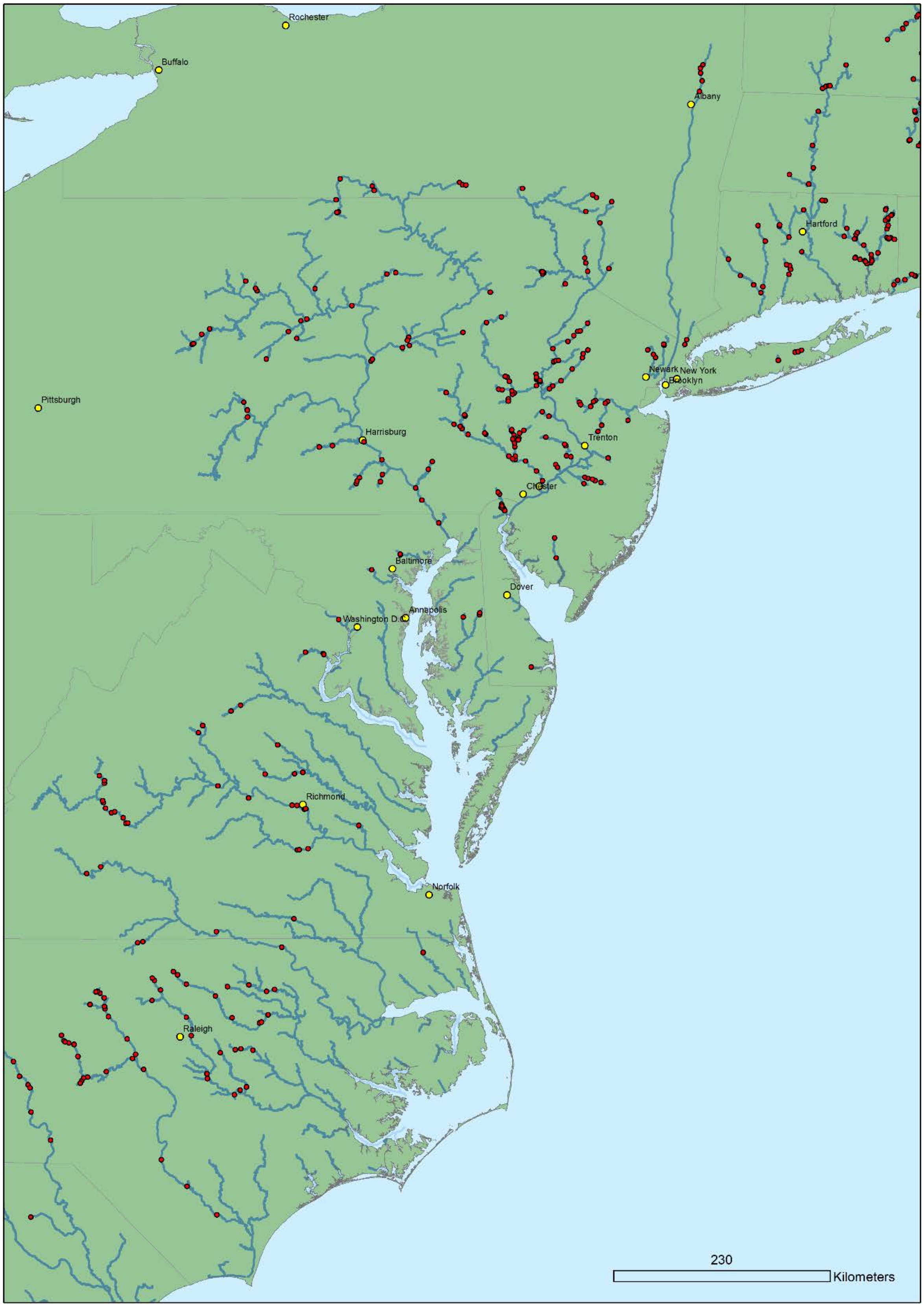


Figure 79. Modeled southern iteroparous habitat with dams indicated by red points.

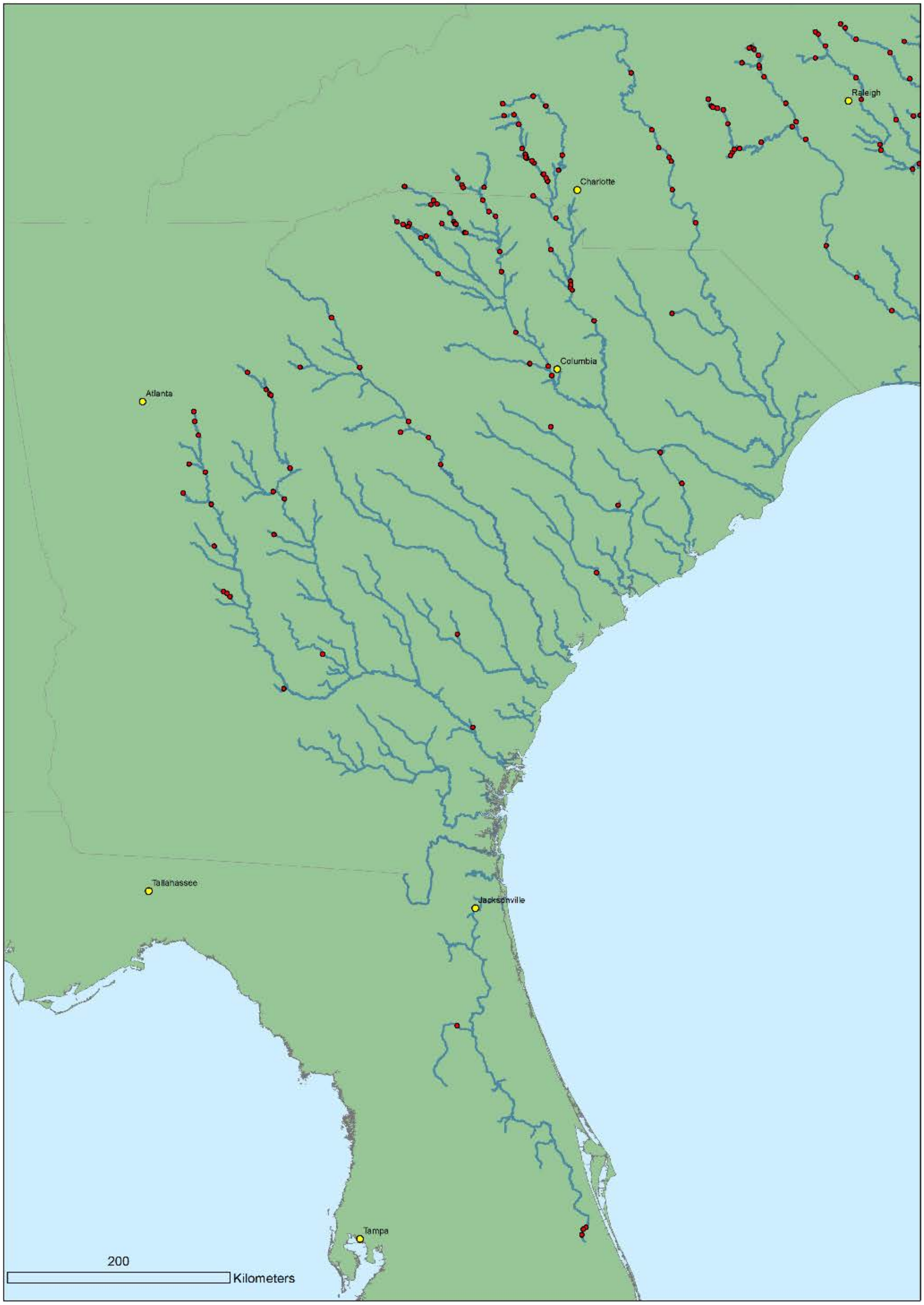


Figure 80. Modeled southern iteroparous habitat with dams indicated by red points.

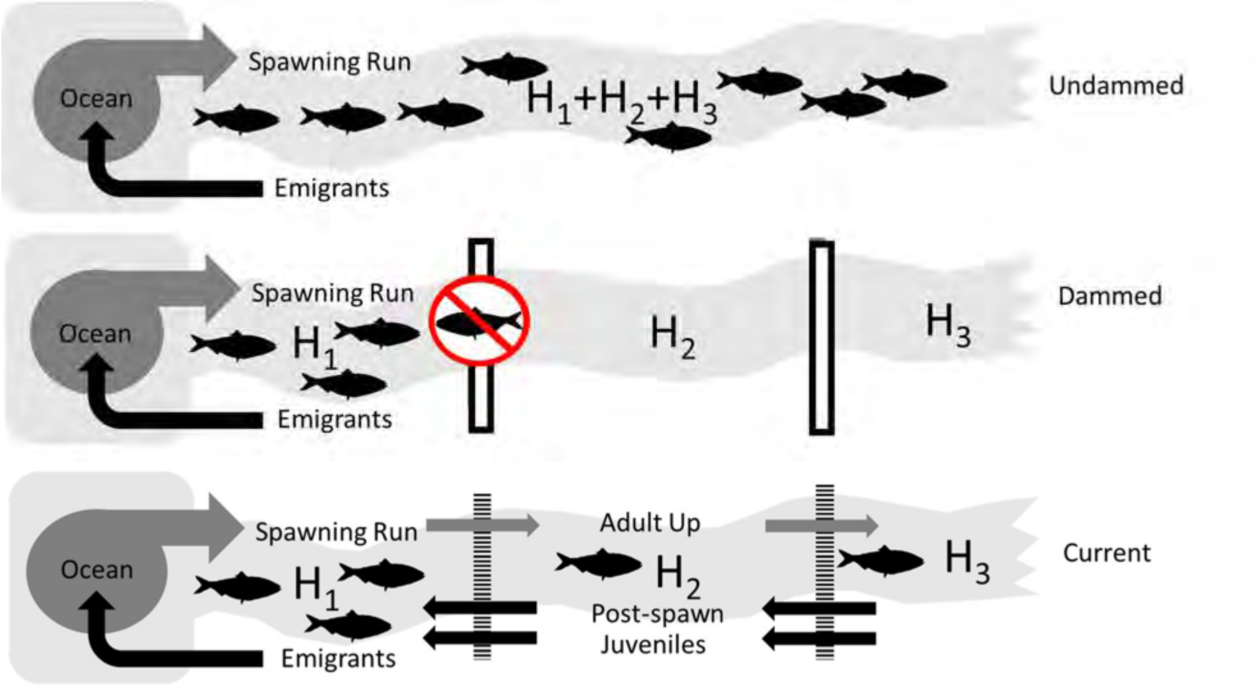


Figure 81. Conceptual diagrams of the three scenarios used to assess the impact of lost habitat and reduced connectivity on the coastwide production potential of American shad due to dams.

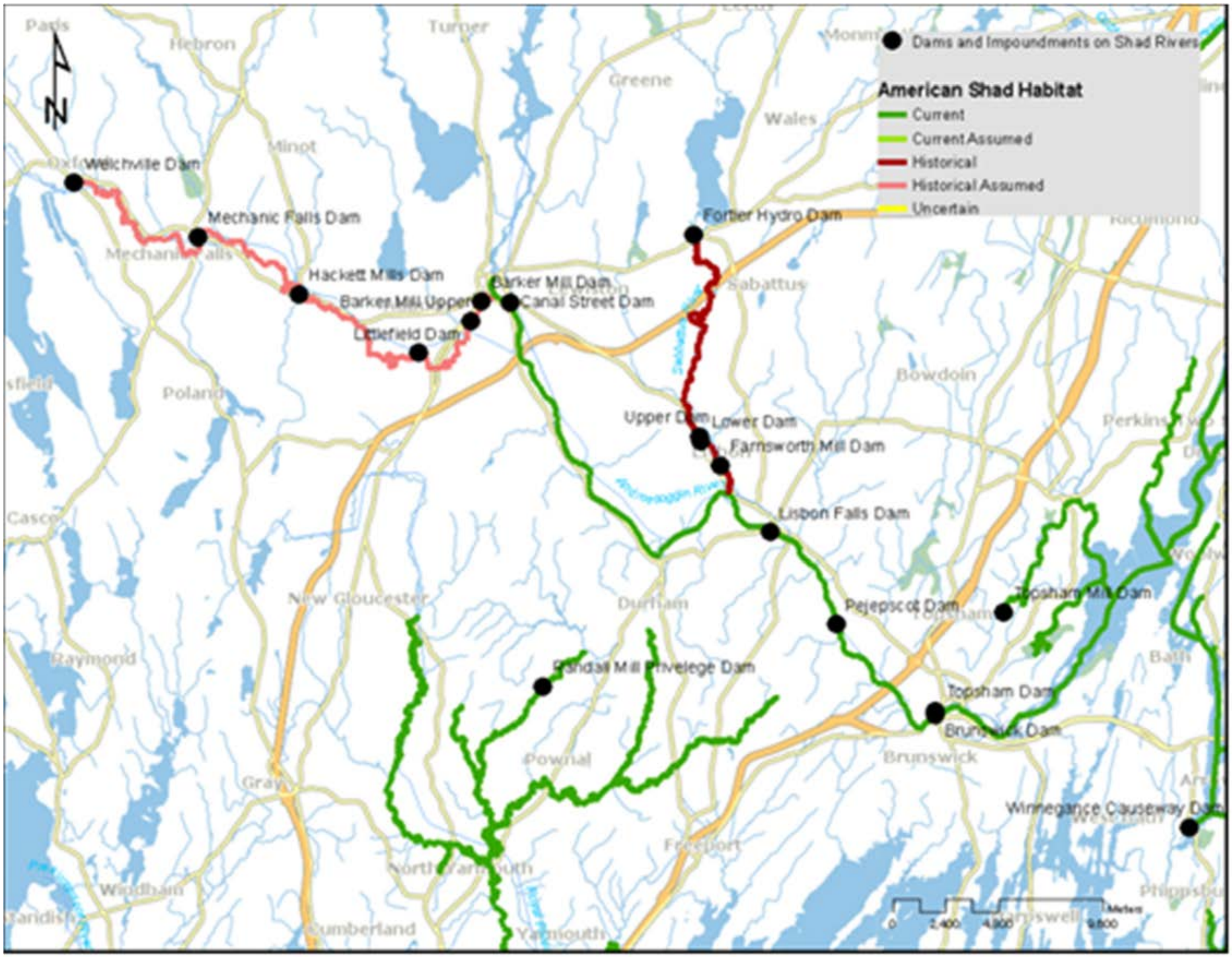


Figure 82. Androscoggin River American shad habitat. Historical habitat is above dams with no fish passage. The upper portion of the Royal River also is shown at the bottom of the figure.

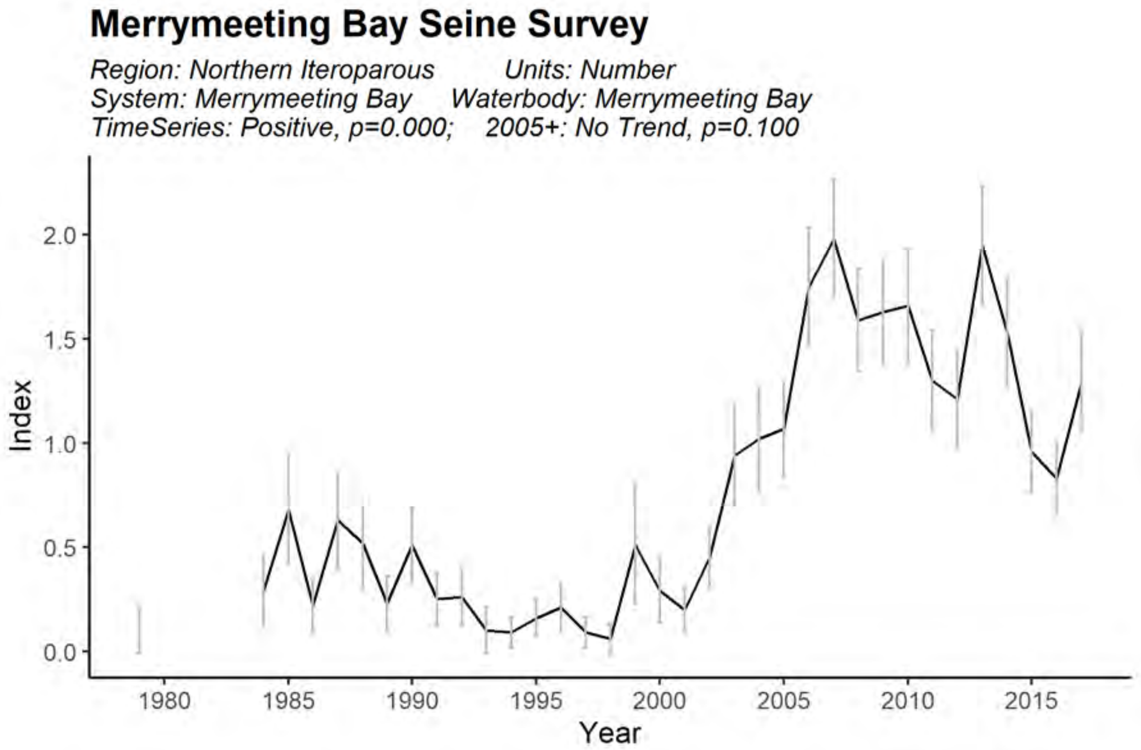


Figure 83. Merrymeeting Bay Seine Survey abundance index and Mann-Kendall results

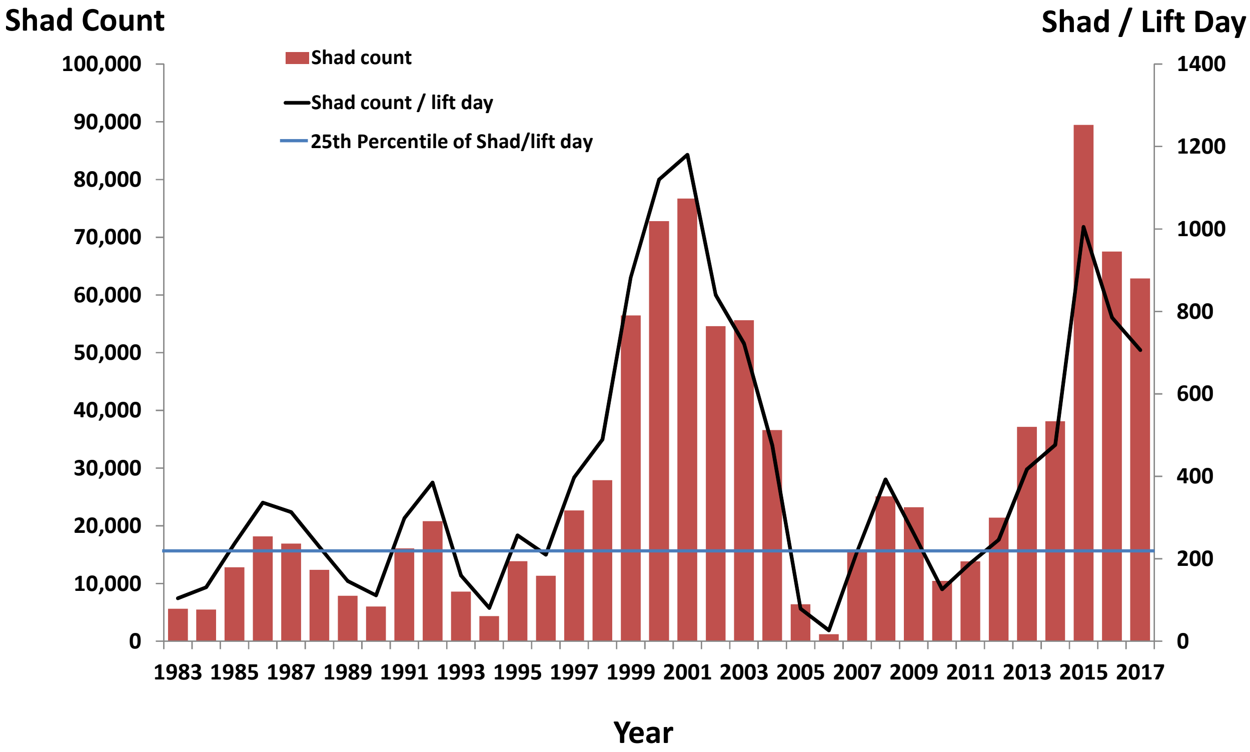


Figure 84. American shad counts at the Essex Dam fish lift in Lawrence, MA, Merrimack River, 1983–2017. Source: MassWildlife, and USFWS Central NE Fisheries Resource Office. Note: 2005 and 2006 counts are not included in the 25th percentile calculation due to high flow.

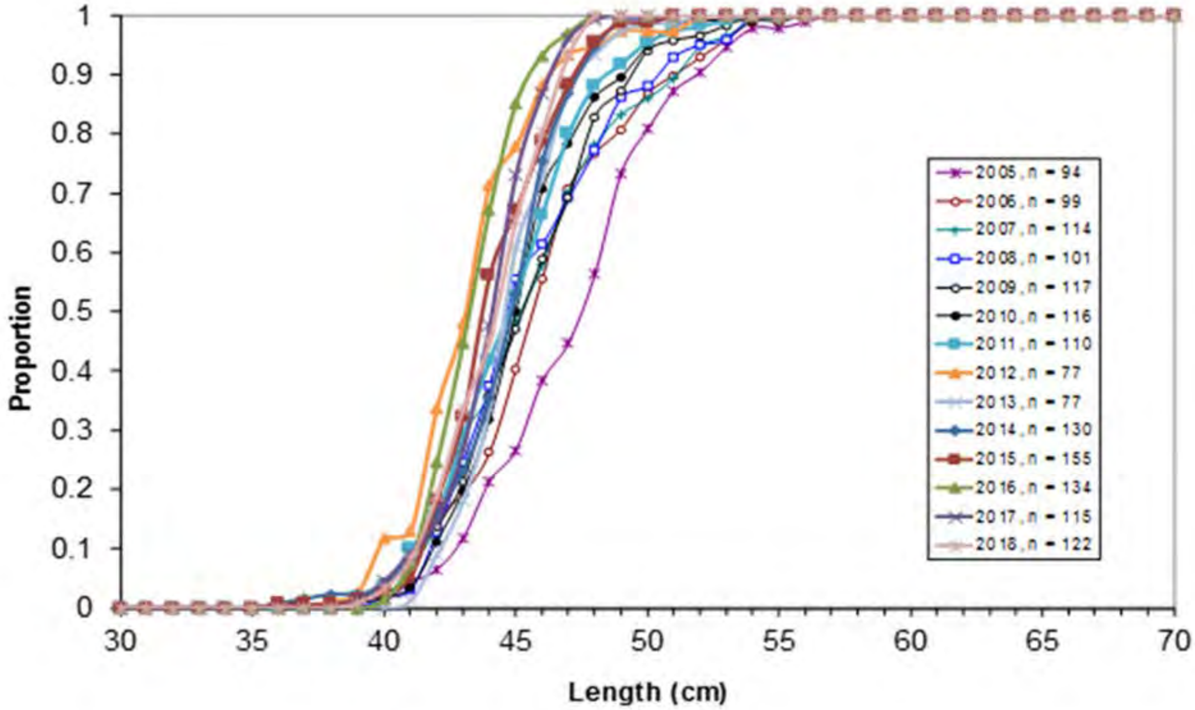


Figure 85. Cumulative length-frequencies for female American shad from the Merrimack River (2005–2018).

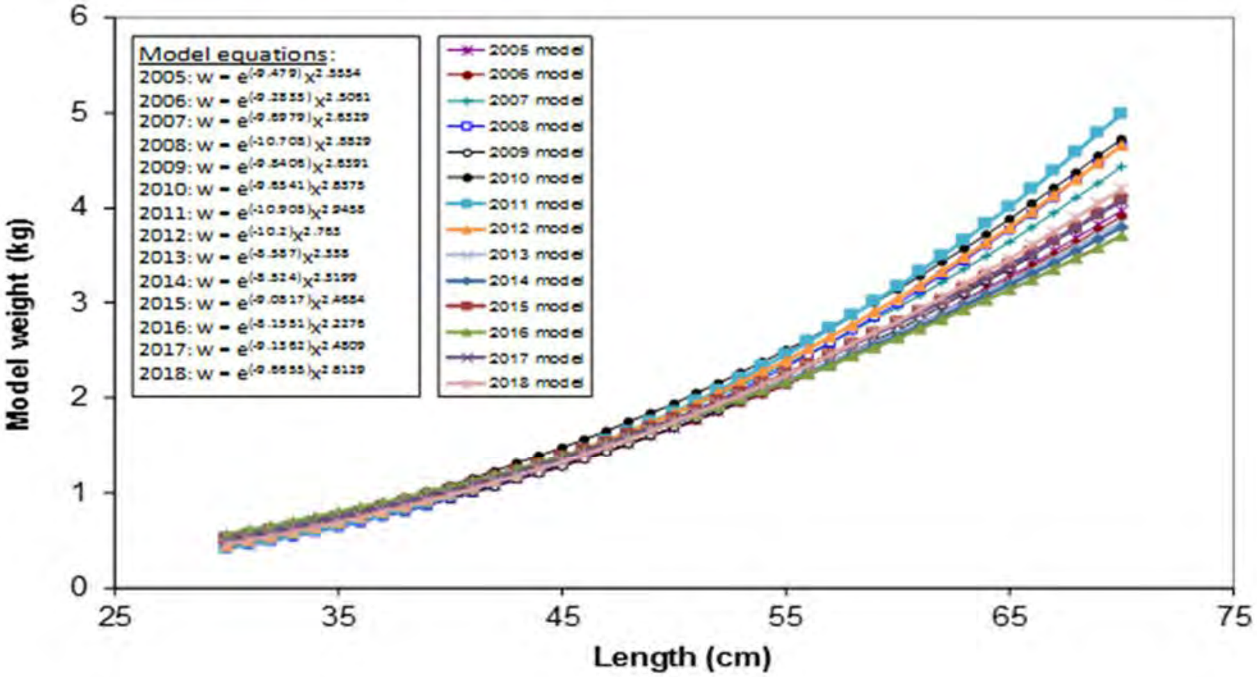


Figure 86. Modeled length-weight relationship for female American shad from the Merrimack River (2005–2018).

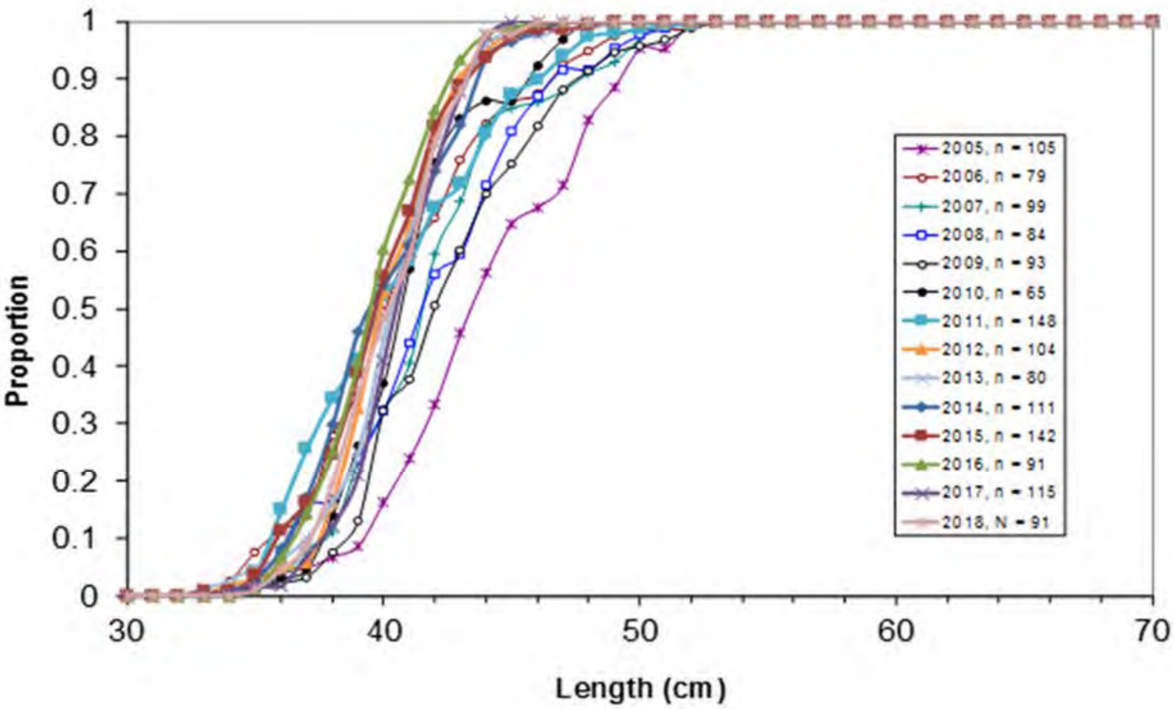


Figure 87. Cumulative length-frequencies for male American shad from the Merrimack River (2005–2018).

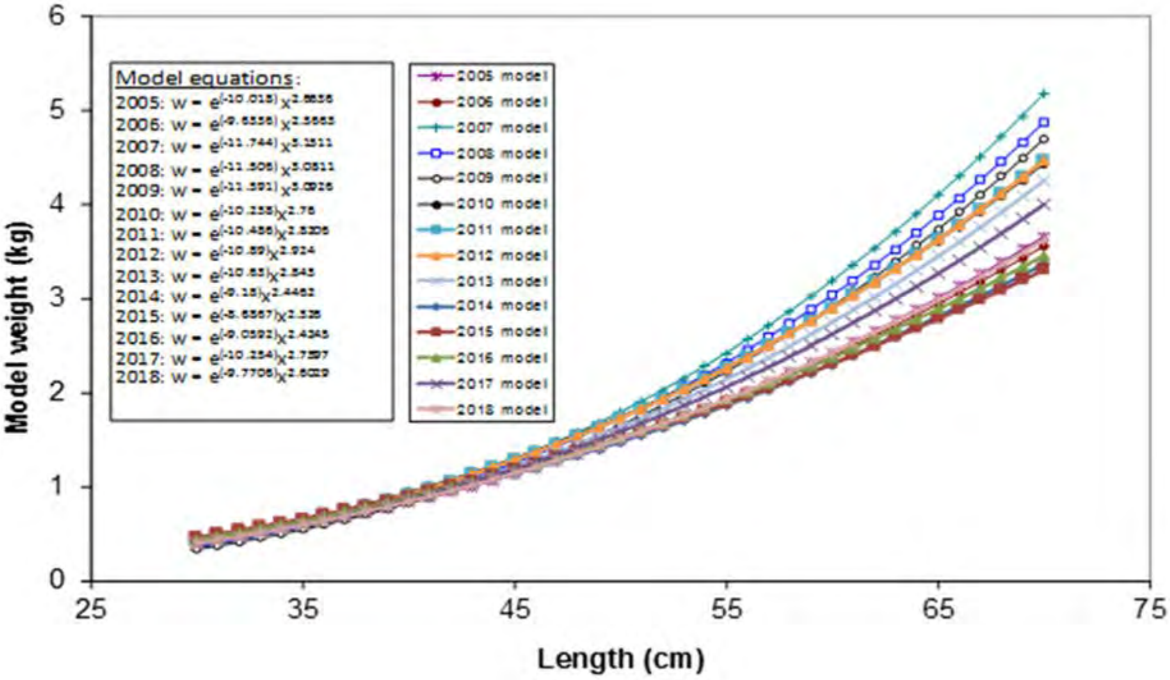


Figure 88. Modeled length-weight relationship for male American shad from the Merrimack River (2005–2018).

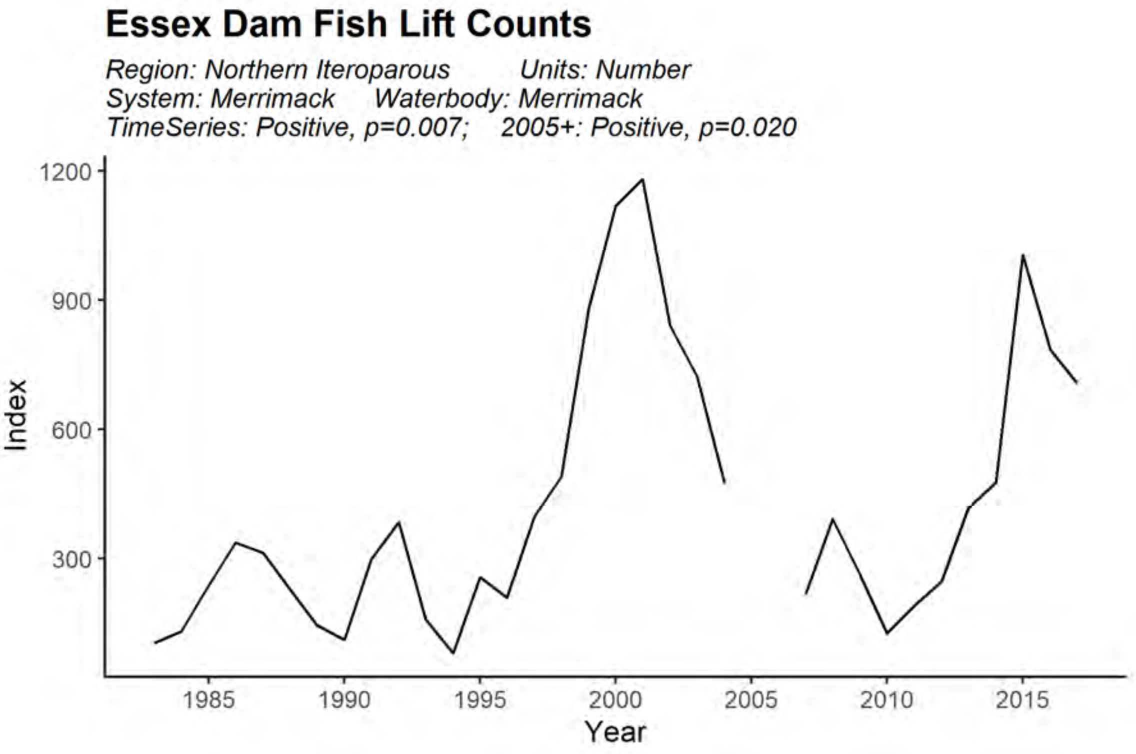


Figure 89. Essex Dam Fish Lift Count abundance index and Mann-Kendall results.

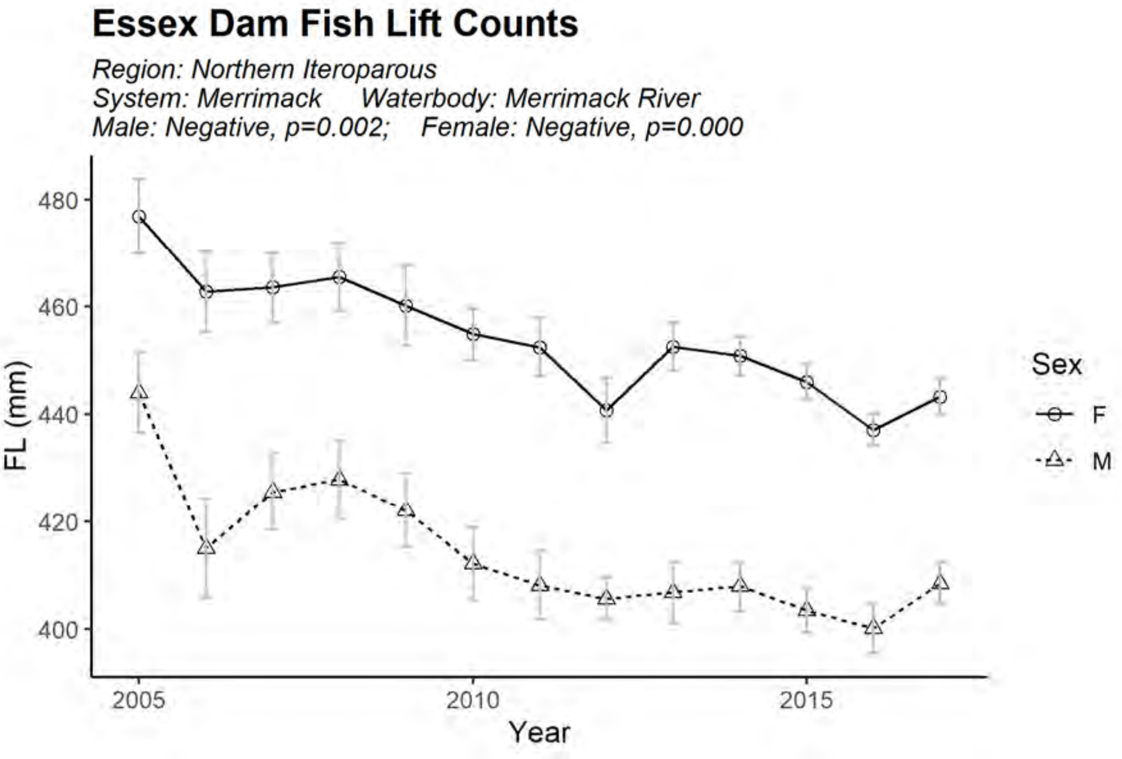


Figure 90. Mean fork length over time from the Essex Dam Fish Lift Count and Mann-Kendall test results.

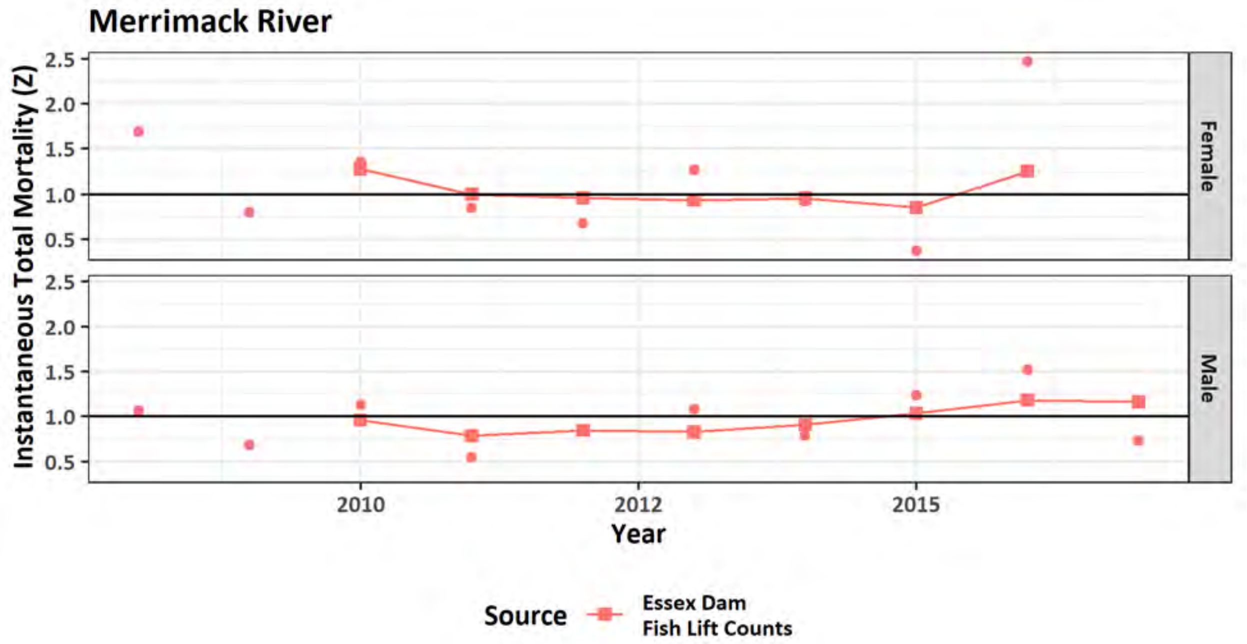


Figure 91. Three year average *Z* estimates via weighted linear regression by sex and monitoring program for the Merrimack River System based on otolith-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual *Z* estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).

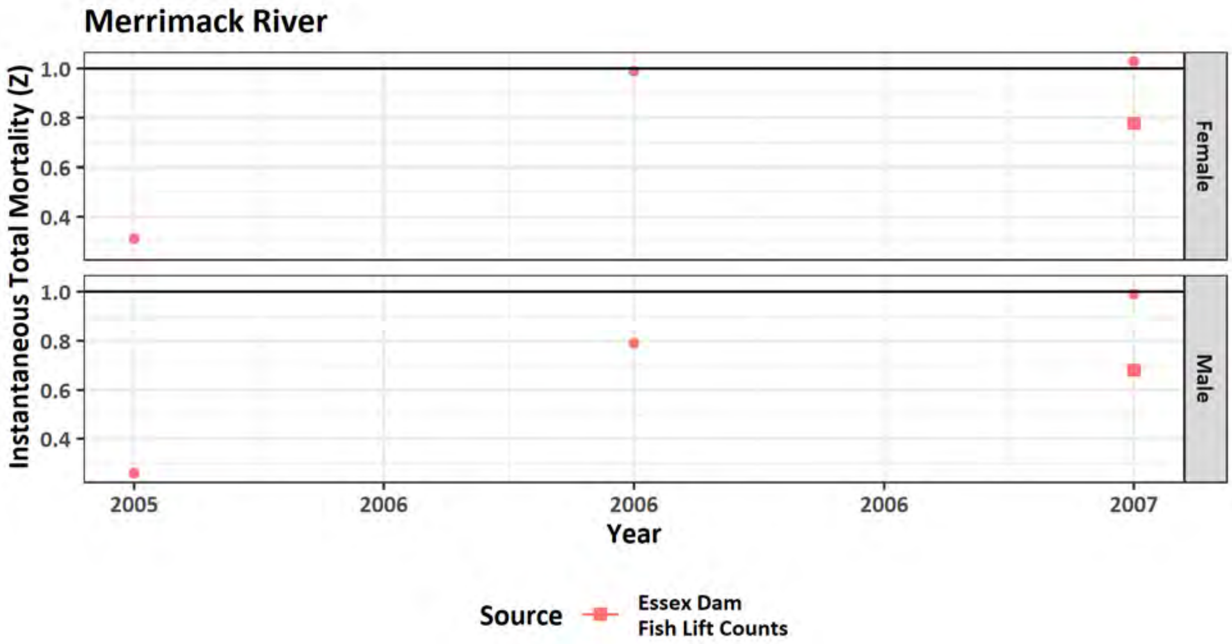


Figure 92. Three year average *Z* estimates via weighted linear regression by sex and monitoring program for the Merrimack River System based on scale-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual *Z* estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).

Figure 93. The Pawcatuck River, Rhode Island, with all dam and restoration locations.

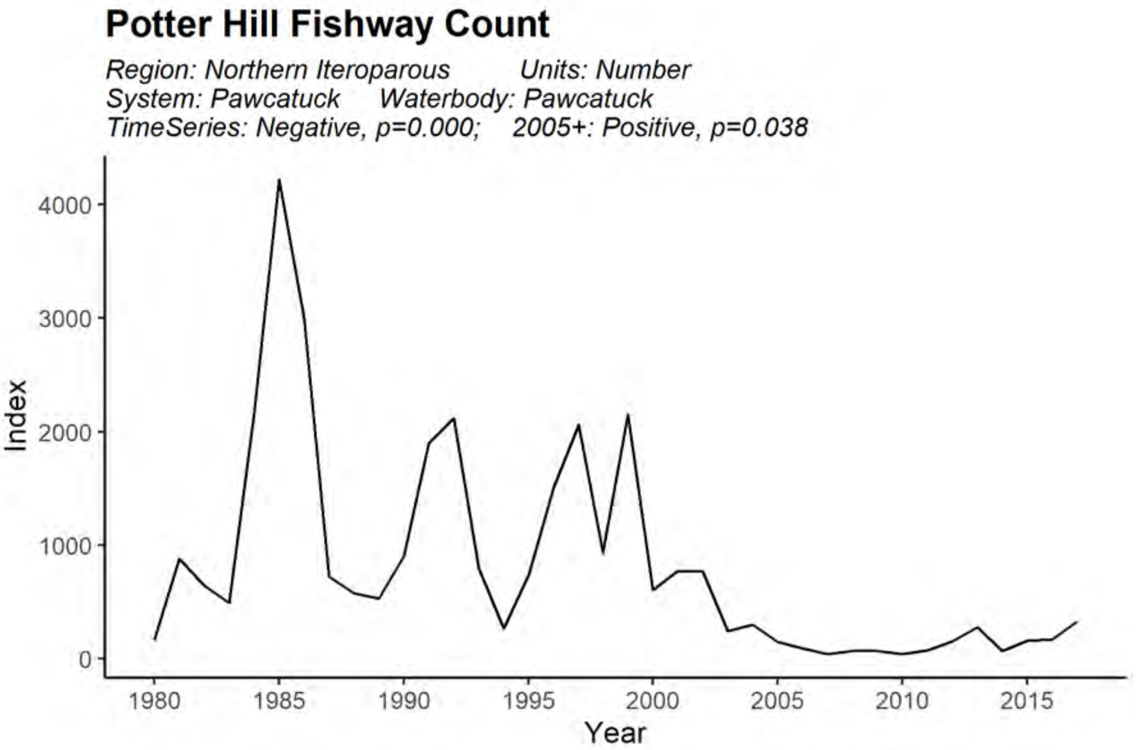


Figure 94. Abundance index for the Potter Hill Fishway Count and Mann-Kendall results.

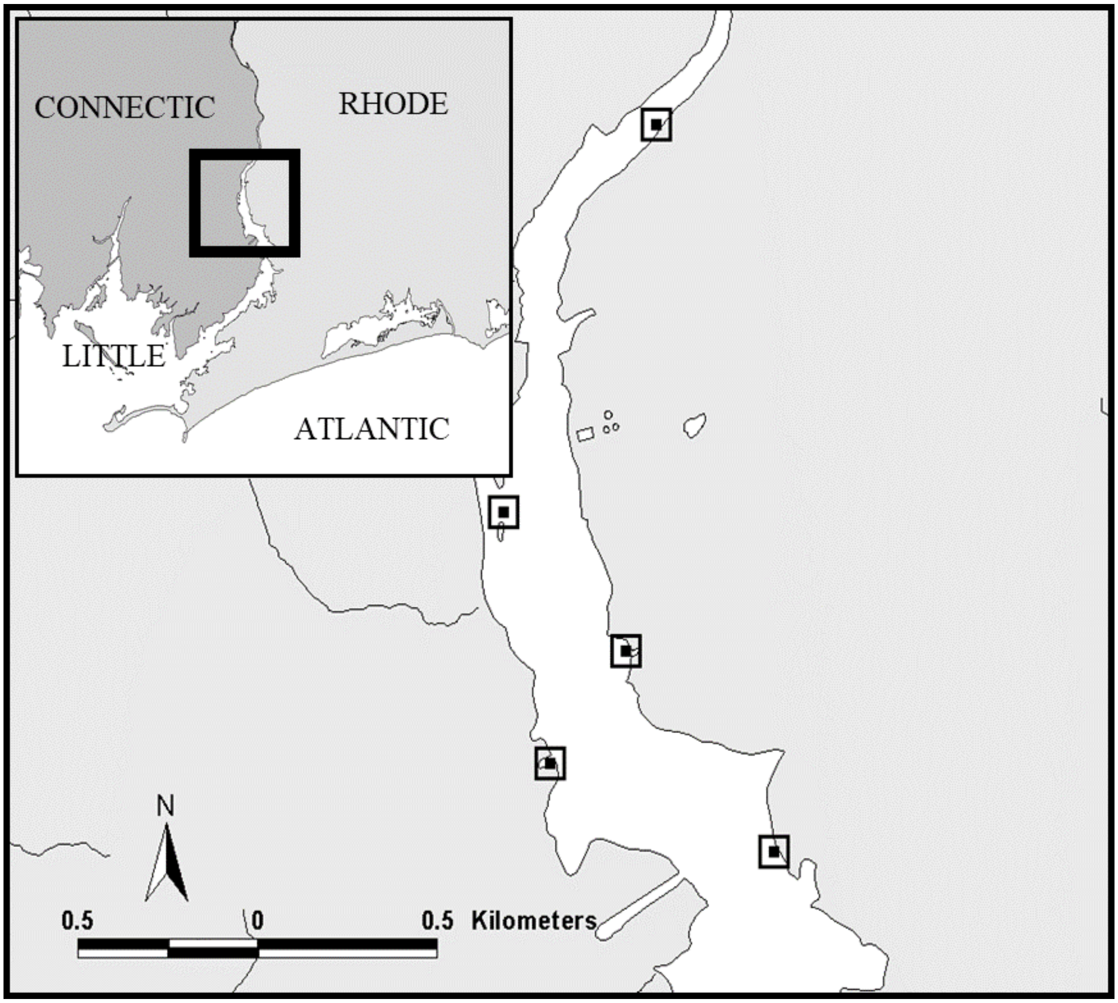


Figure 95. Sampling locations for the juvenile shad beach seine survey in the Pawcatuck River, RI.

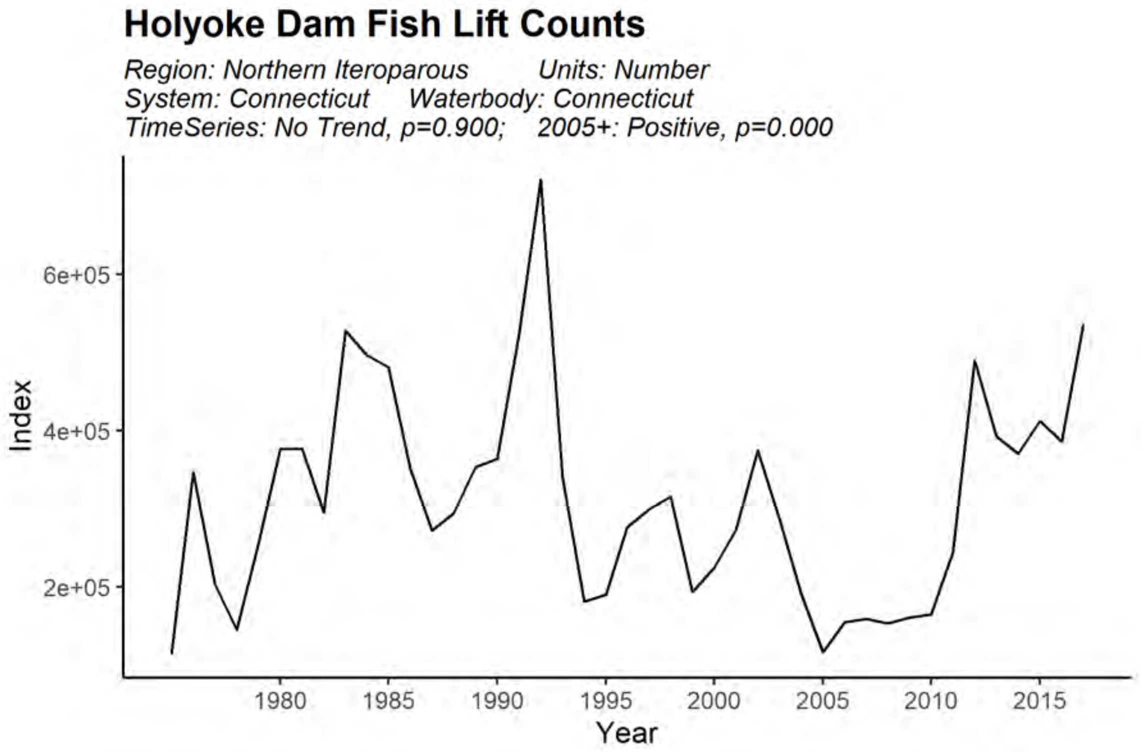


Figure 96. Holyoke Dam Fish Lift Count abundance index and Mann-Kendall test results.

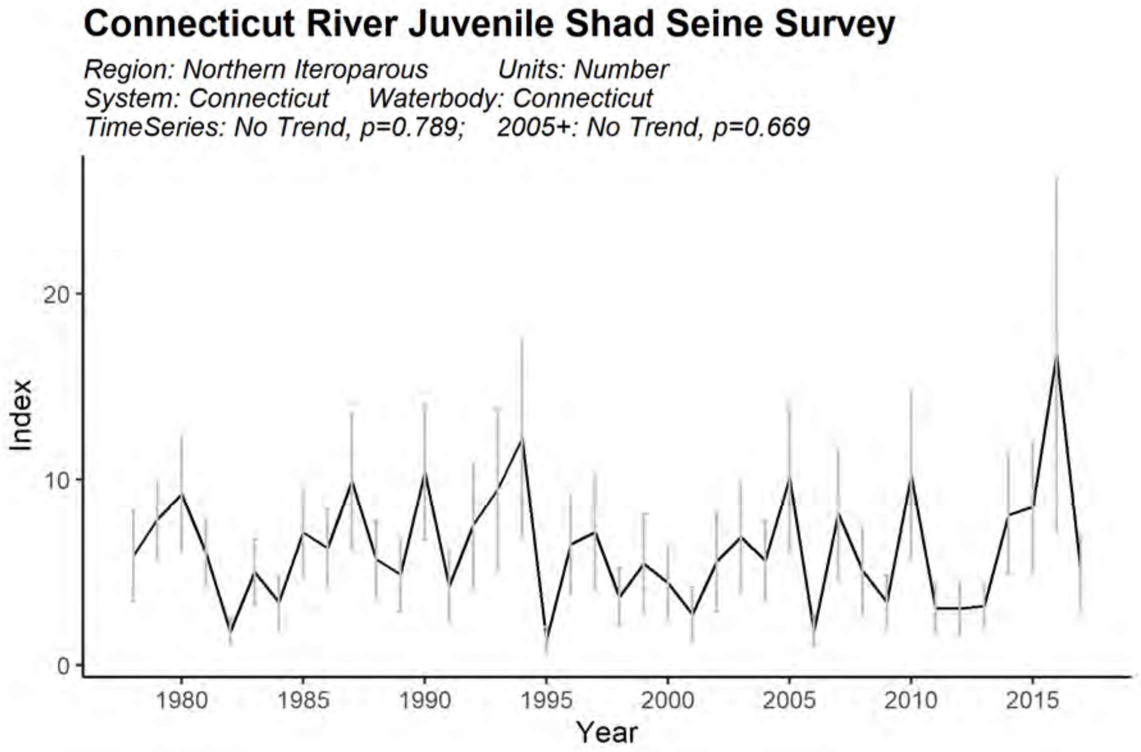


Figure 97. Connecticut River Juvenile Shad Seine Survey abundance index and Mann-Kendall test results.

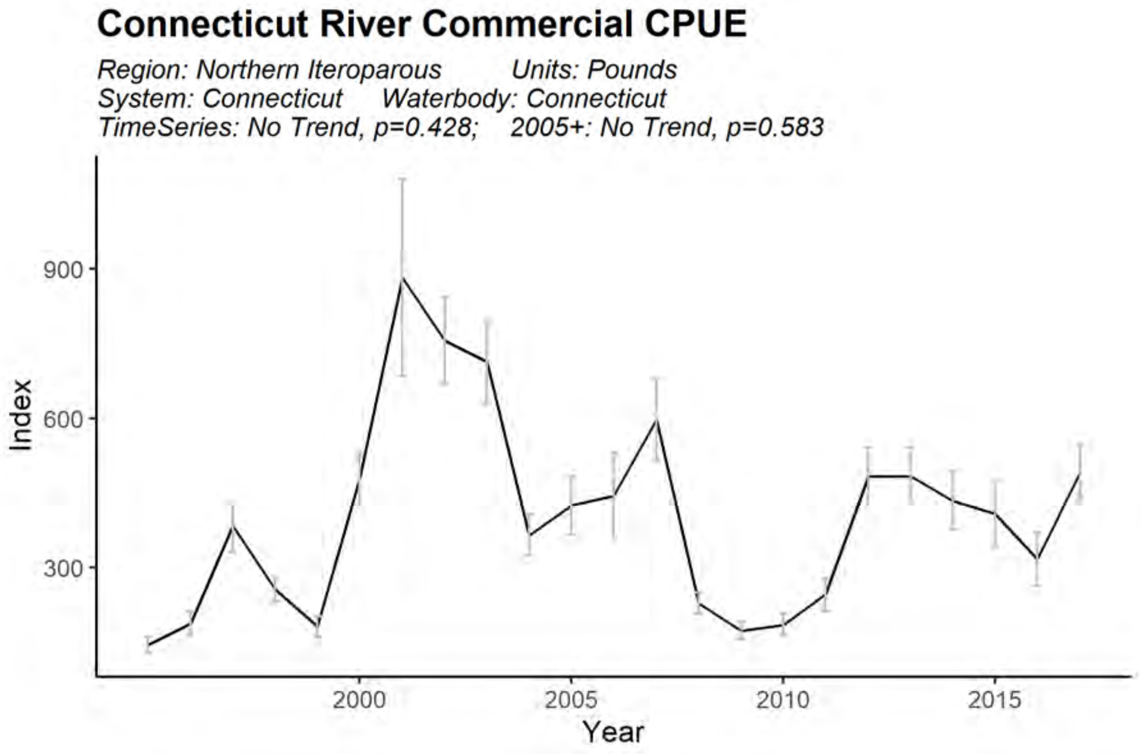


Figure 98. Connecticut River Commercial CPUE and Mann-Kendall test results.

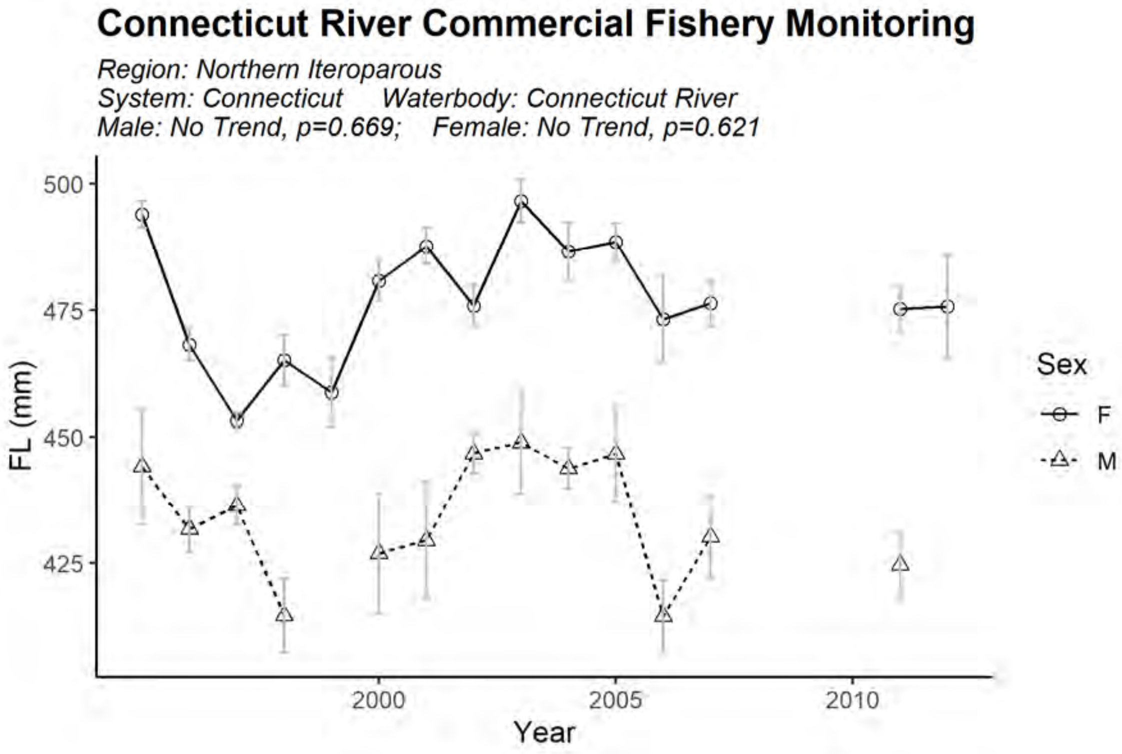


Figure 99. Mean fork length over time in the Connecticut River Commercial Fishery Monitoring program and Mann-Kendall test results.

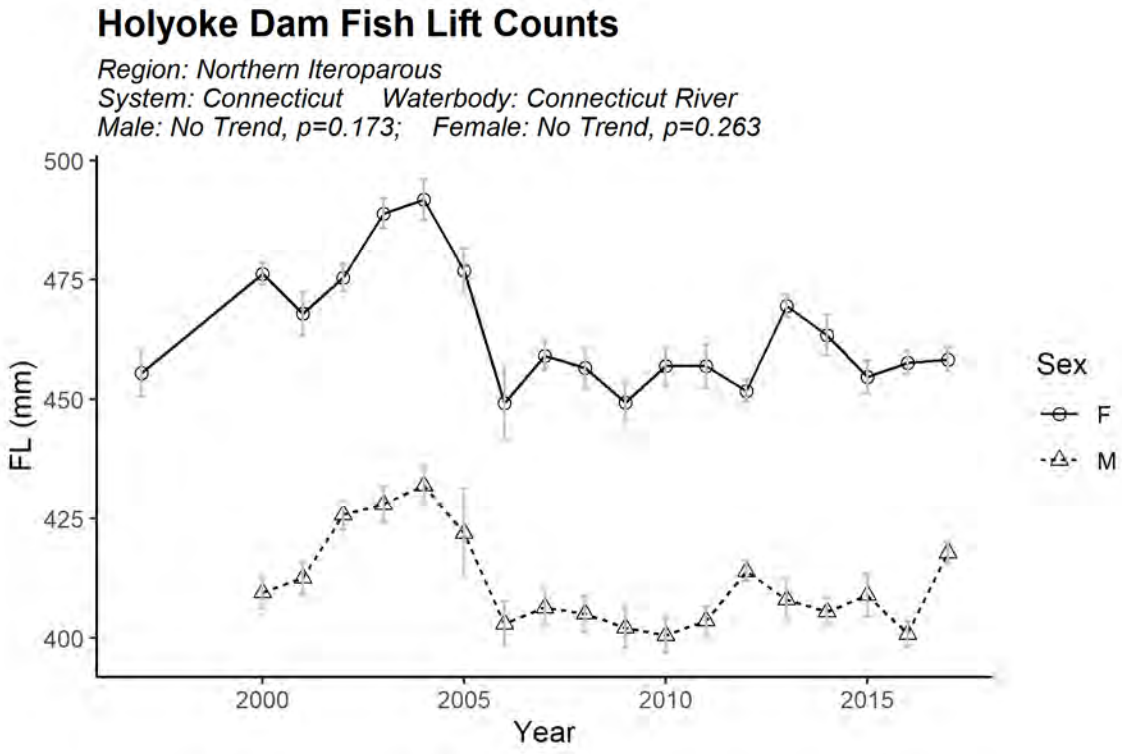


Figure 100. Mean fork length over time in the Connecticut River Holyoke Dam Fish Lift sampling program and Mann-Kendall test results.

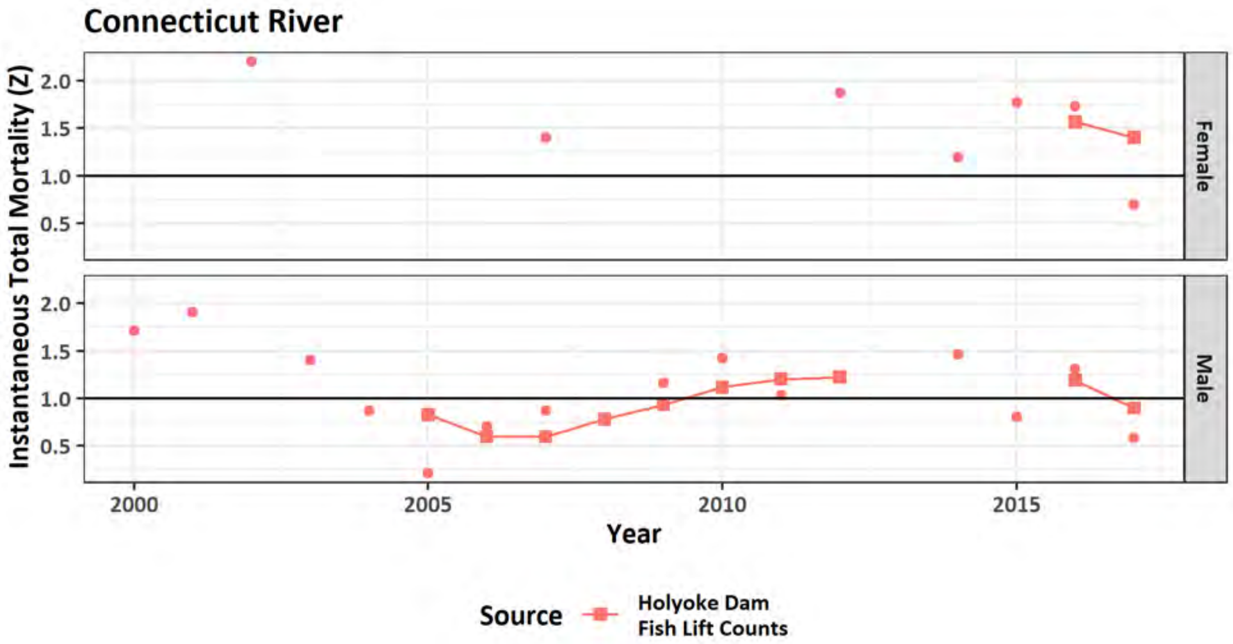


Figure 101. **Three year average *Z* estimates via weighted linear regression by sex and monitoring program for the Connecticut River System based on scale-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual Z estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).**

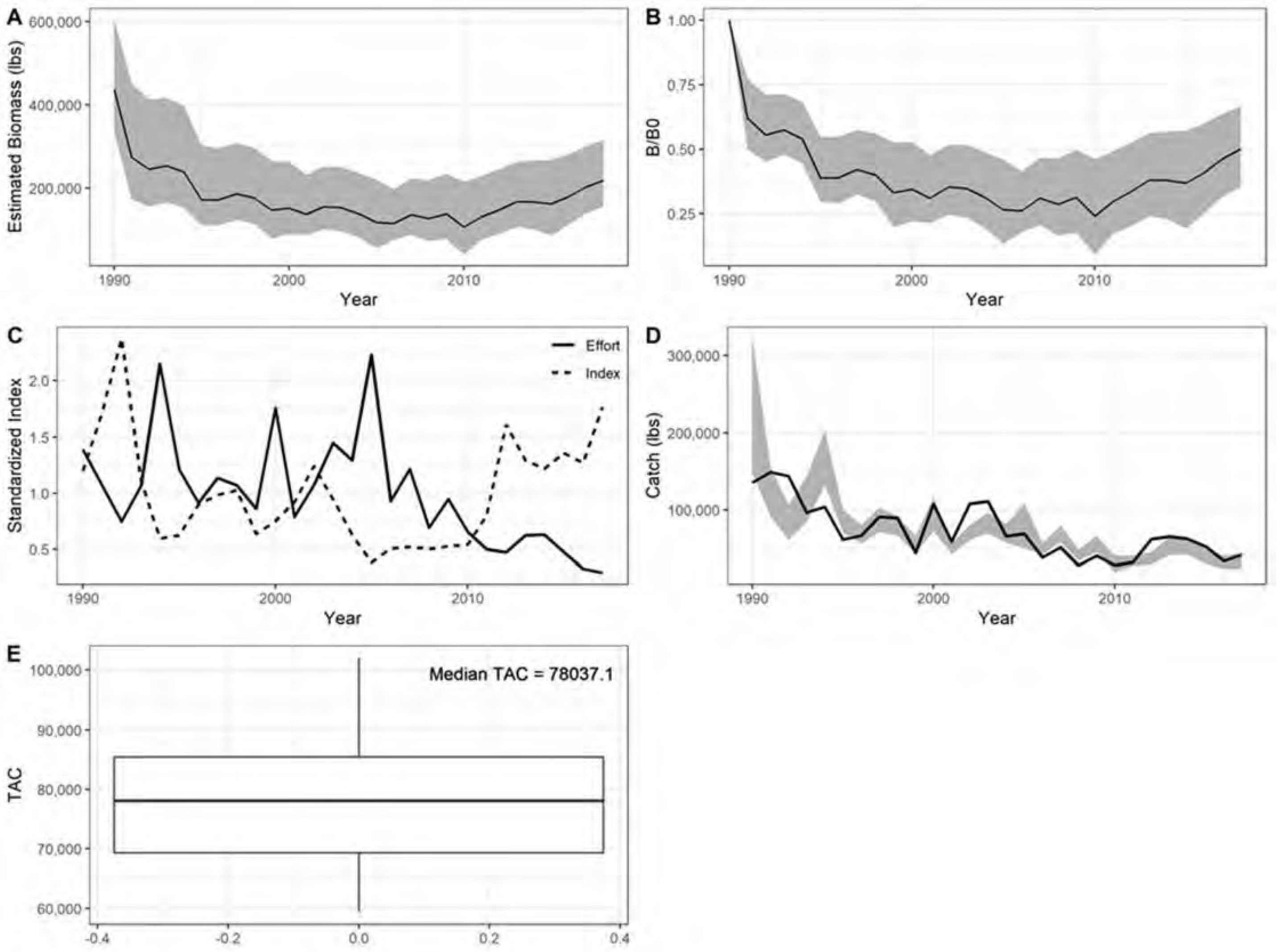


Figure 102. Output of delay-difference model for the Connecticut American shad stock using the Holyoke Dam Fish Lift Count index. (A) Estimated biomass of the population over time. The black line represents the median biomass over 100 simulations. (B) Ratio of estimated biomass to initial biomass. The black line represents the median biomass ratio over 100 simulations. (C) Standardized index and fishery effort over time. (D) Total catch over time. The black line represents the observed catch and the gray area represents estimates over 100 simulations. (E) Boxplot of Total Allowable Catch (TAC) estimates over 100 simulations.

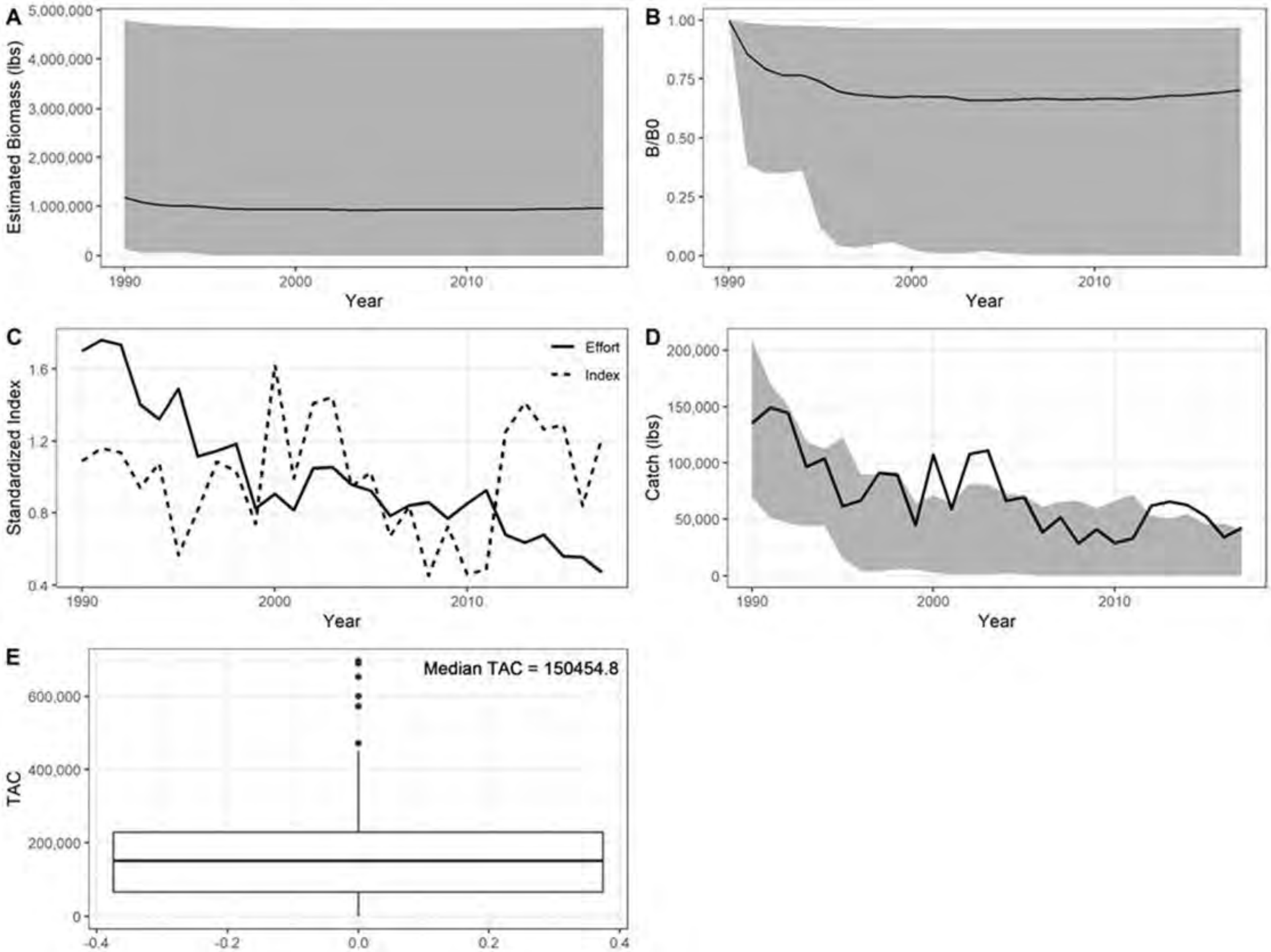


Figure 103. Output of delay-difference model for the Connecticut American shad stock using the commercial CPUE index. (A) Estimated biomass of the population over time. The black line represents the median biomass over 100 simulations. (B) Ratio of estimated biomass to initial biomass. The black line represents the median biomass ratio over 100 simulations. (C) Standardized index and fishery effort over time. (D) Total catch over time. The black line represents the observed catch and the gray area represents estimates over 100 simulations. (E) Boxplot of Total Allowable Catch (TAC) estimates over 100 simulations.

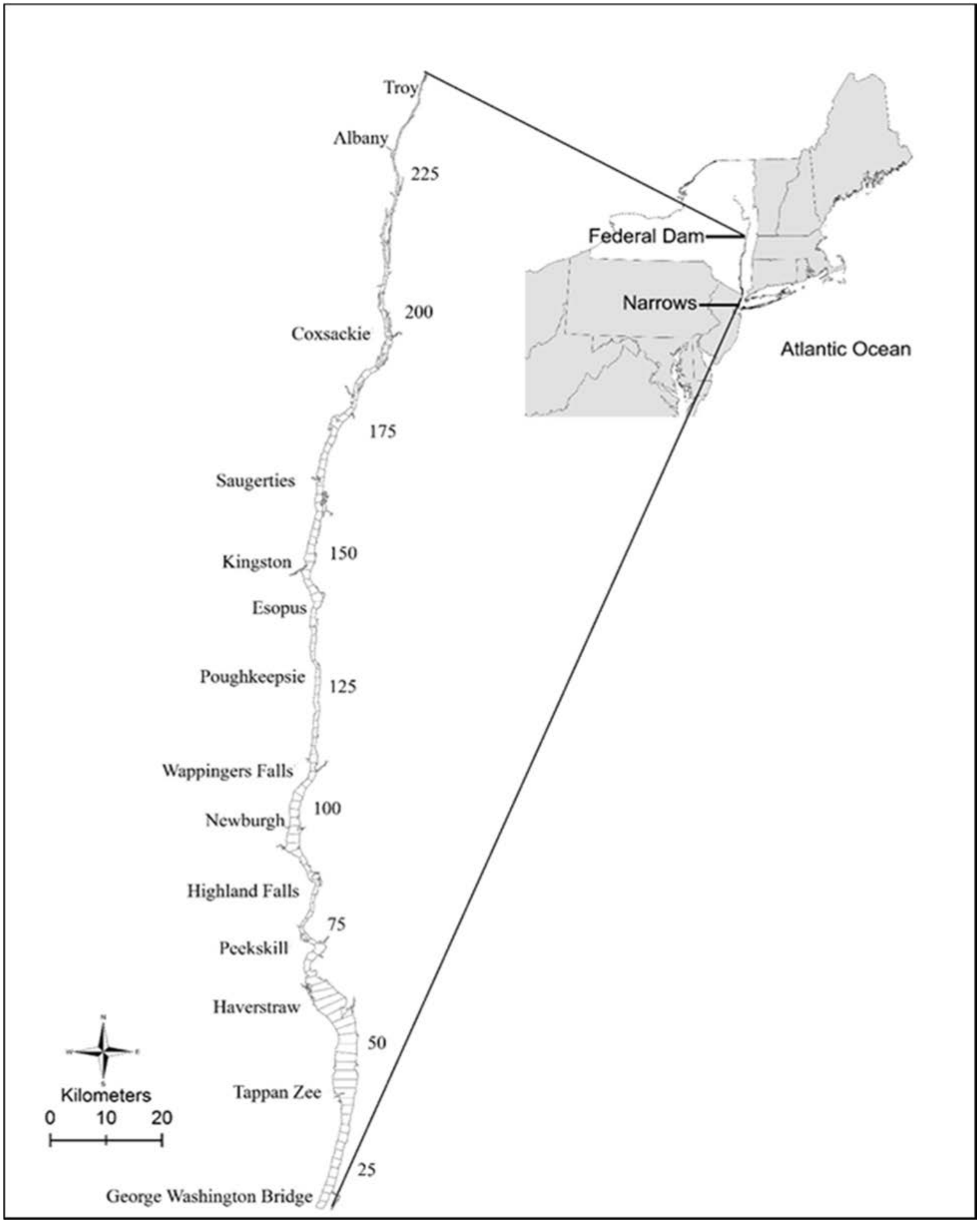


Figure 104. Map of the tidal Hudson River.

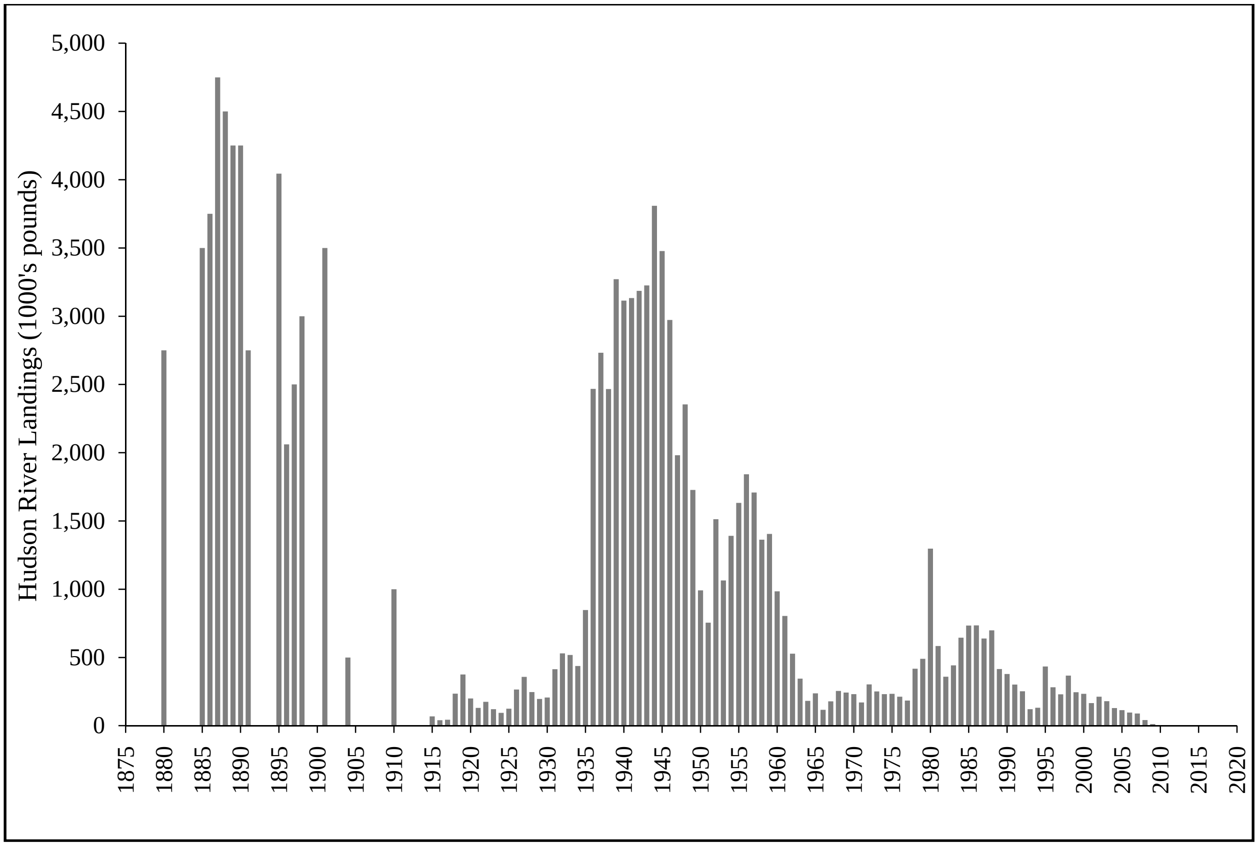


Figure 105. Historic American shad landings (Hudson River only).

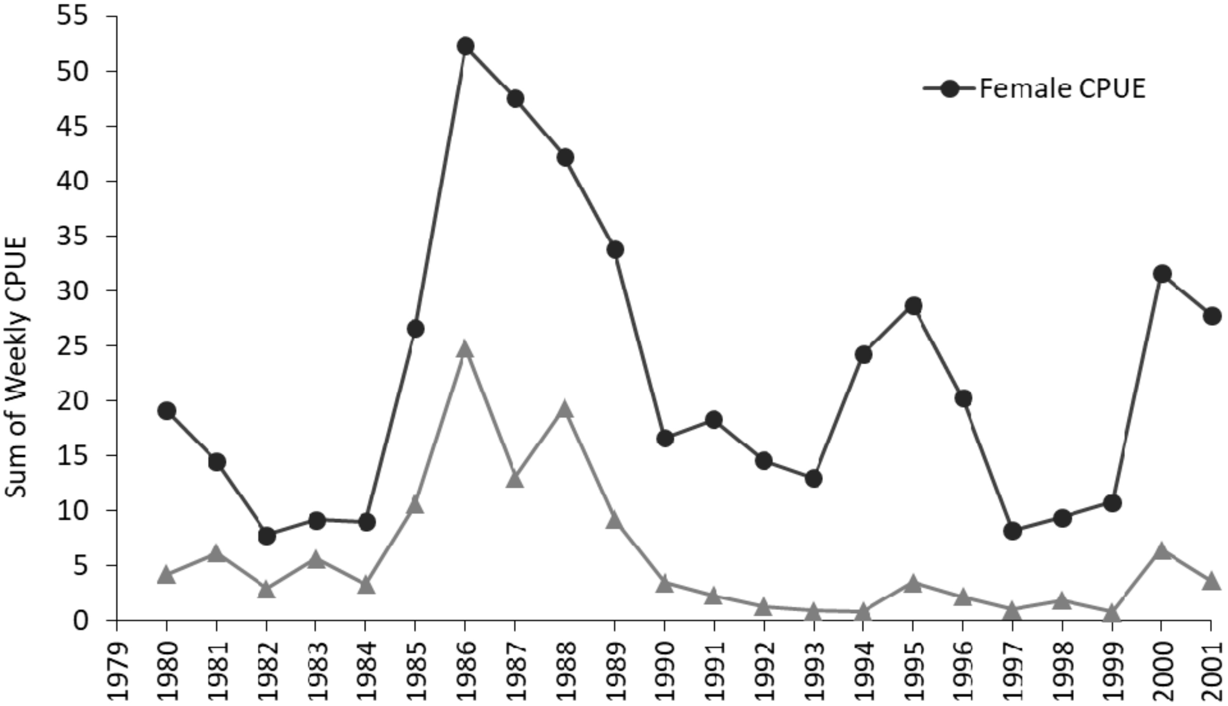


Figure 106. Annual CPUE estimates for American shad from observed commercial monitoring trips.

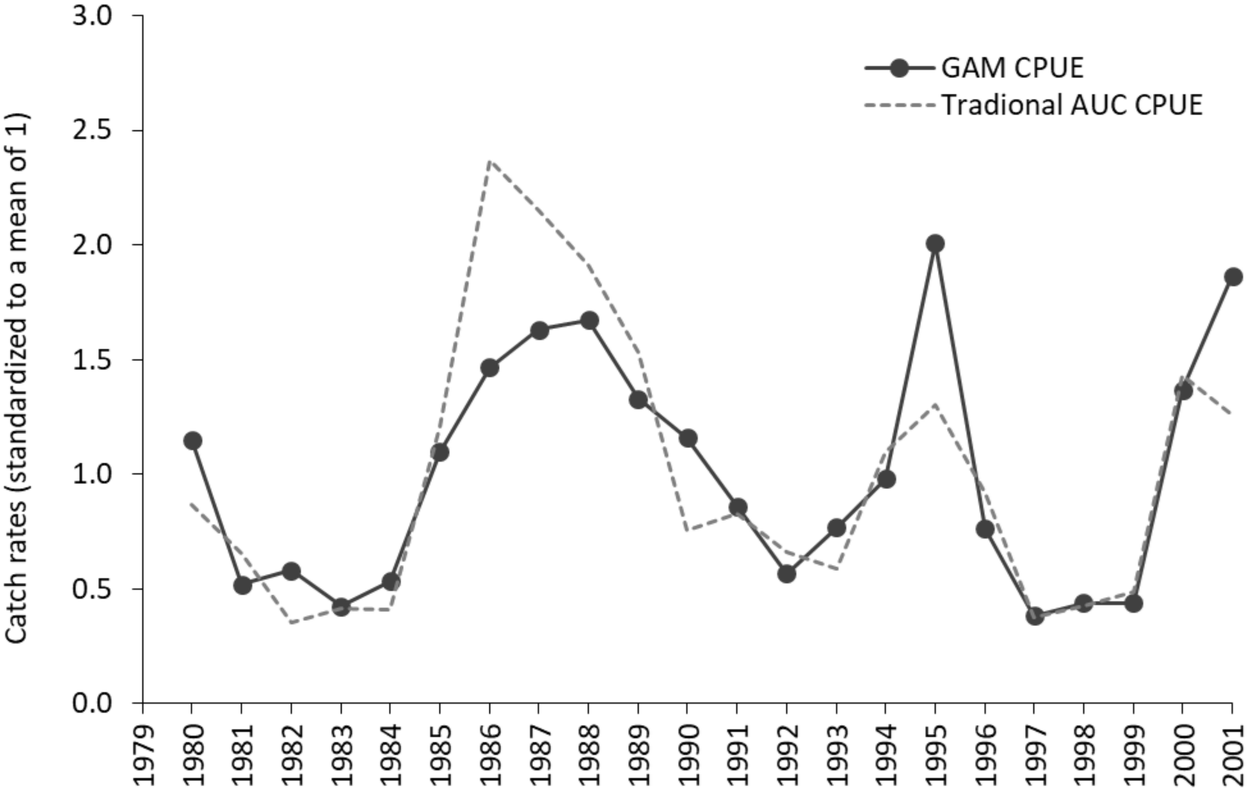


Figure 107. Comparison of two methods for CPUE estimation for catches observed in the Commercial Fishery Monitoring Survey.

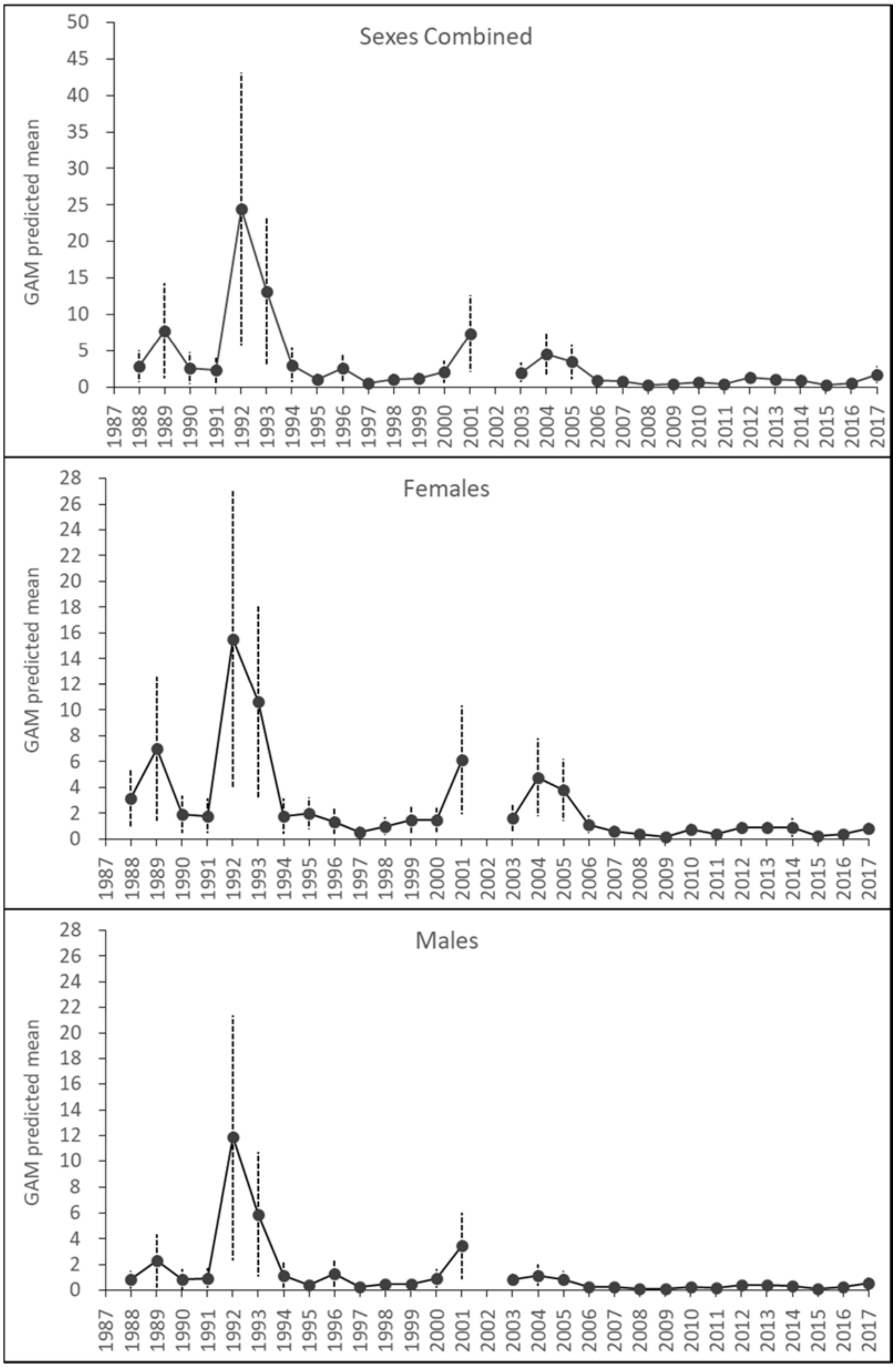


Figure 108. GAM predicted catch rates of American shad from the fishery-independent seine survey.

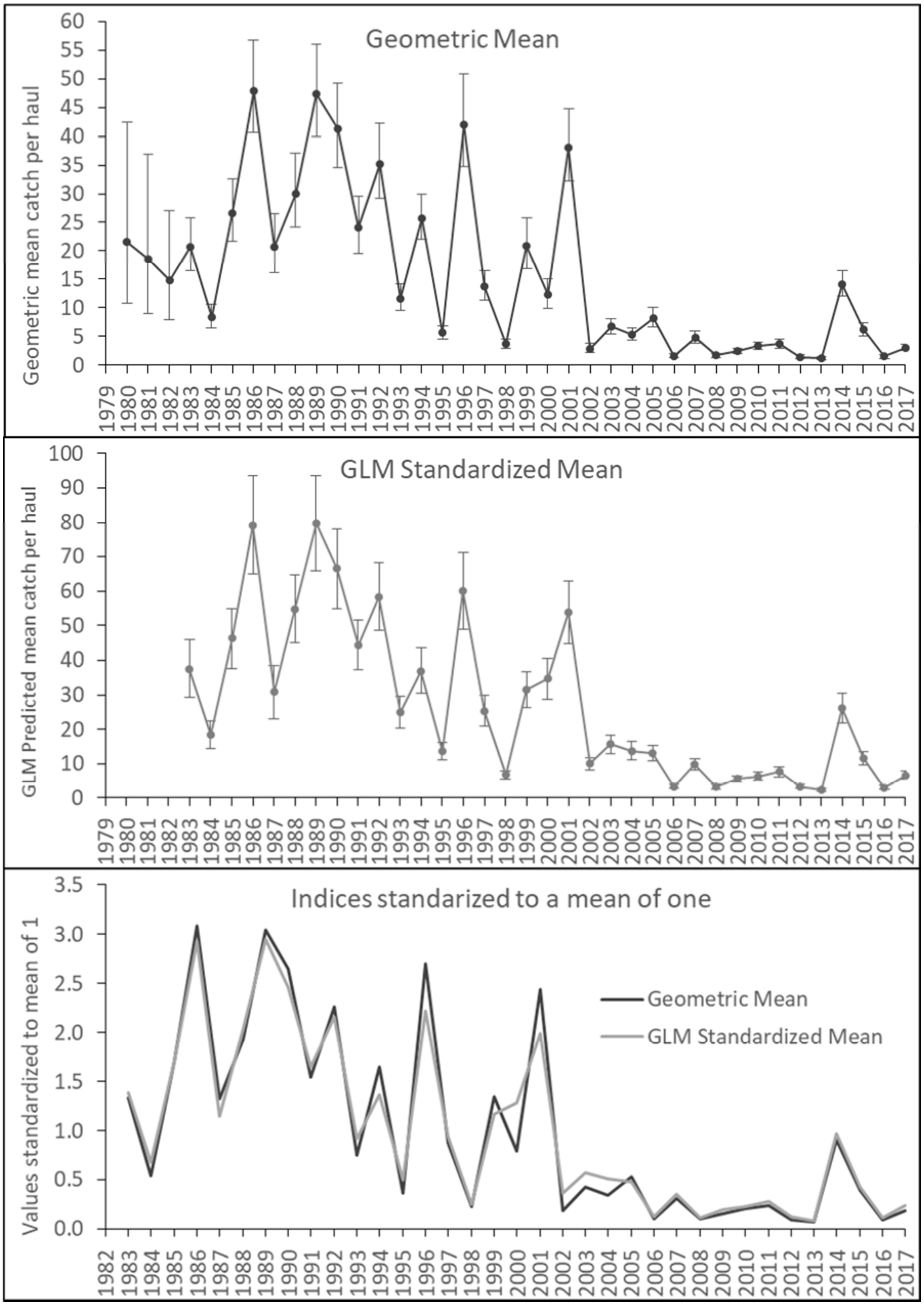


Figure 109. Comparison of two annual CPUE estimates for catches in the NYSDEC YOY seine survey.

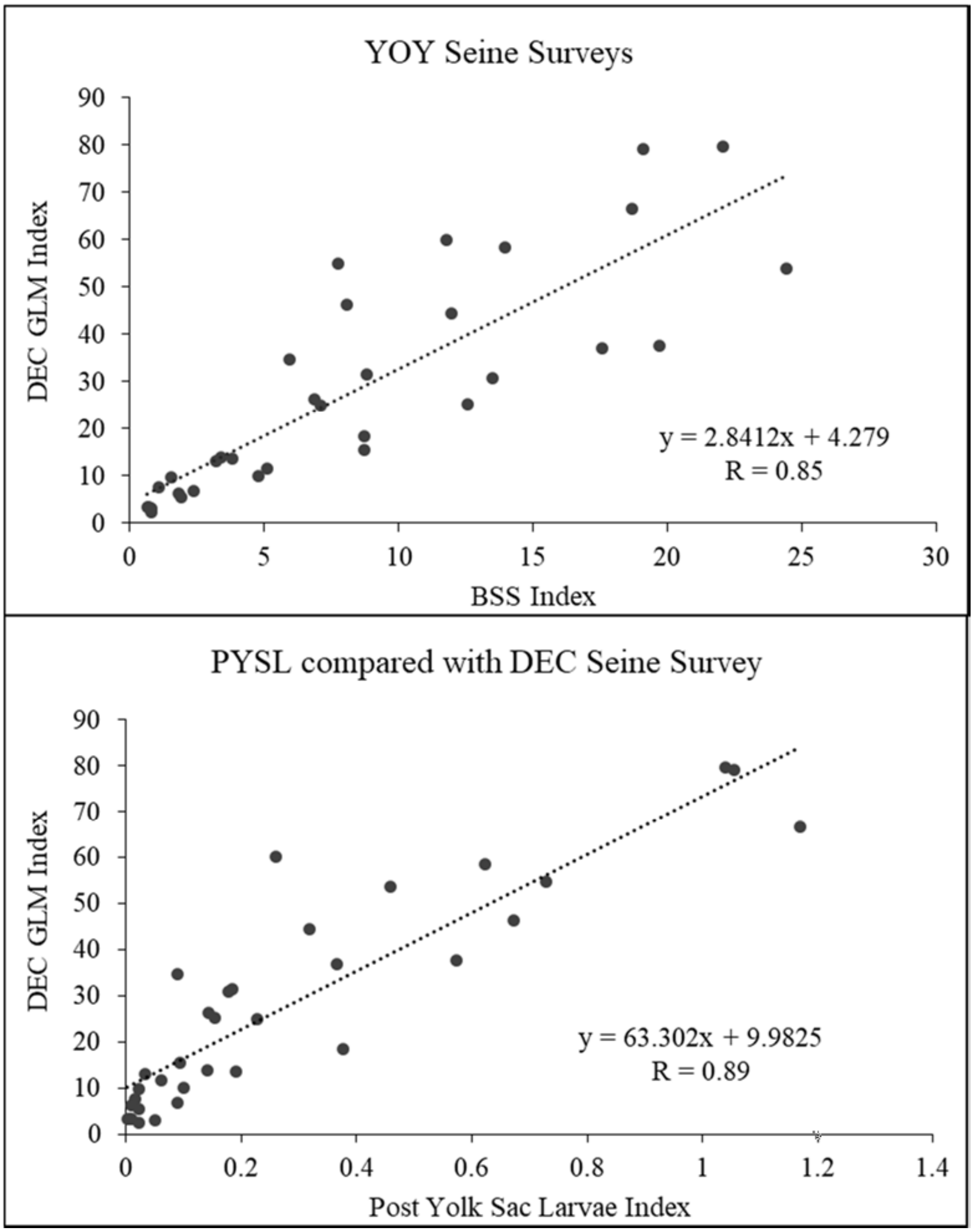


Figure 110. Correlation figures for the two YOY seine surveys (top) and the PYSL index with the NYSDEC YOY seine survey (bottom).

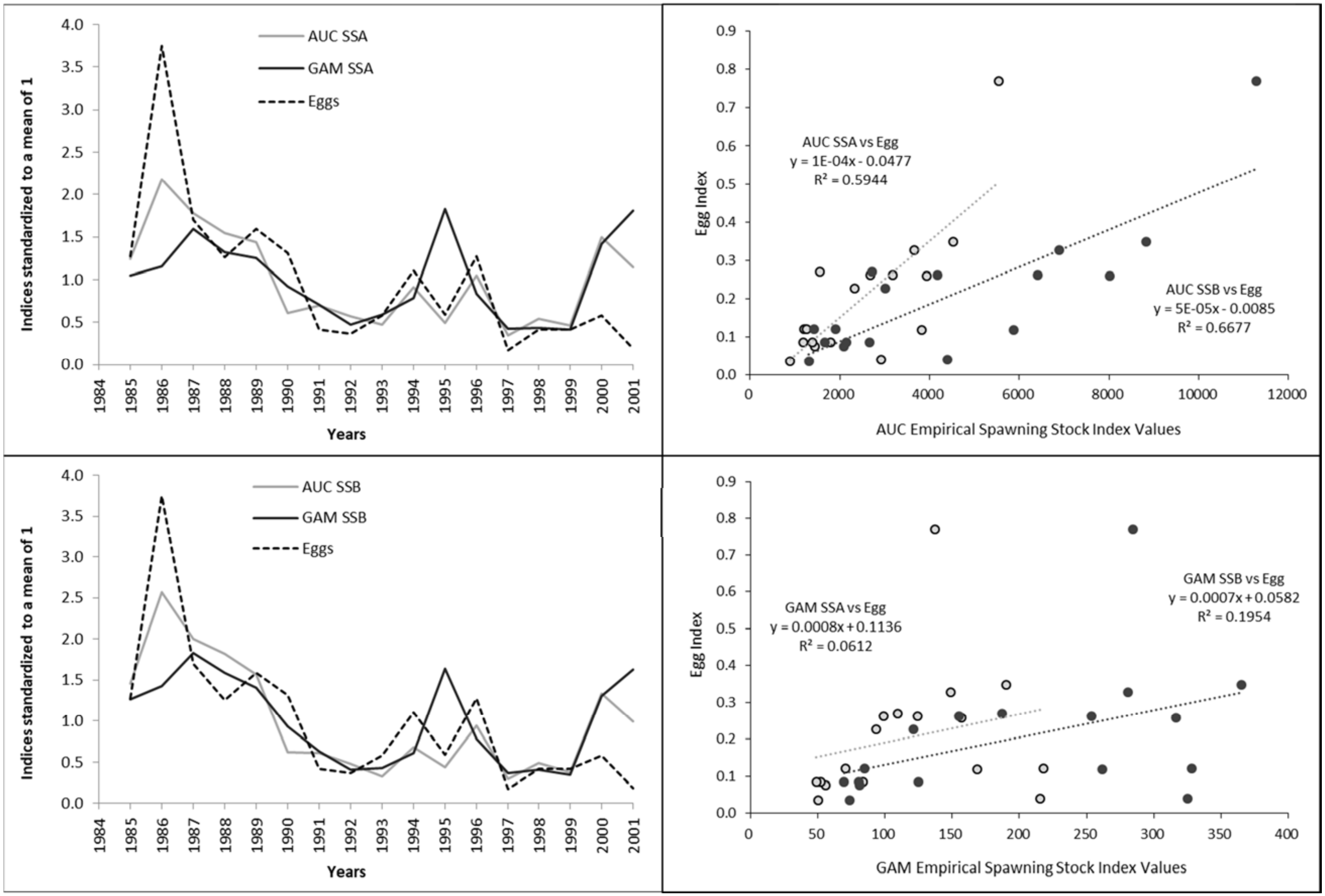


Figure 111. Comparison of the two methods for calculating spawning stock abundance and biomass estimates with the EGG estimates from the HRG Long River Survey.

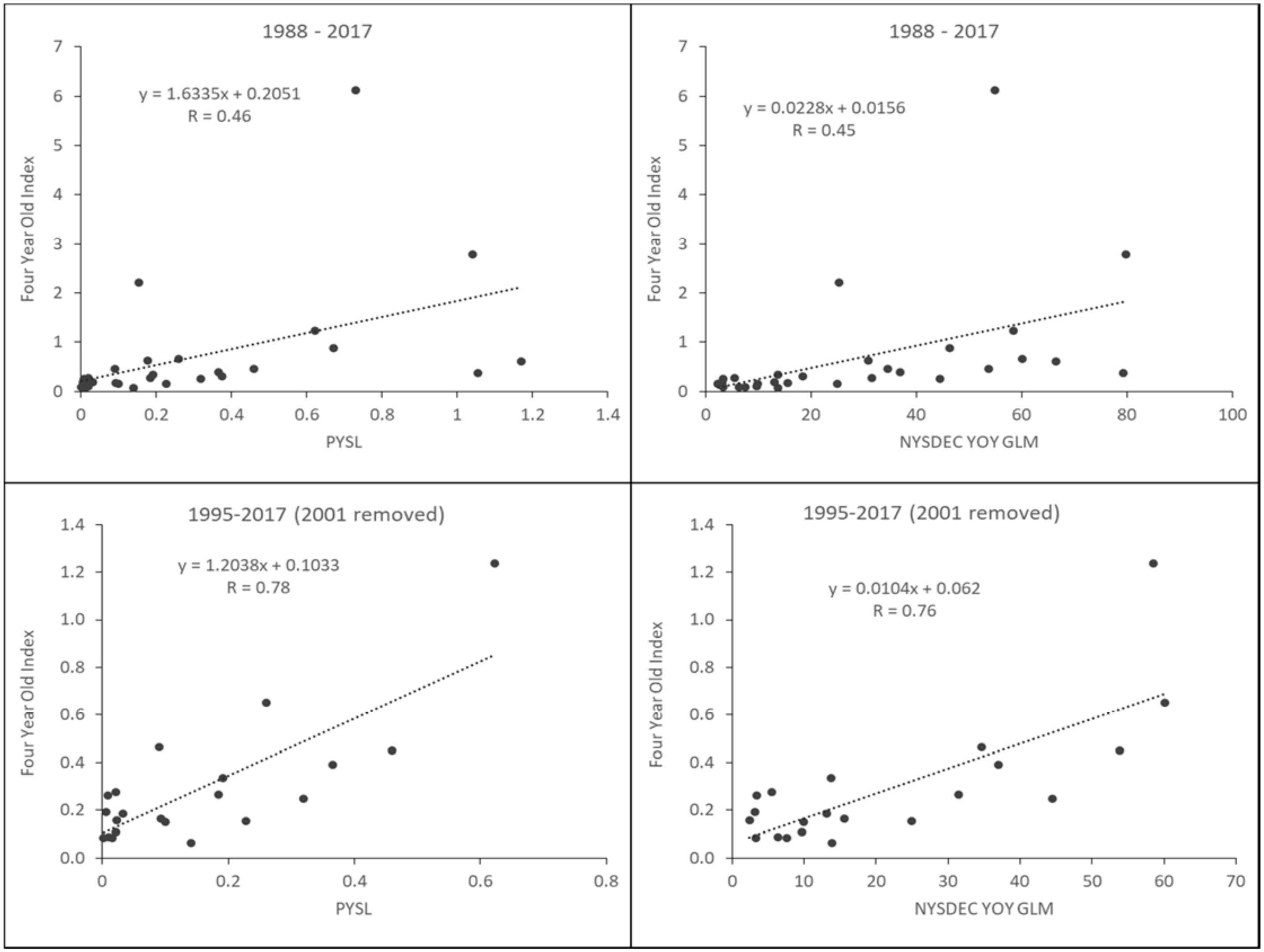


Figure 112. Comparison of the four-year-old abundance index with the PYSL and NYSDEC YOY indices. Top graphs represent all survey years, while the bottom graphs represent the best subset of years for comparison.

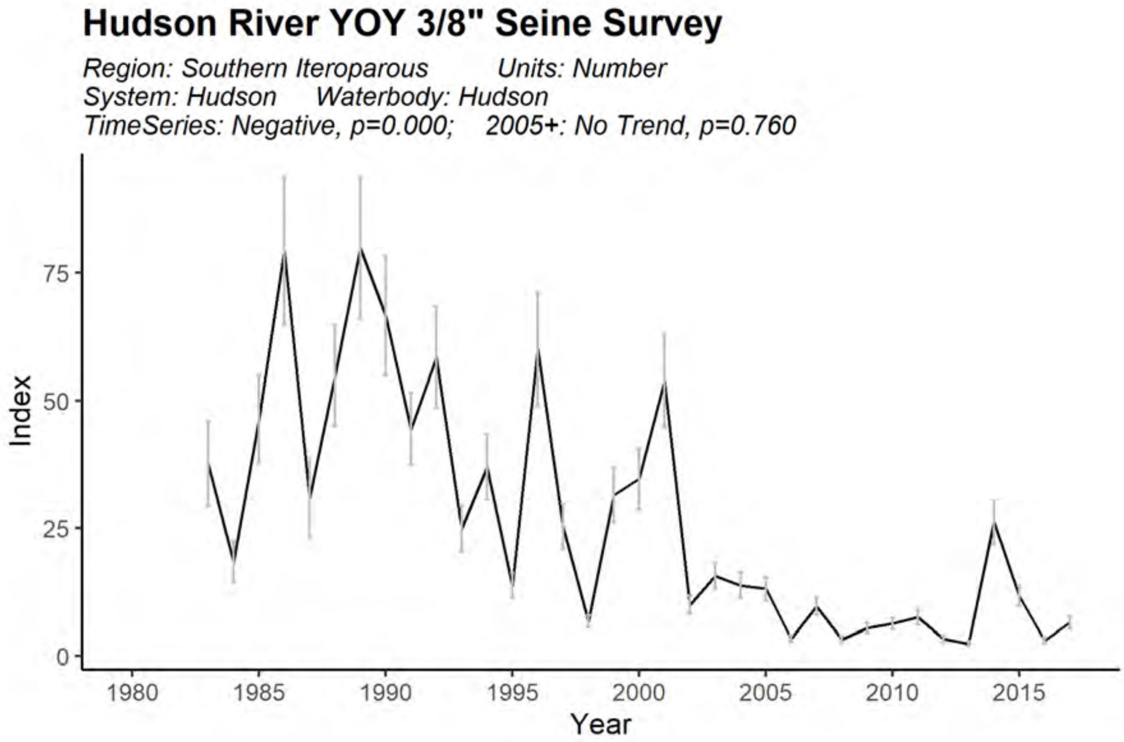


Figure 113. **Hudson River YOY 3/8" Seine Survey abundance index and Mann-Kendall results.**

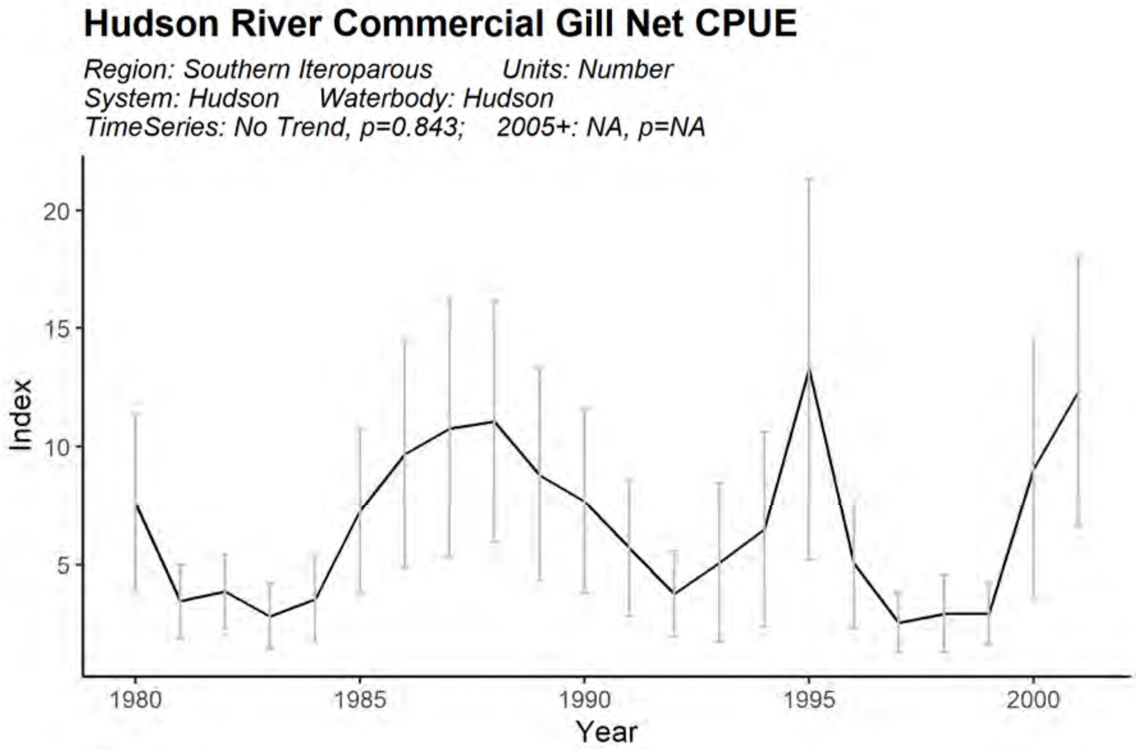


Figure 114. **Hudson River Commercial Gill Net CPUE abundance index and Mann-Kendall results.**

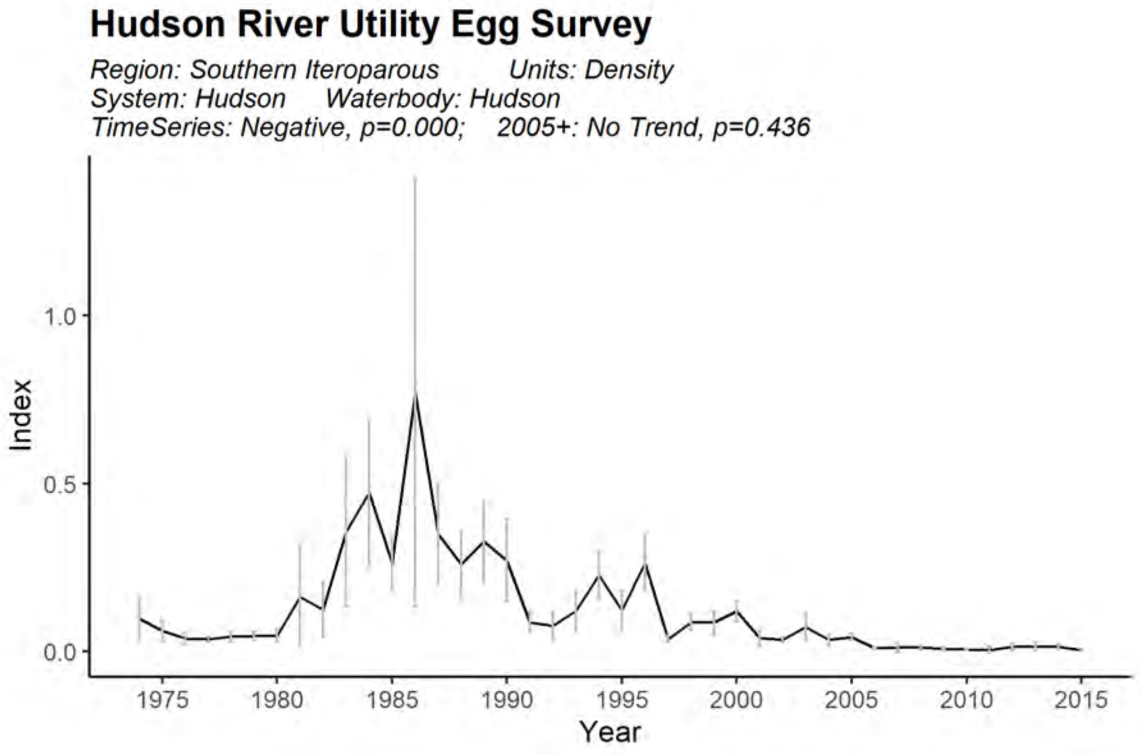


Figure 115. Hudson River Utility Egg Survey index and Mann-Kendall results.

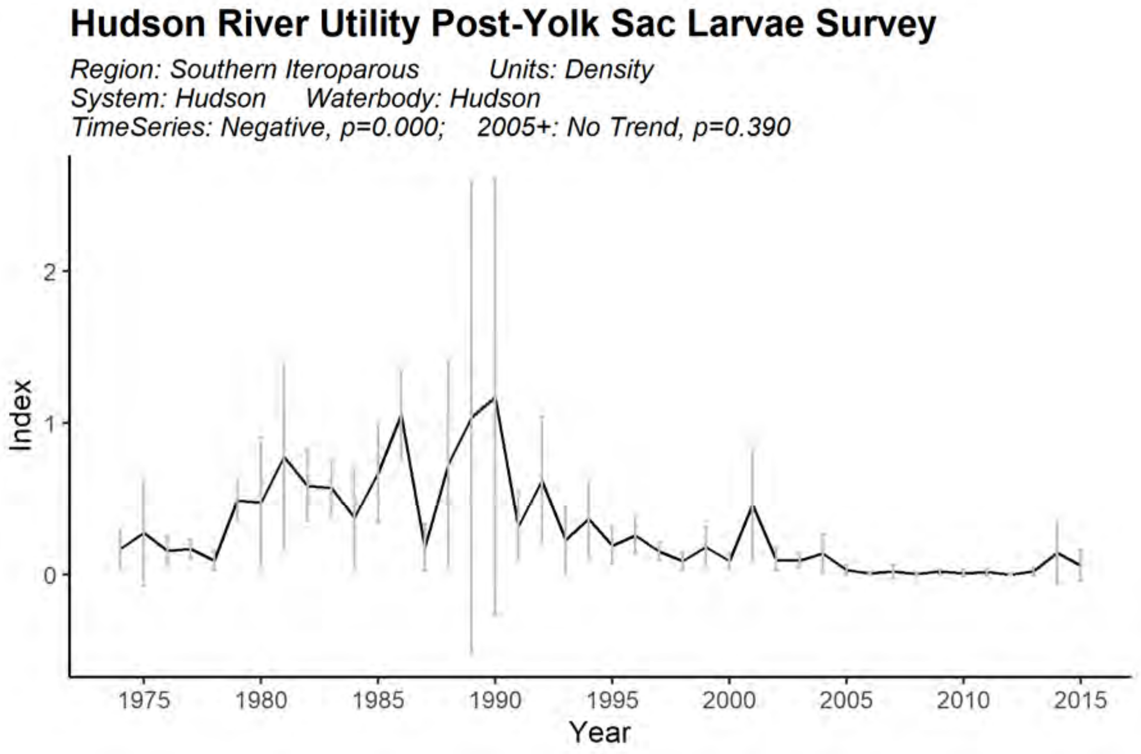


Figure 116. Hudson River Utility Post-Yolk Sac Larvae Survey index and Mann-Kendall results.

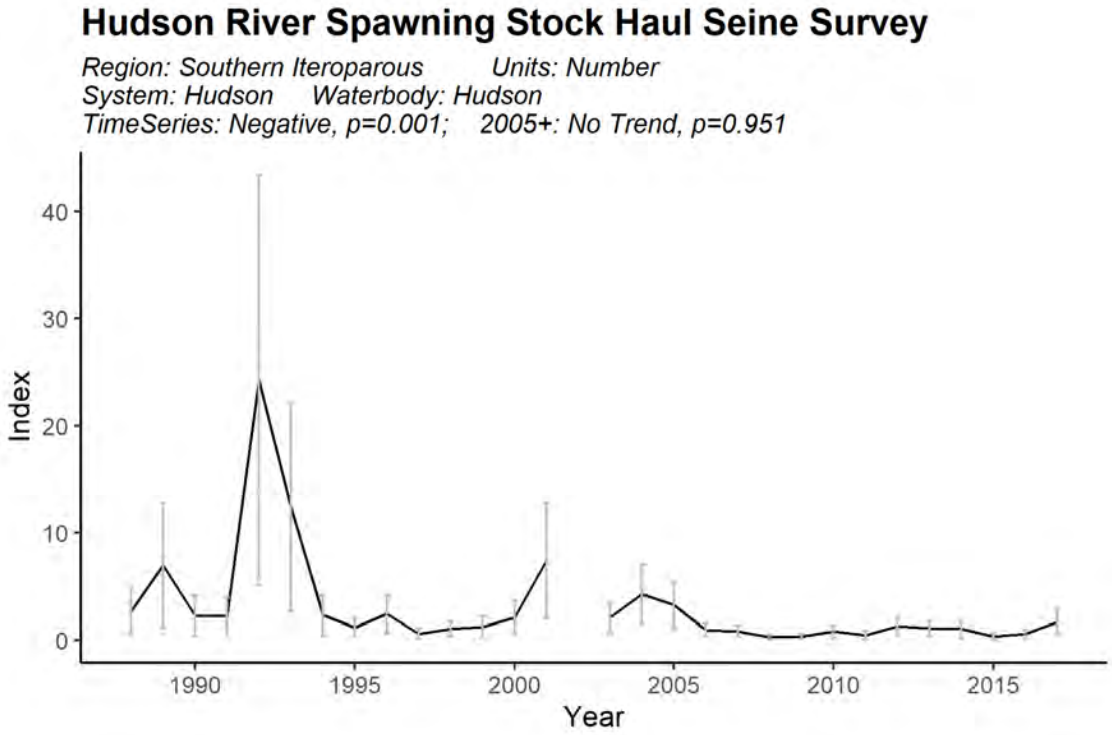


Figure 117. Hudson River Spawning Stock Haul Seine Survey index and Mann-Kendall results.

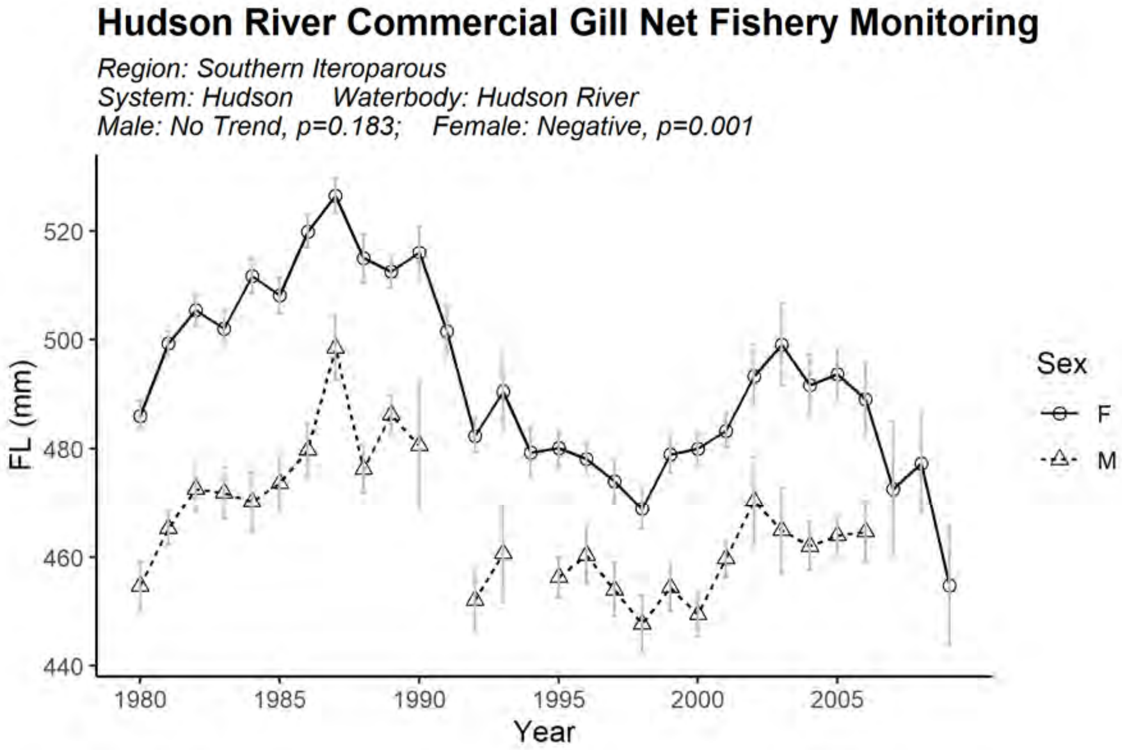


Figure 118. Mean fork length over time from the Hudson River Commercial Gill Net Fishery Monitoring program and Mann-Kendall results.

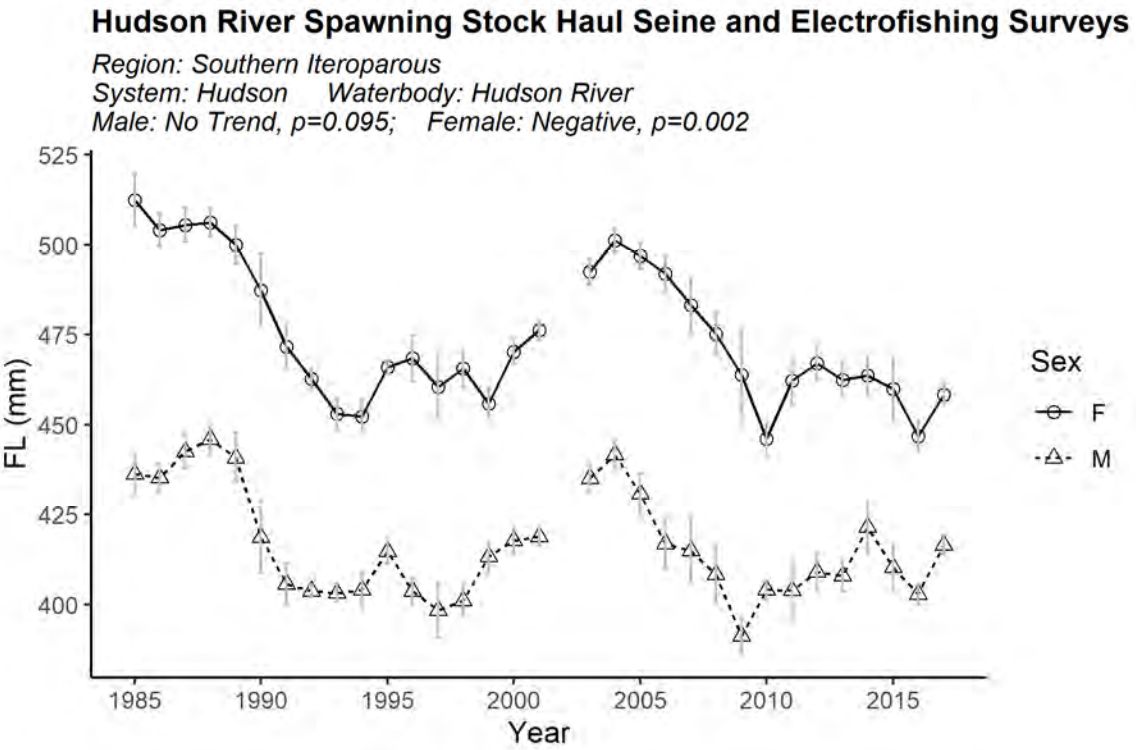


Figure 119. Mean fork length over time from the Hudson River Spawning Stock Haul Seine and Electrofishing Surveys and Mann-Kendall results.

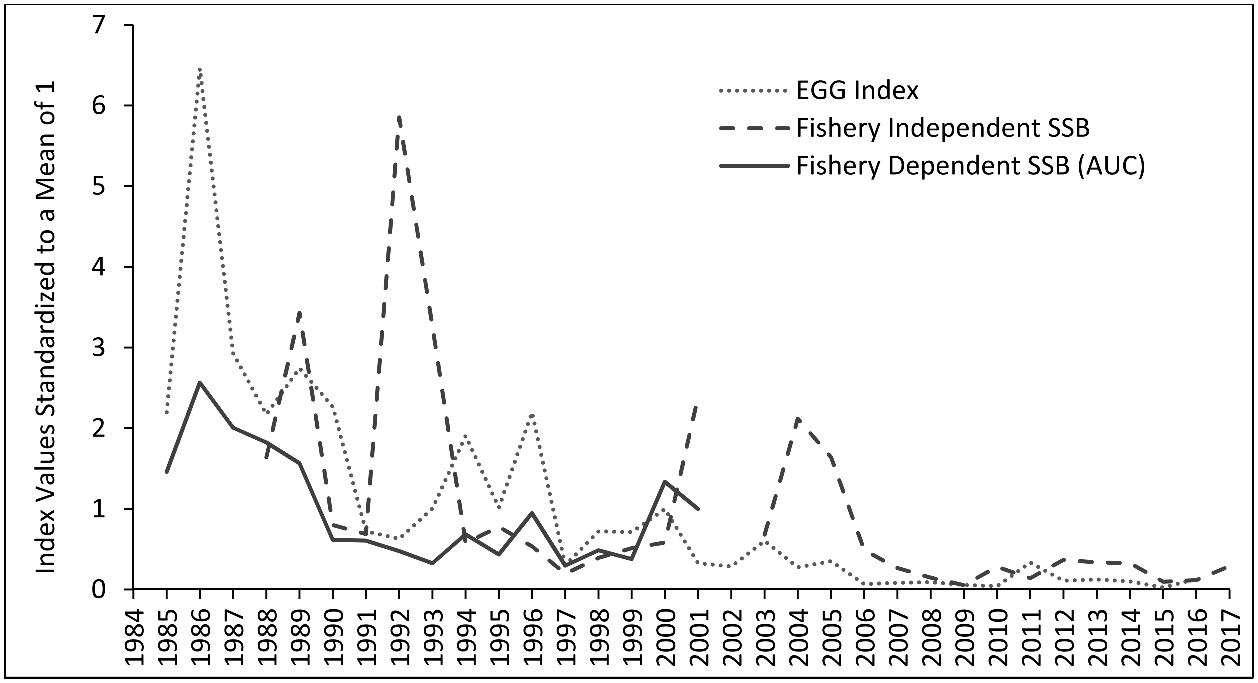


Figure 120. Comparison of the fishery-dependent and –independent spawning stock biomass estimates with EGG index.

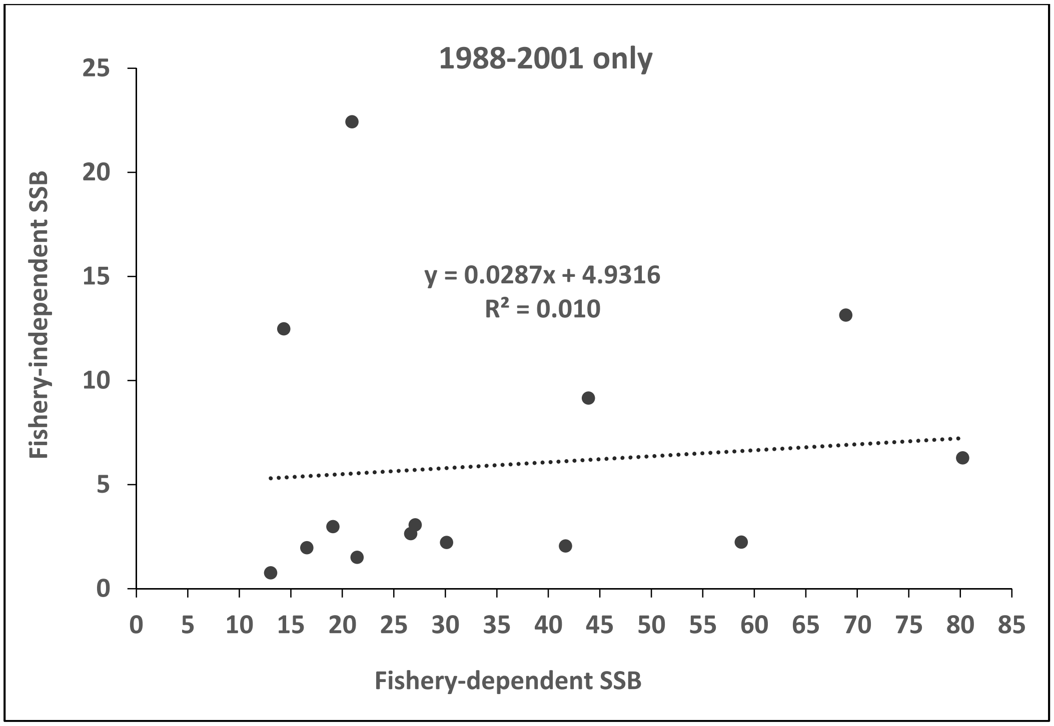


Figure 121. Comparison between the fishery-independent and –dependent spawning stock biomass estimates.

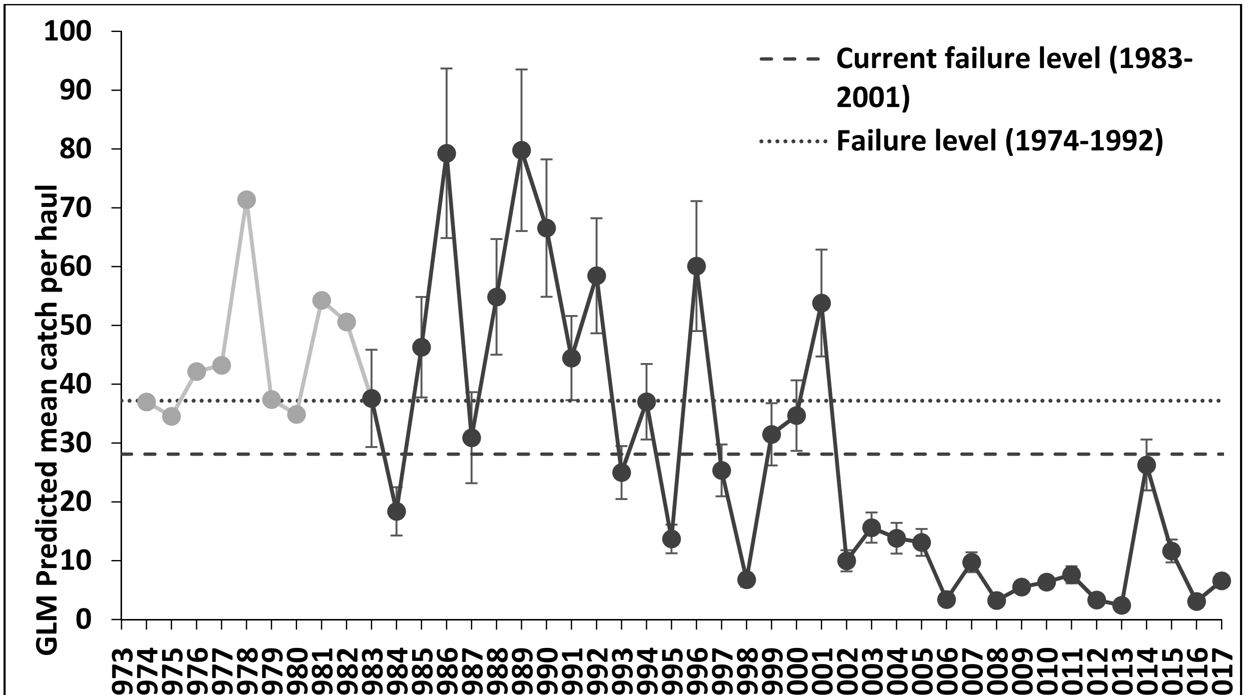


Figure 122. True and estimated NYSDEC YOY GLM Relative Abundance Index with respective failure levels (25th percentile of subset of years).

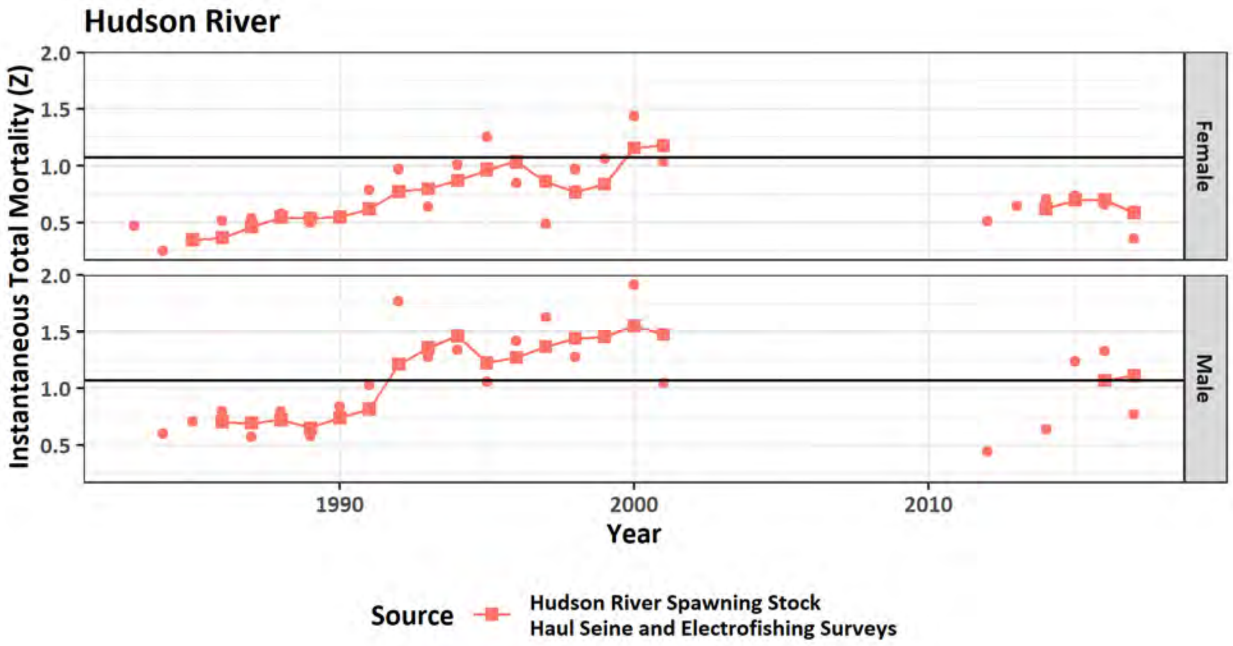


Figure 123. Three year average *Z* estimates via weighted linear regression by sex and monitoring program for the Hudson River System based on scale-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual *Z* estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (▯)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).

Figure 124. Map of Delaware River Basin.

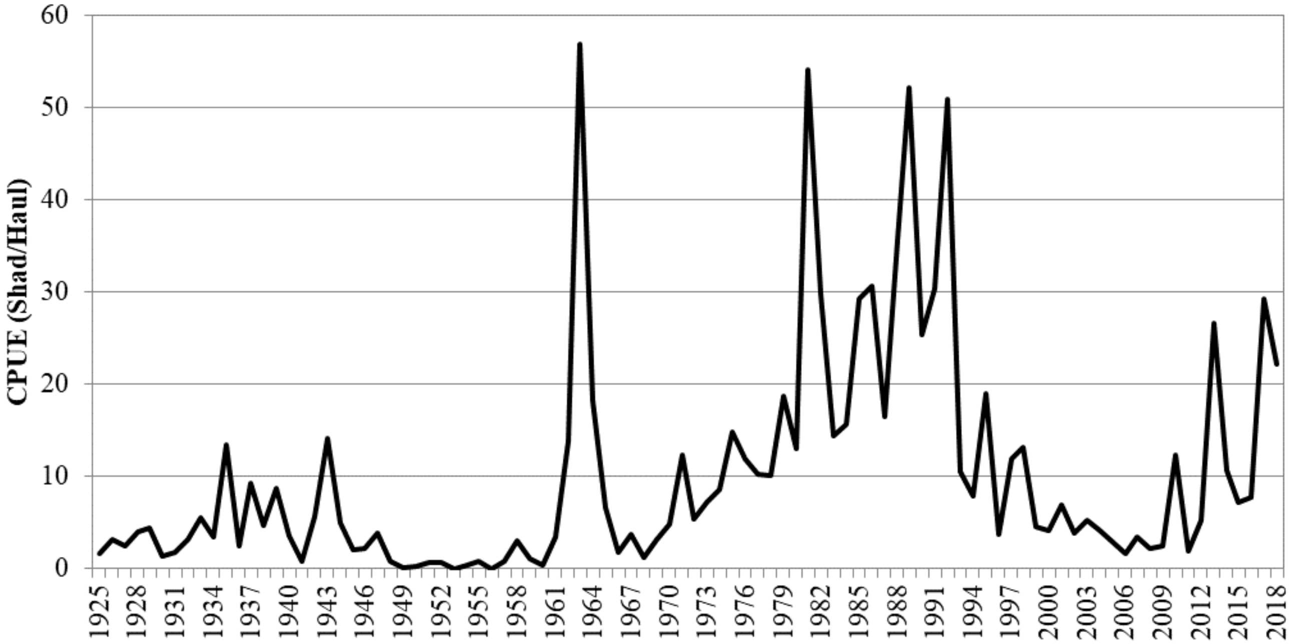


Figure 125. CPUE in the Lewis haul seine fishery, Delaware River.

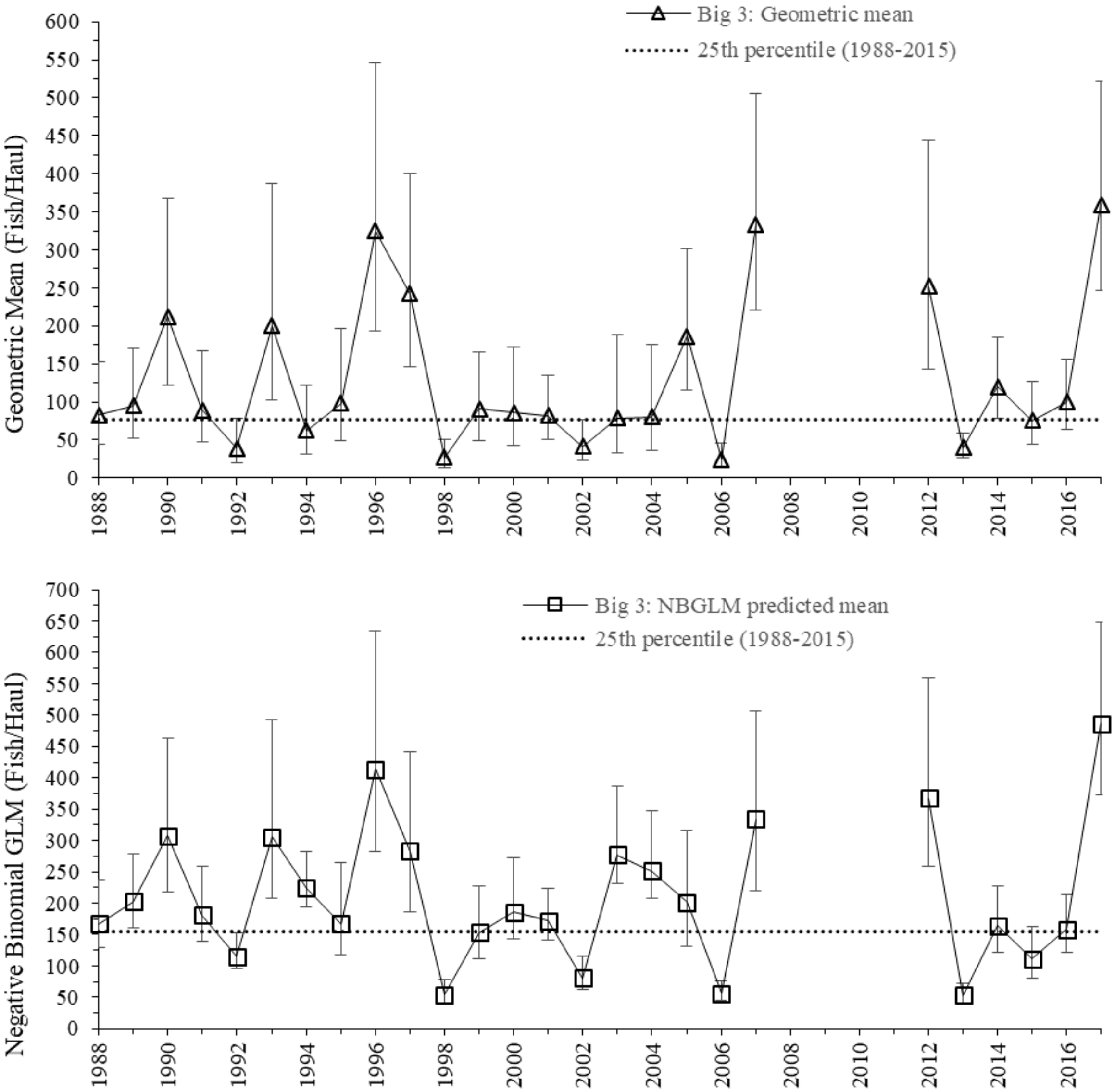


Figure 126. Juvenile American shad CPUE (geometric means, top, and negative binomial GLM, bottom) for the non-tidal Delaware River collected from beach seine sampling at Phillipsburg, Water Gap and Milford Beach. No sampling was conducted in 2018.

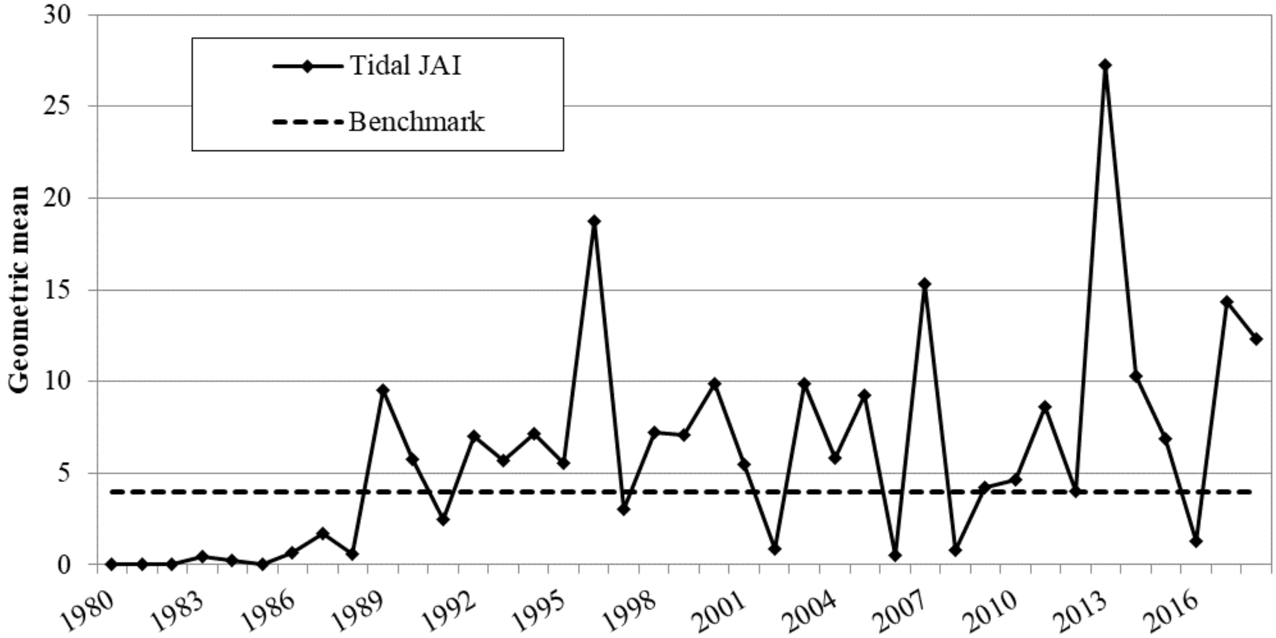


Figure 127. The Delaware River tidal American shad JAI (geometric mean). The GM values are based on catches from Region 2 and 3 of the NJDFW tidal seine sites.

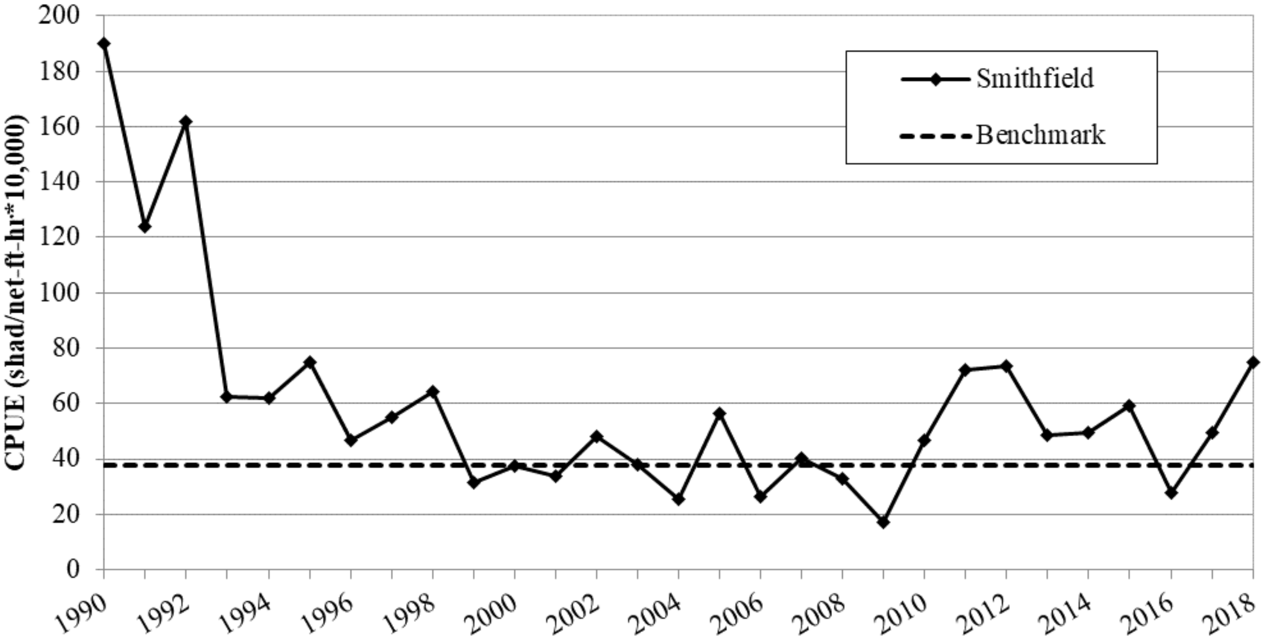


Figure 128. The Delaware River spawning adult American shad index at Smithfield Beach.

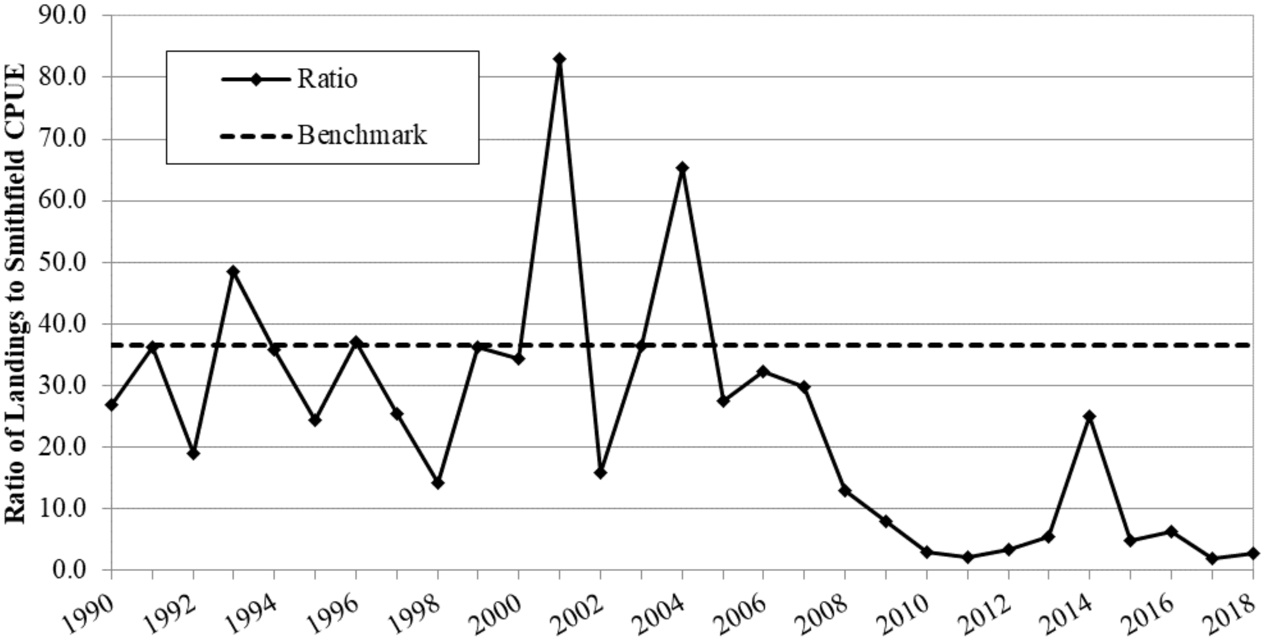


Figure 129. Ratio of Delaware River stock landings divided by Smithfield Beach CPUE (divided by 100) with an 85th percentile benchmark.

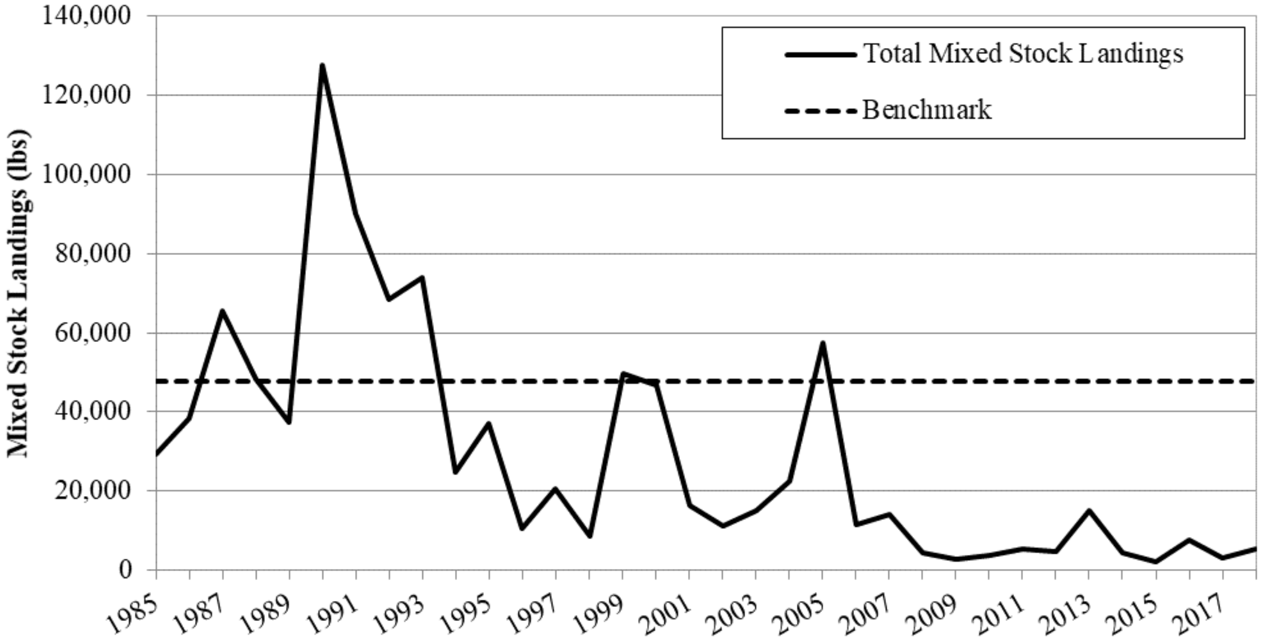


Figure 130. Landings in the Delaware Bay from the mixed-stock fishery with a 75th percentile benchmark.

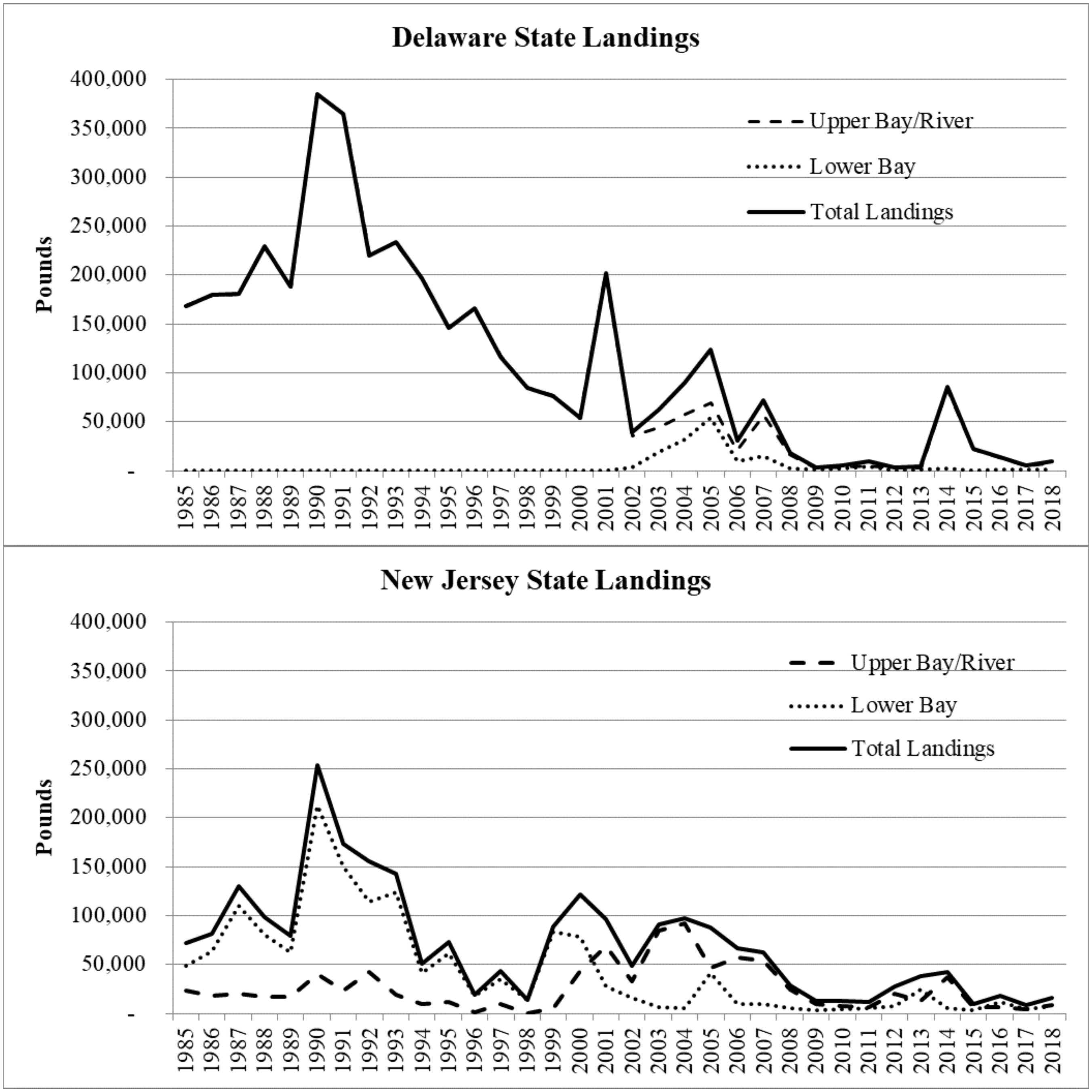


Figure 131. American shad commercial harvest for the states of Delaware and New Jersey, in pounds. Delineation point from Bowers Beach, Delaware to Gandy's Beach, New Jersey.

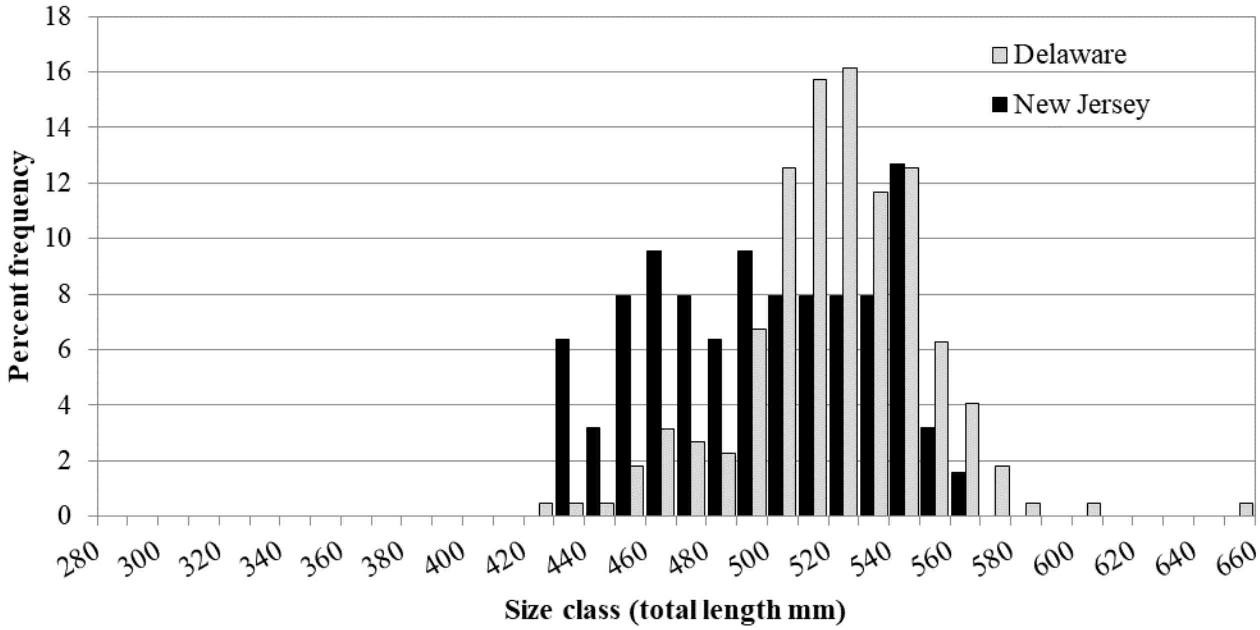


Figure 132. American shad length frequencies from commercial harvest for the states of Delaware and New Jersey.

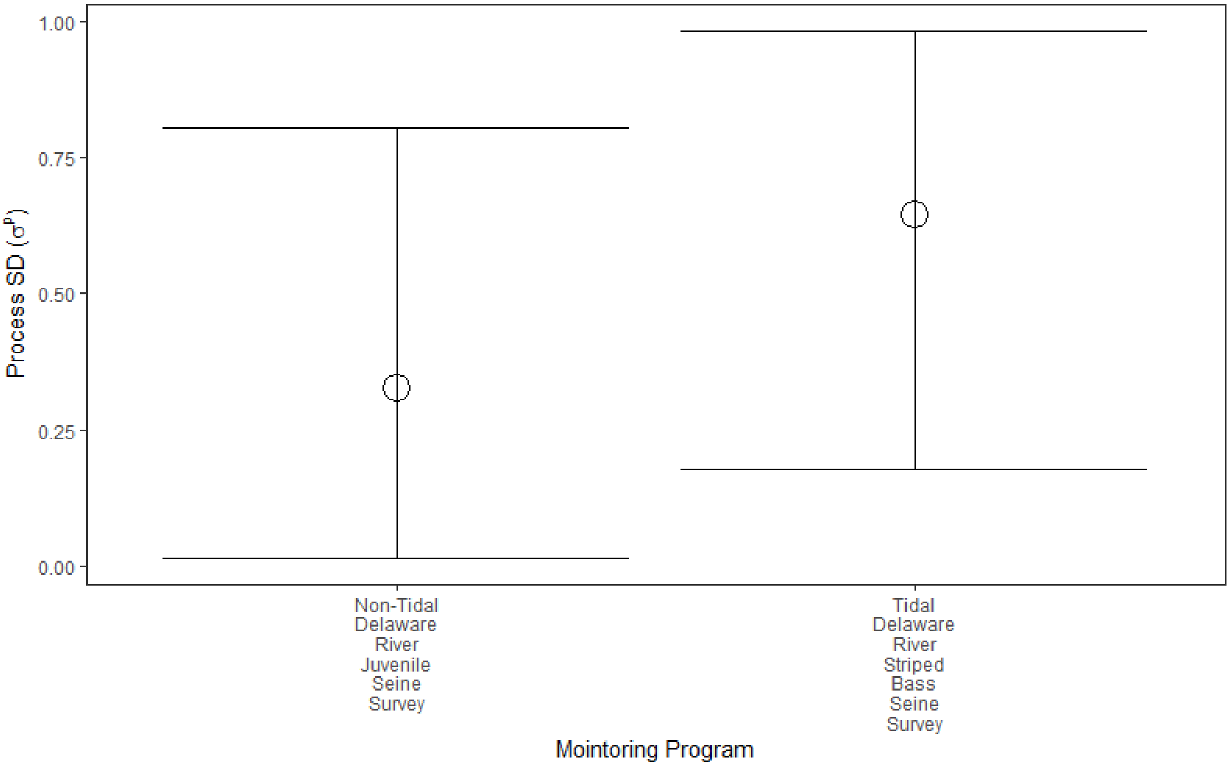


Figure 133. Delaware YOY survey-specific process error estimates.

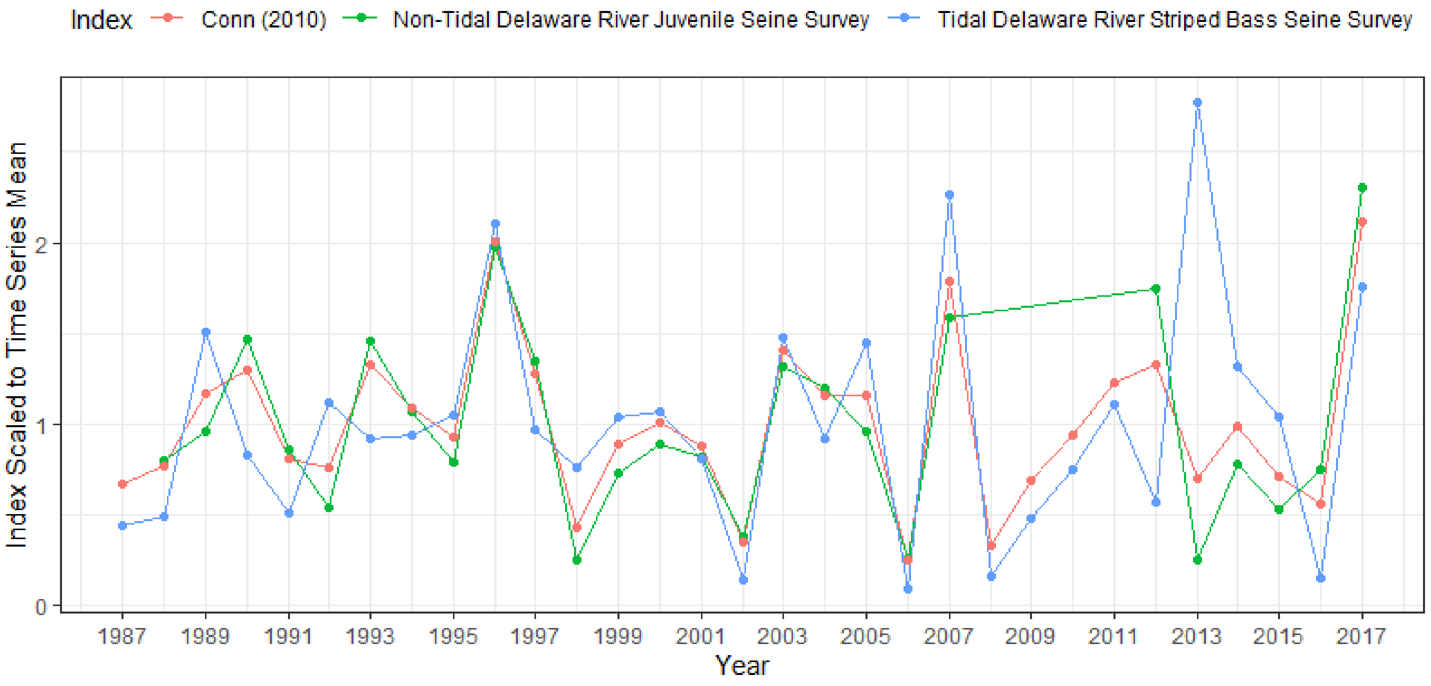


Figure 134. Delaware YOY survey-specific indices compared to the hierarchical index (Conn 2010).

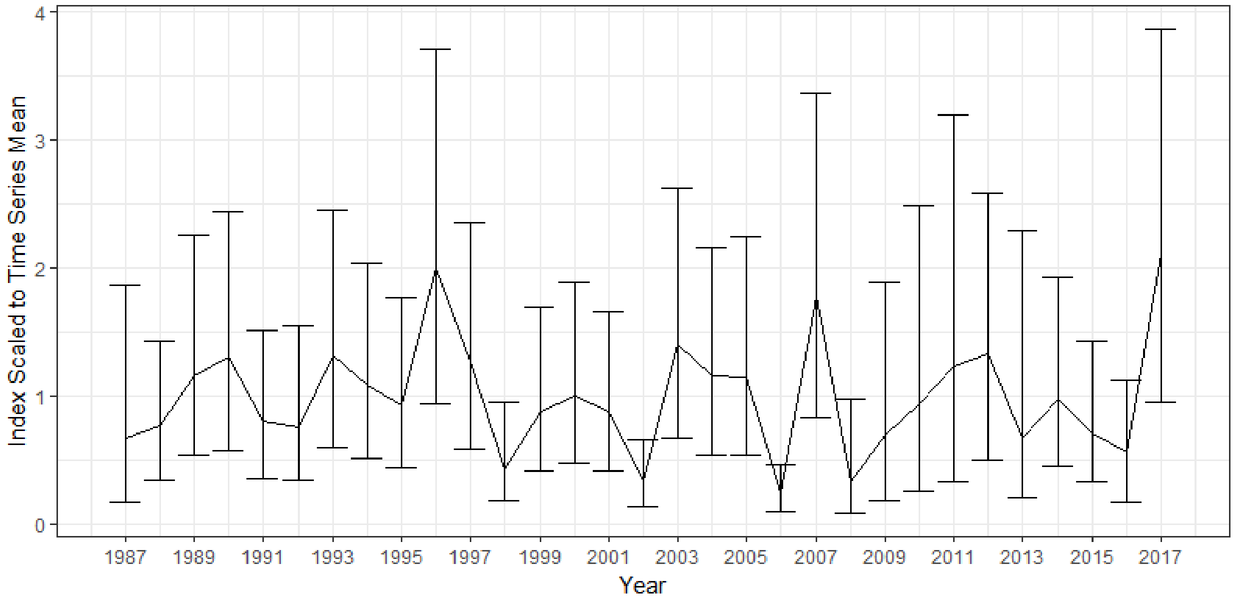


Figure 135. Hierarchical index of Delaware YOY abundance. Error bars represent 95% credibility intervals.

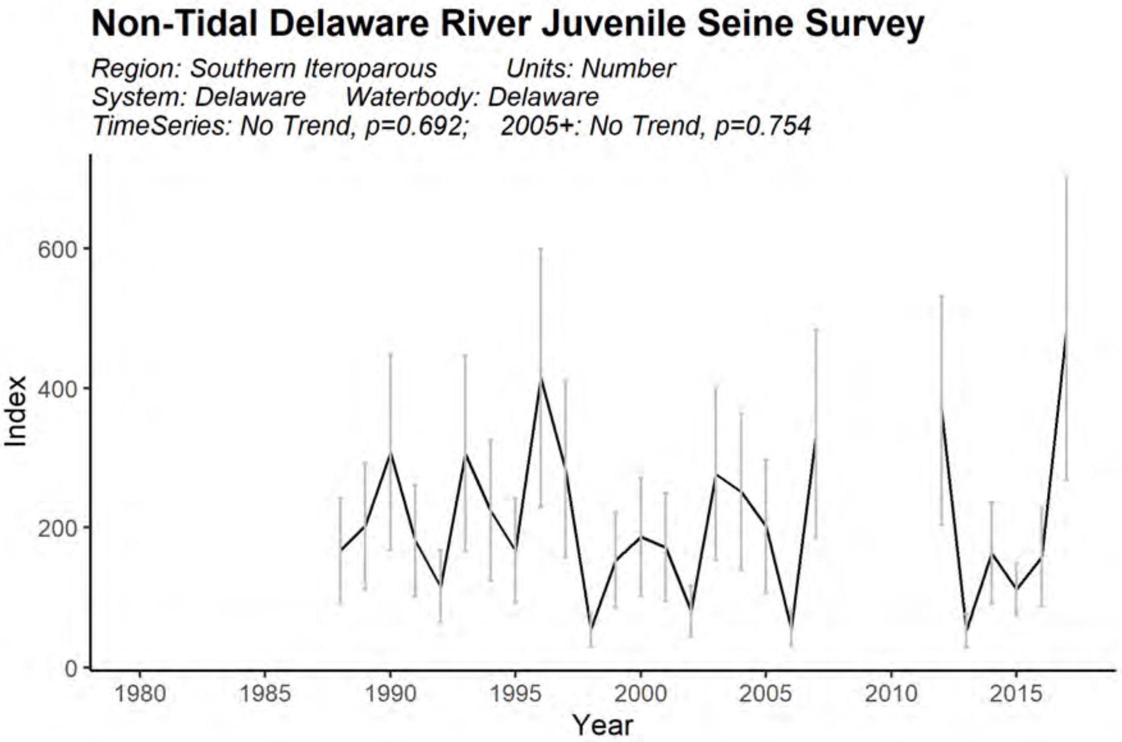


Figure 136. Non-Tidal Delaware River Juvenile Seine Survey index with Mann-Kendall results.

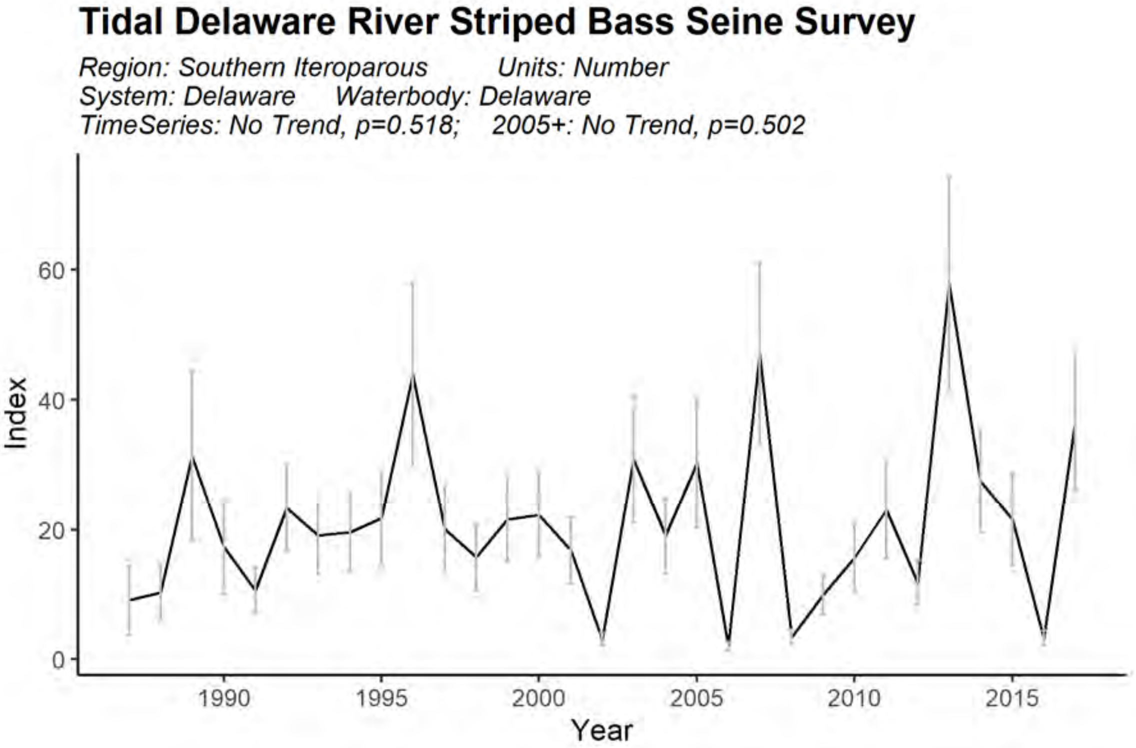


Figure 137. Tidal Delaware River Striped Bass Seine Survey index and Mann-Kendall results.

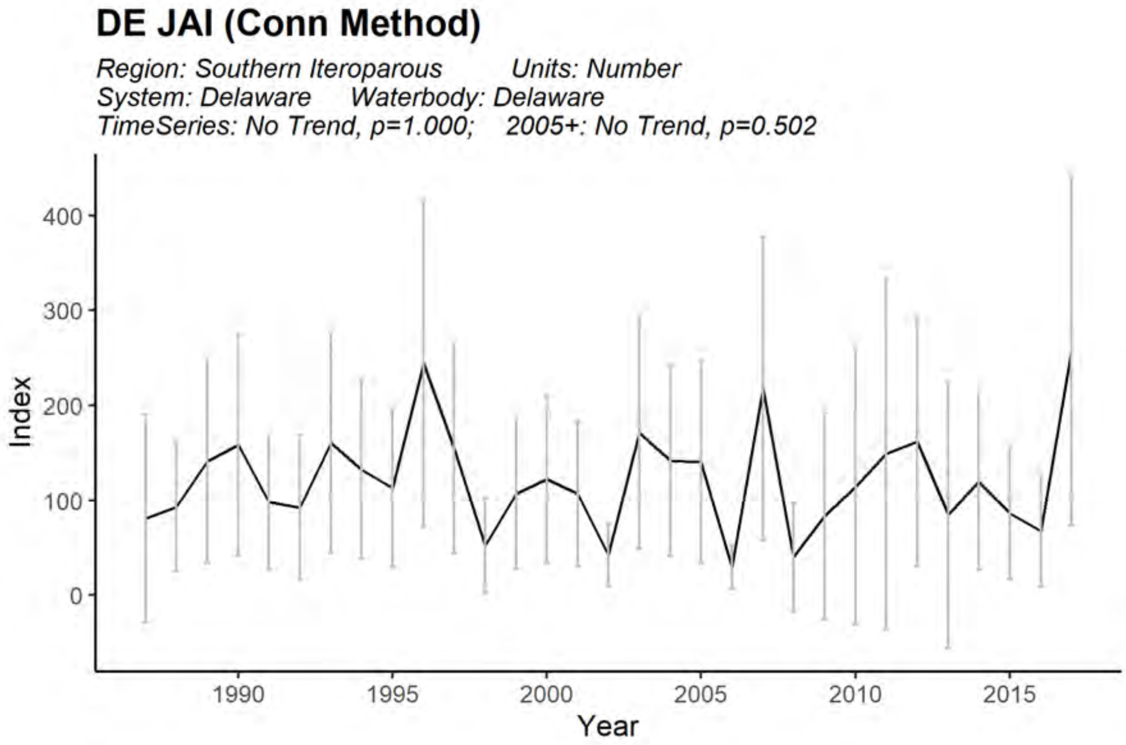


Figure 138. Hierarchical index of Delaware YOY abundance and Mann-Kendall results.

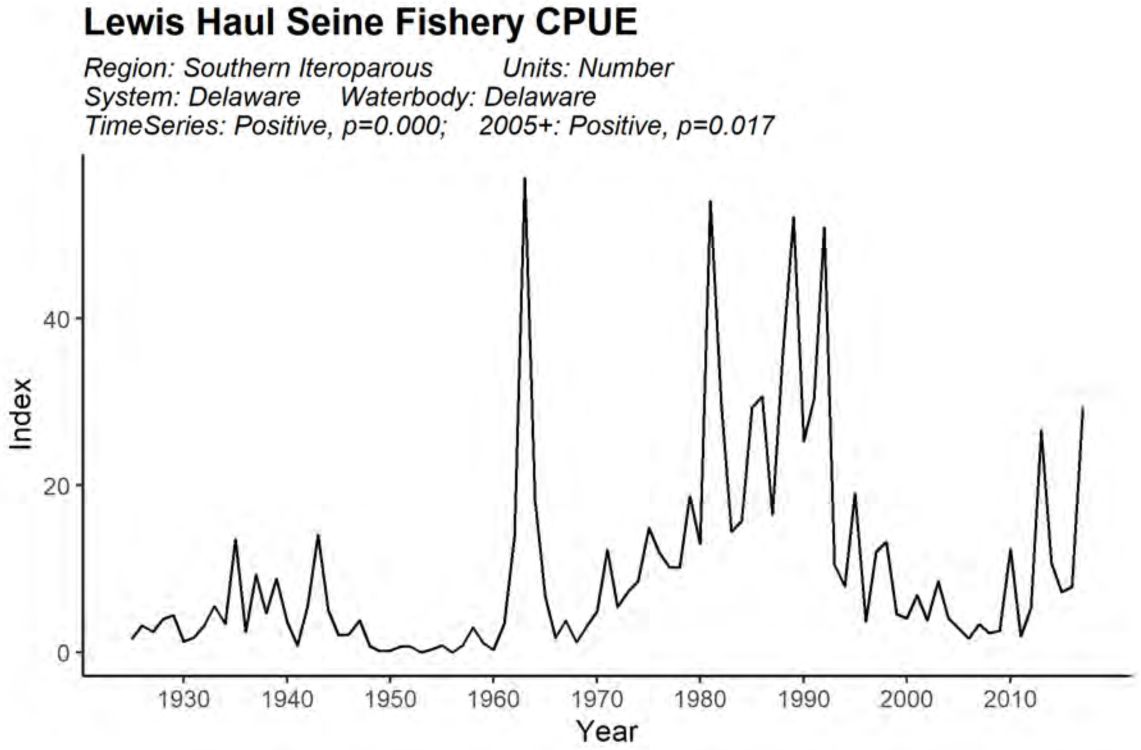


Figure 139. Lewis Haul Seine Fishery CPUE index and Mann-Kendall results.

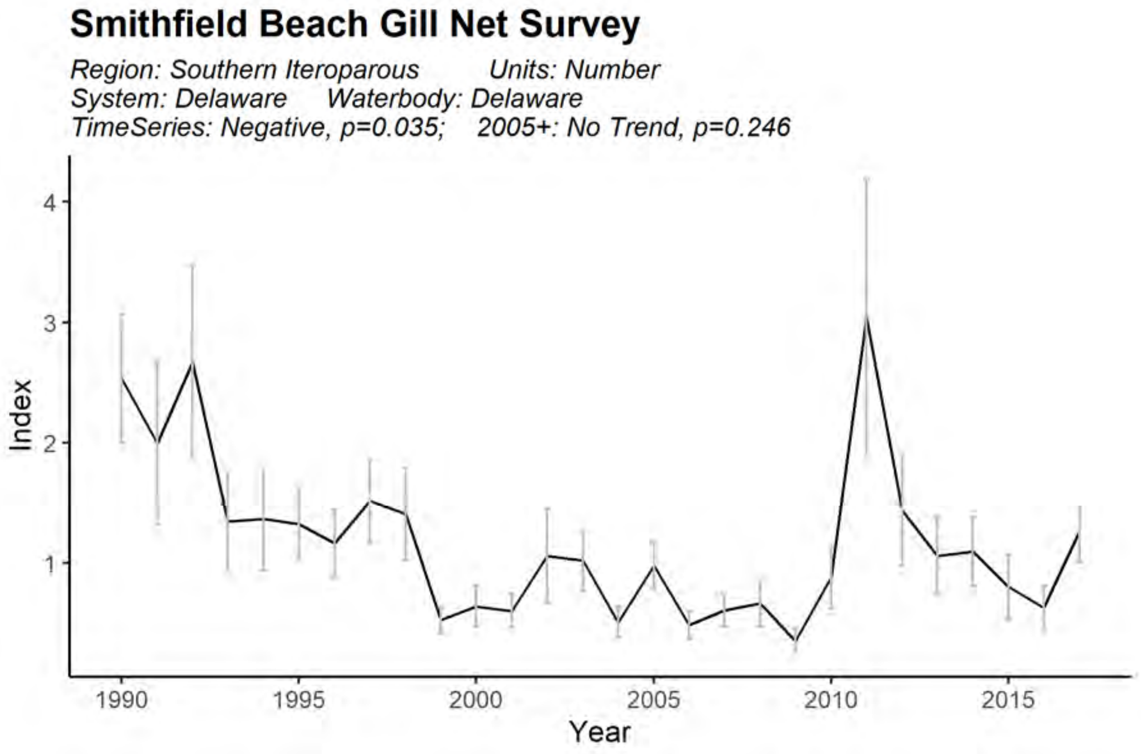


Figure 140. Smithfield Beach Gill Net Survey index and Mann-Kendall results.

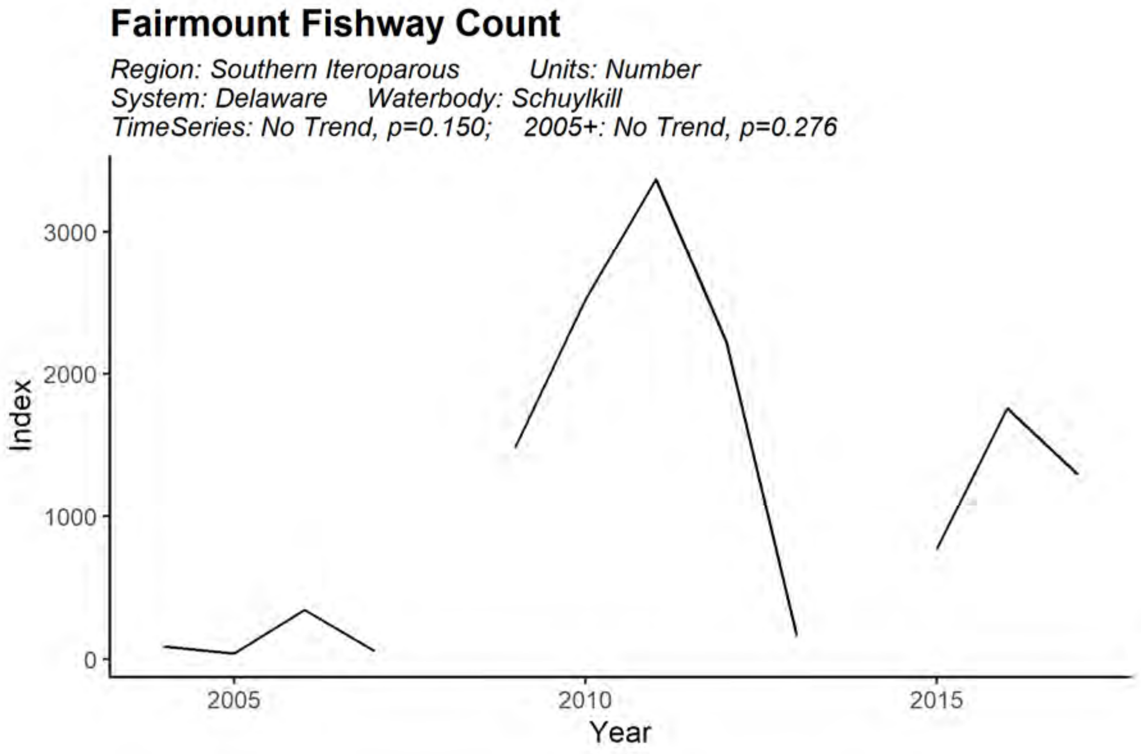
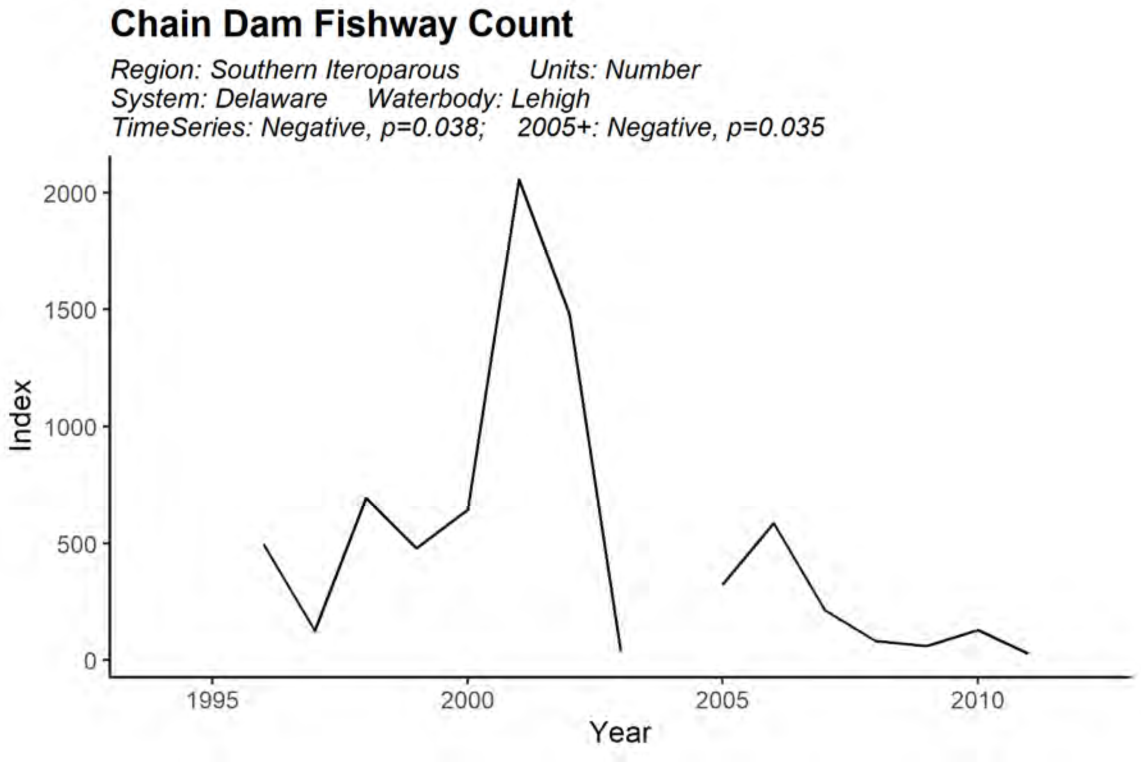


Figure 141. Fairmount Fishway Count index and Mann-Kendall results.



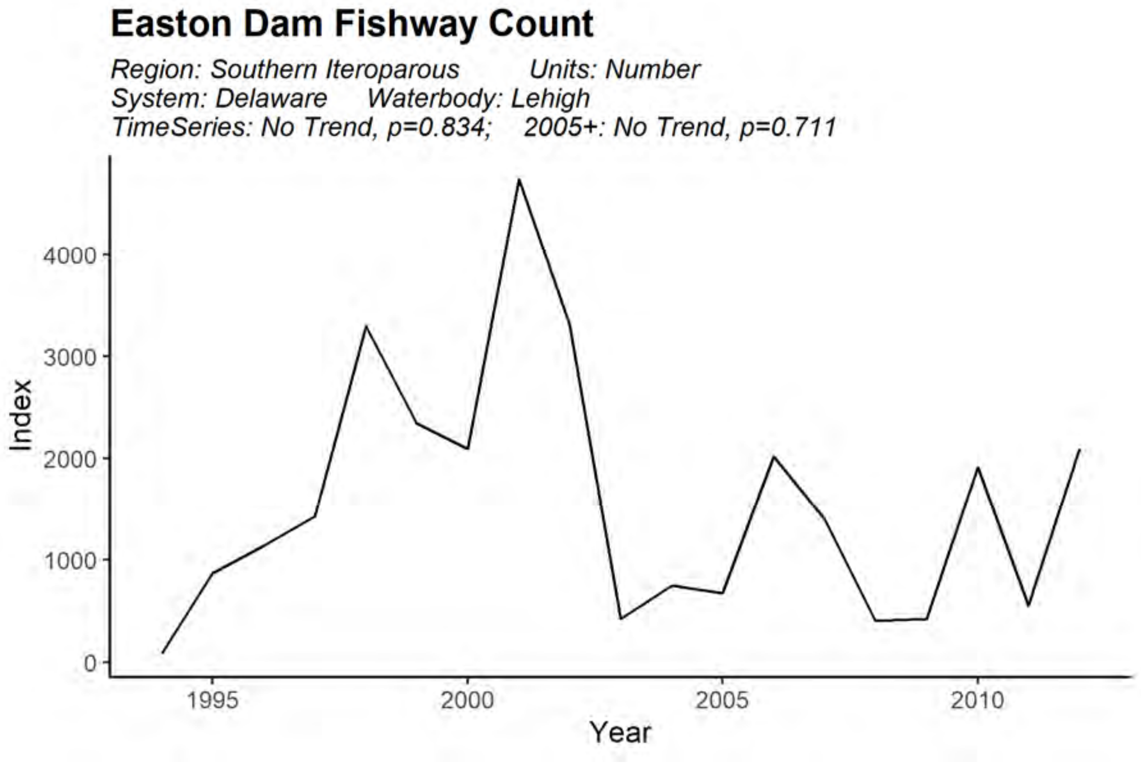


Figure 142. Run counts and Mann-Kendall results for the Chain Dam Fishway Count (top) and Easton Dam Fishway Count (bottom) on the Lehigh River.

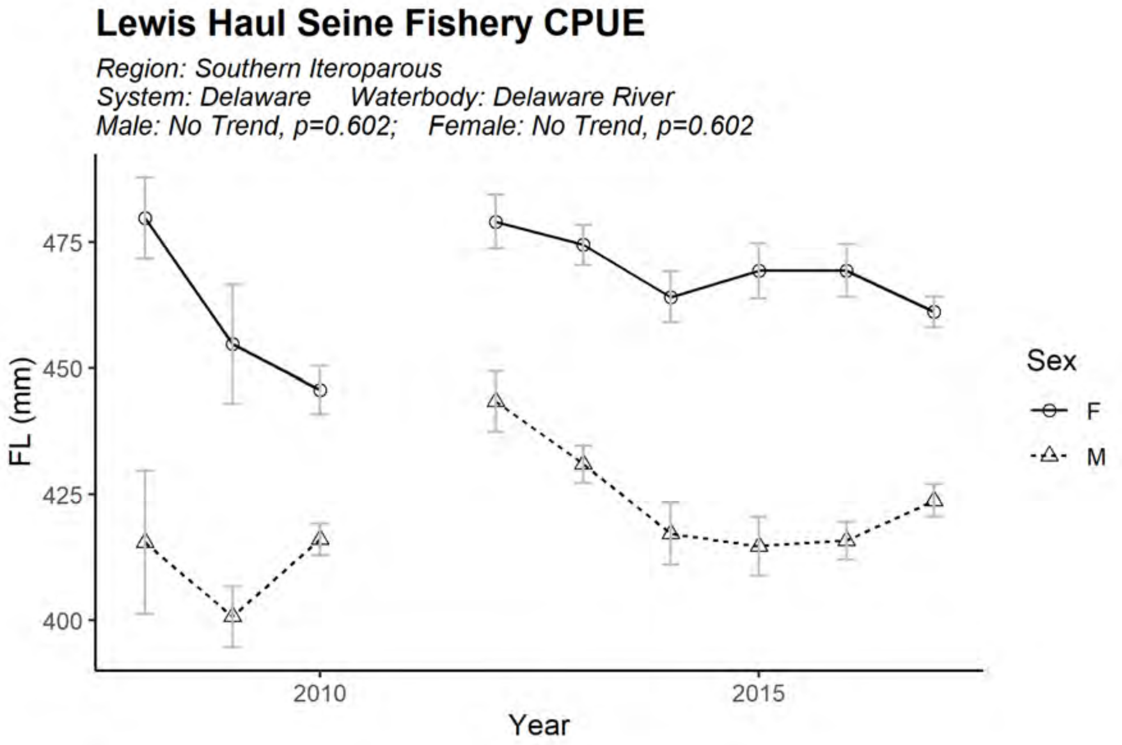


Figure 143. Mean length for male and female American shad in the Delaware River from the Lewis Haul Seine Fishery Monitoring.

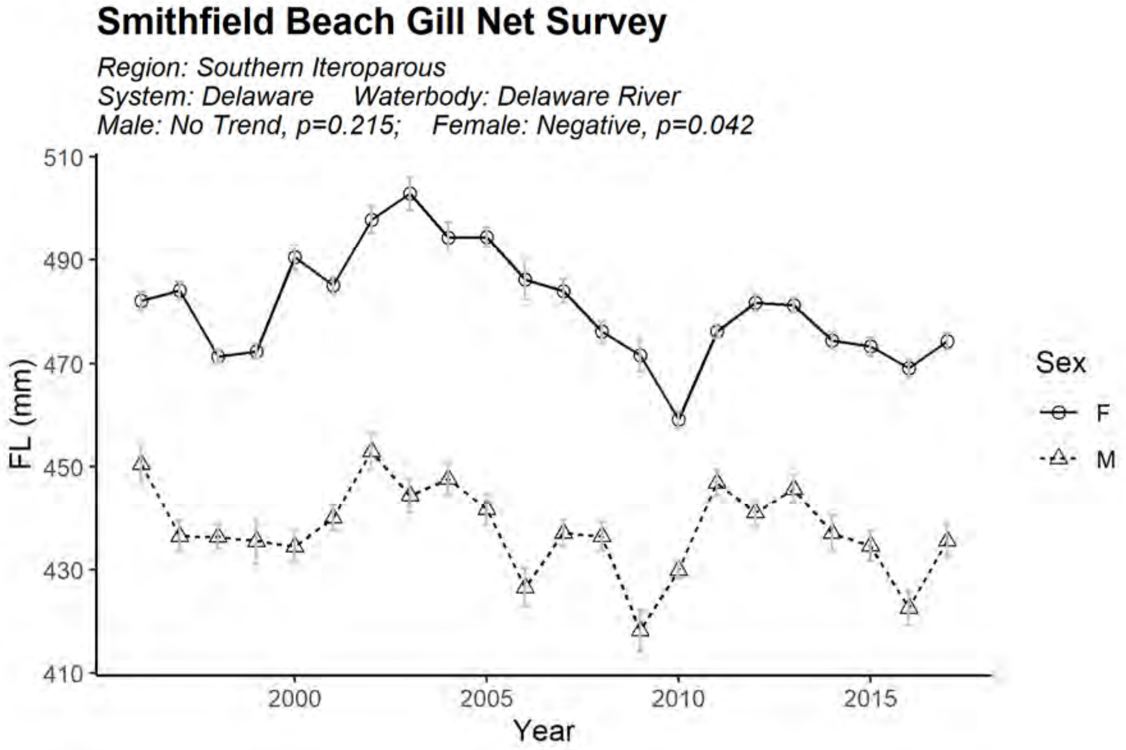


Figure 144. Mean length for male and female American shad in the Delaware River from the Smithfield Beach Gill Net Survey.

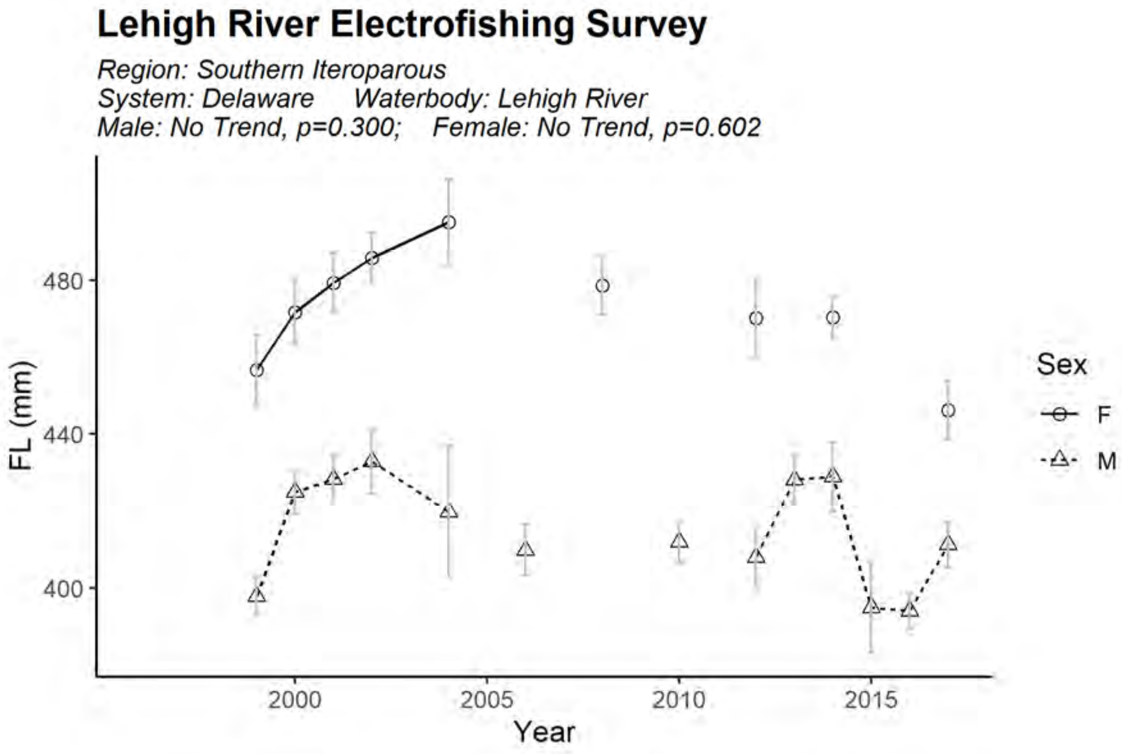


Figure 145. **Mean length for male and female American shad from the Lehigh River Electrofishing Survey.**

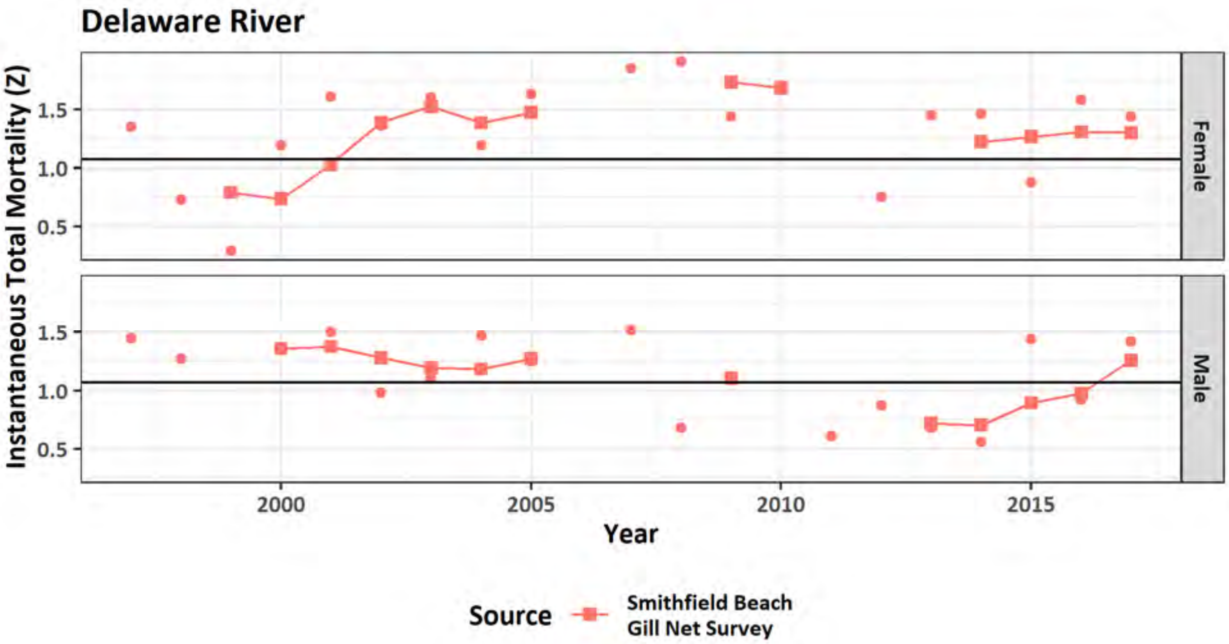


Figure 146. Three year average *Z* estimates via weighted linear regression by sex and monitoring program for the Delaware River System based on otolith-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual *Z* estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).

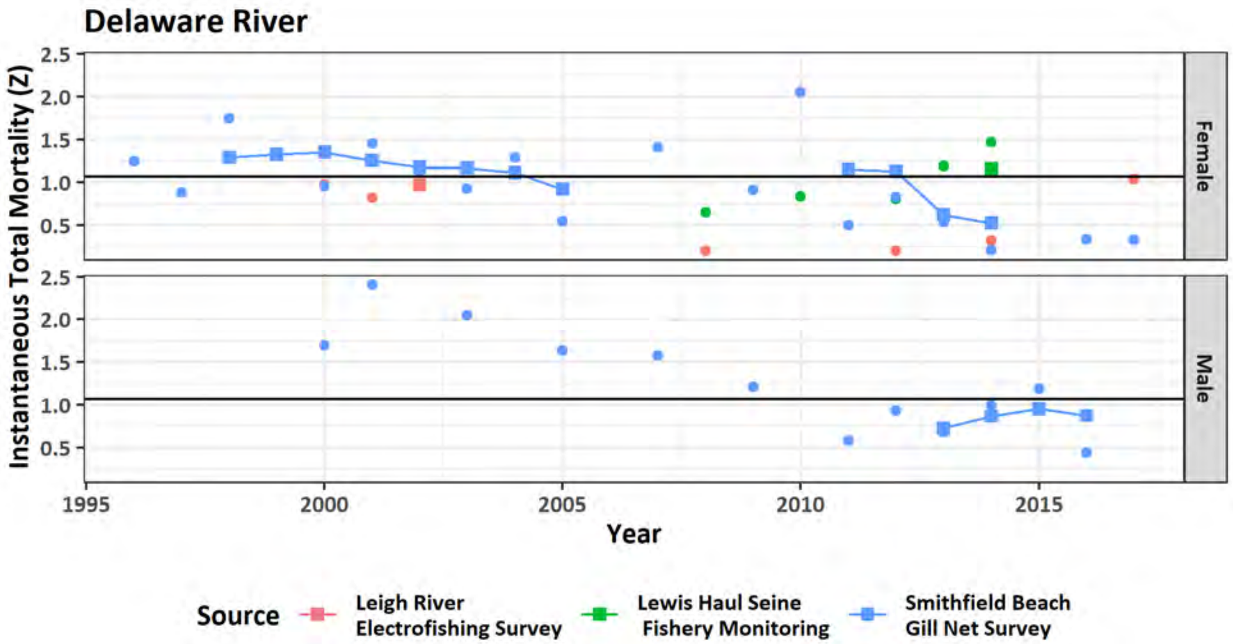


Figure 147. Three year average *Z* estimates via weighted linear regression by sex and monitoring program for the Delaware River System based on scale-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual *Z* estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).

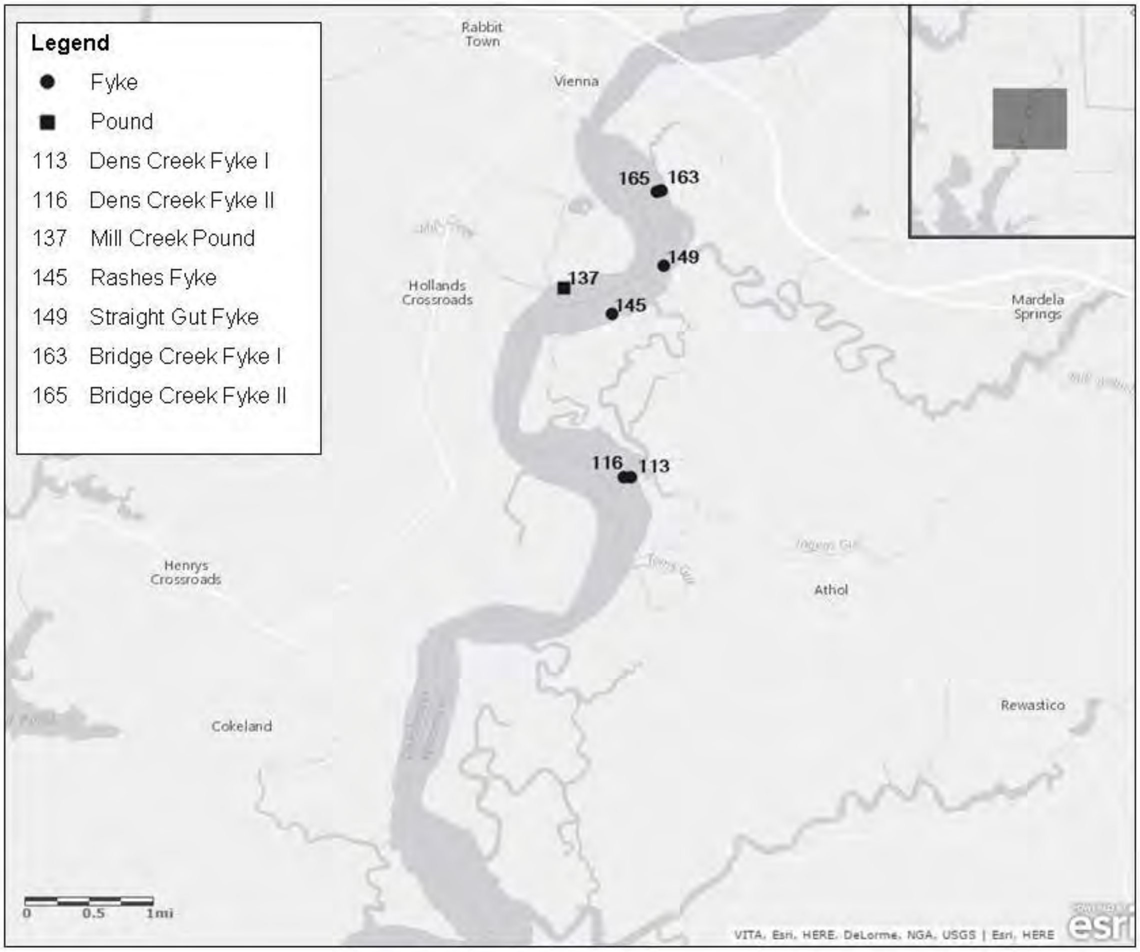


Figure 148. Nanticoke River fishery-dependent pound and fyke net sampling locations for 2017.

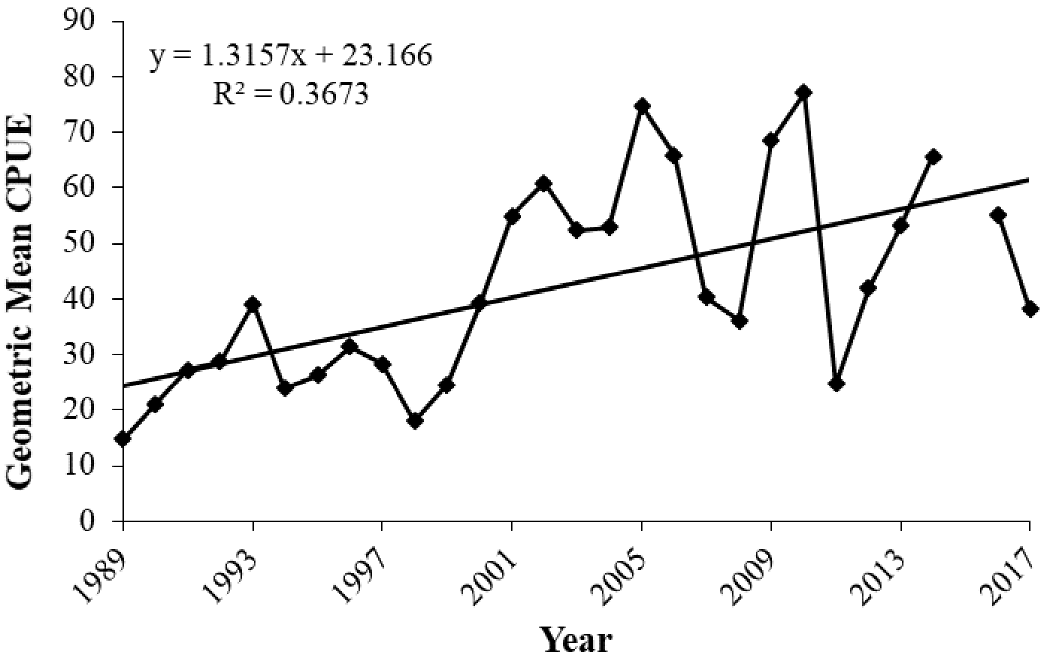


Figure 149. Arcsine-transformed percentage occurrence of repeat spawning American shad, sexes combined, captured in the Nanticoke River fishery-dependent pound and fyke net survey, 1989-2017.

Figure 150. The electrofishing raft used to collect adult shad for shad hatchery operations and spawning stock sampling.

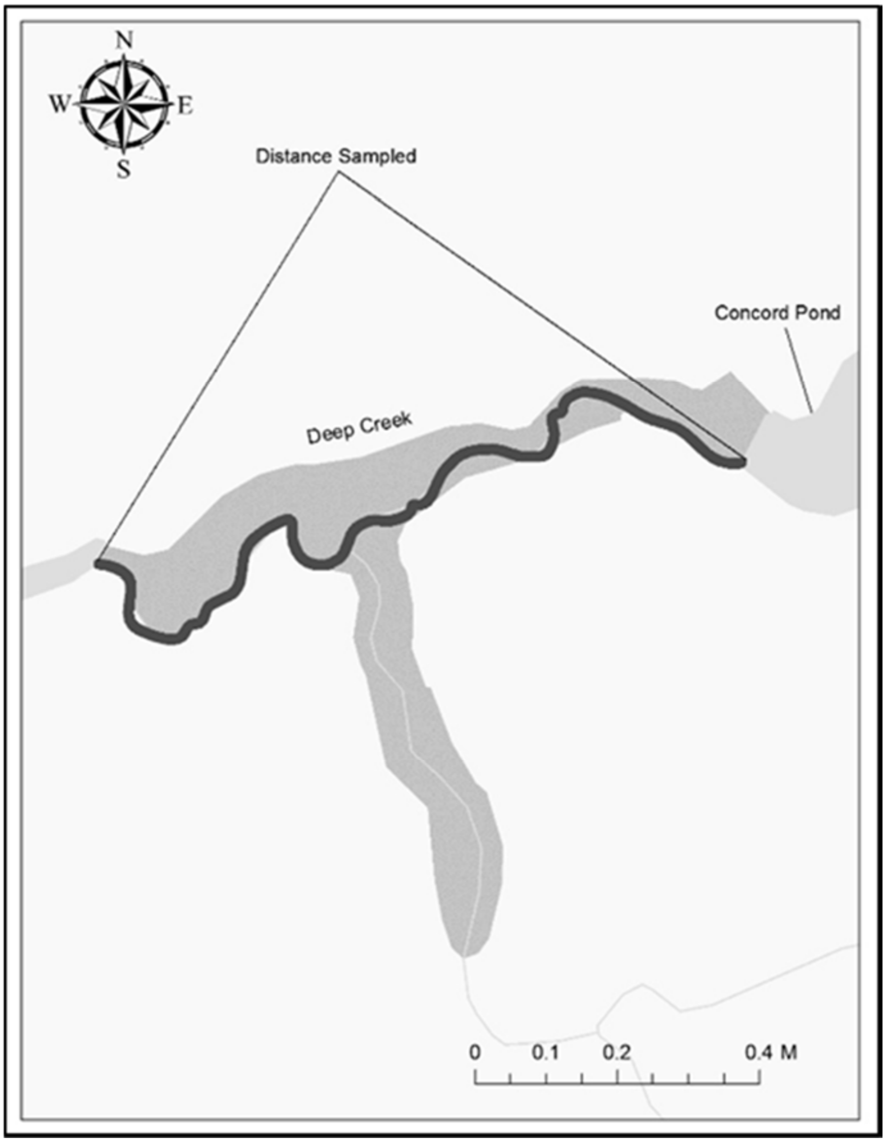


Figure 151. The section sampled on Deep Creek with the electrofishing raft to determine the adult index of abundance for American and Hickory Shad.

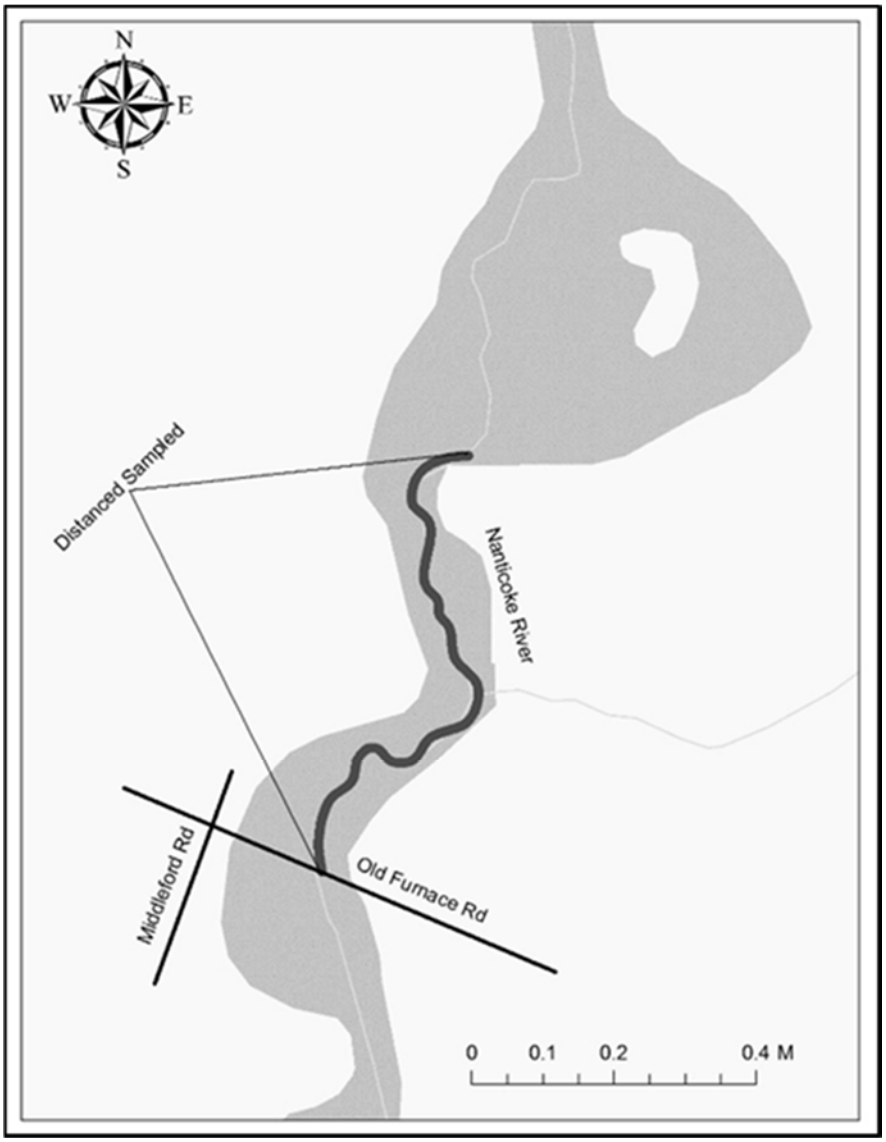


Figure 152. **The section sampled on the Nanticoke River with the electrofishing raft to determine an abundance of adult American and Hickory Shad.**

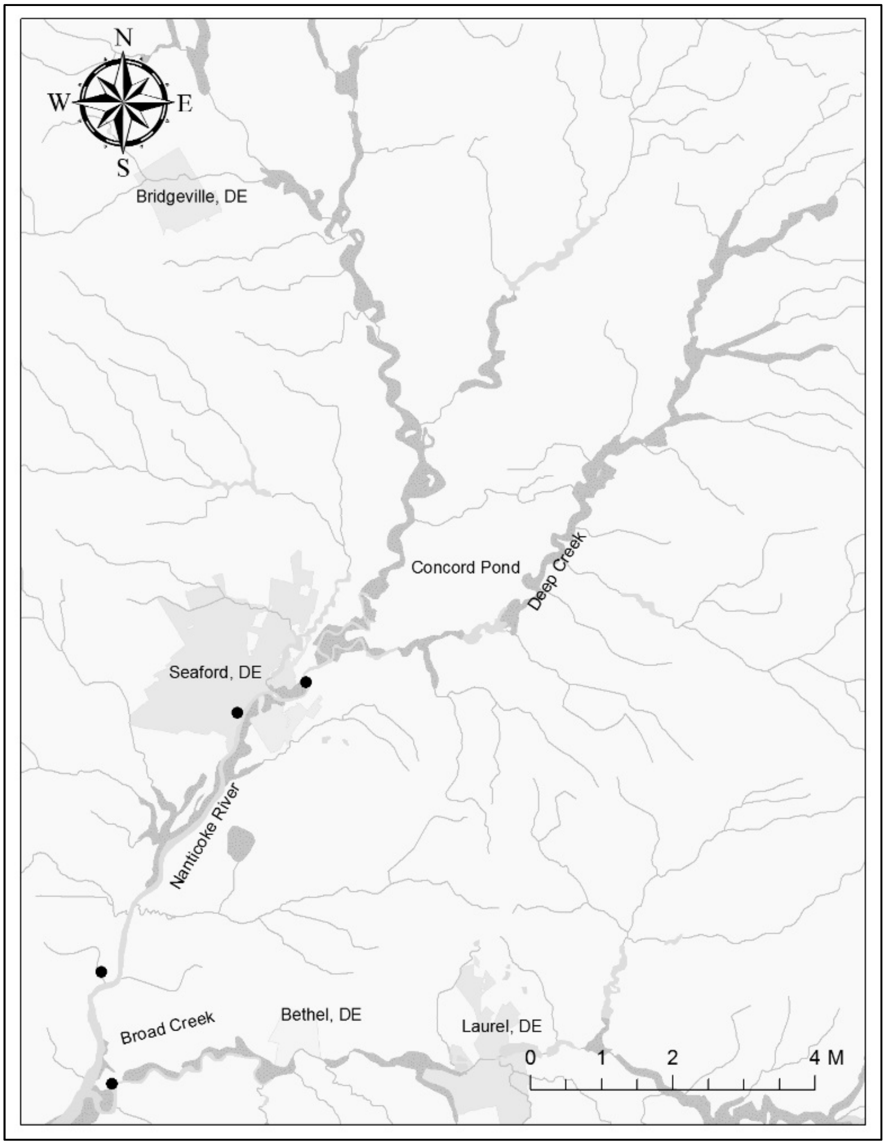


Figure 153. The location of the four haul seine sites on the Nanticoke River in Delaware. Each seine site is designated by a dot.

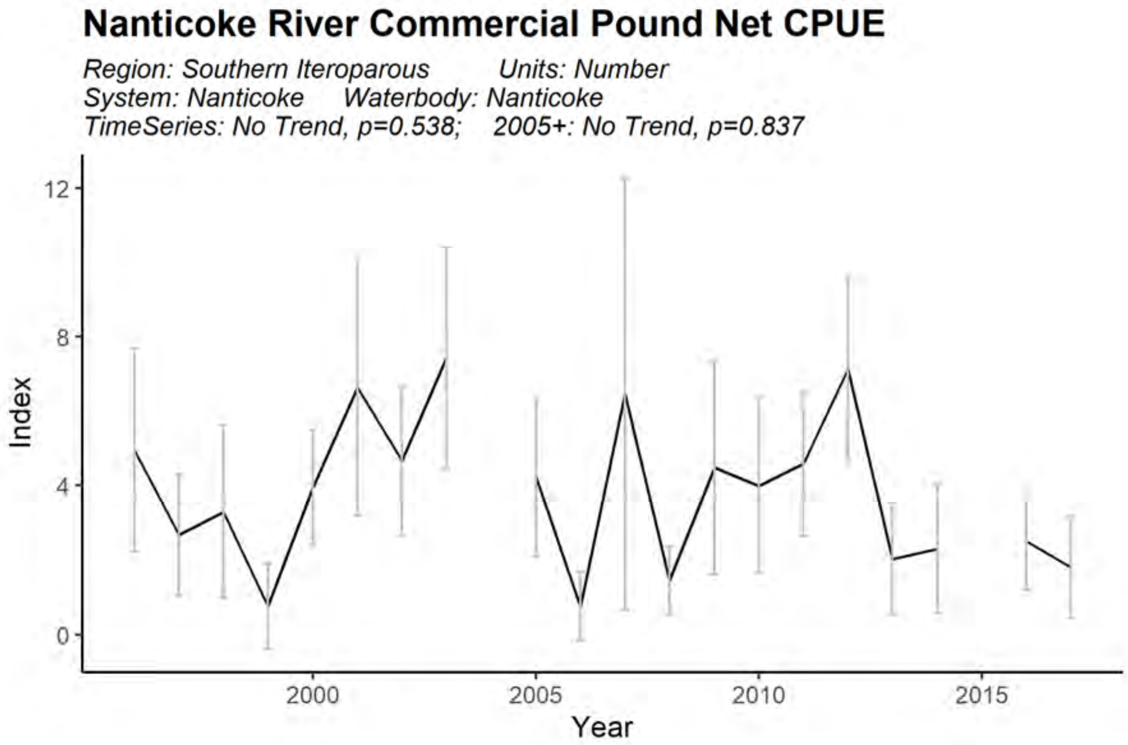


Figure 154. Nanticoke River Commercial Pound Net CPUE and Mann-Kendall analysis results.

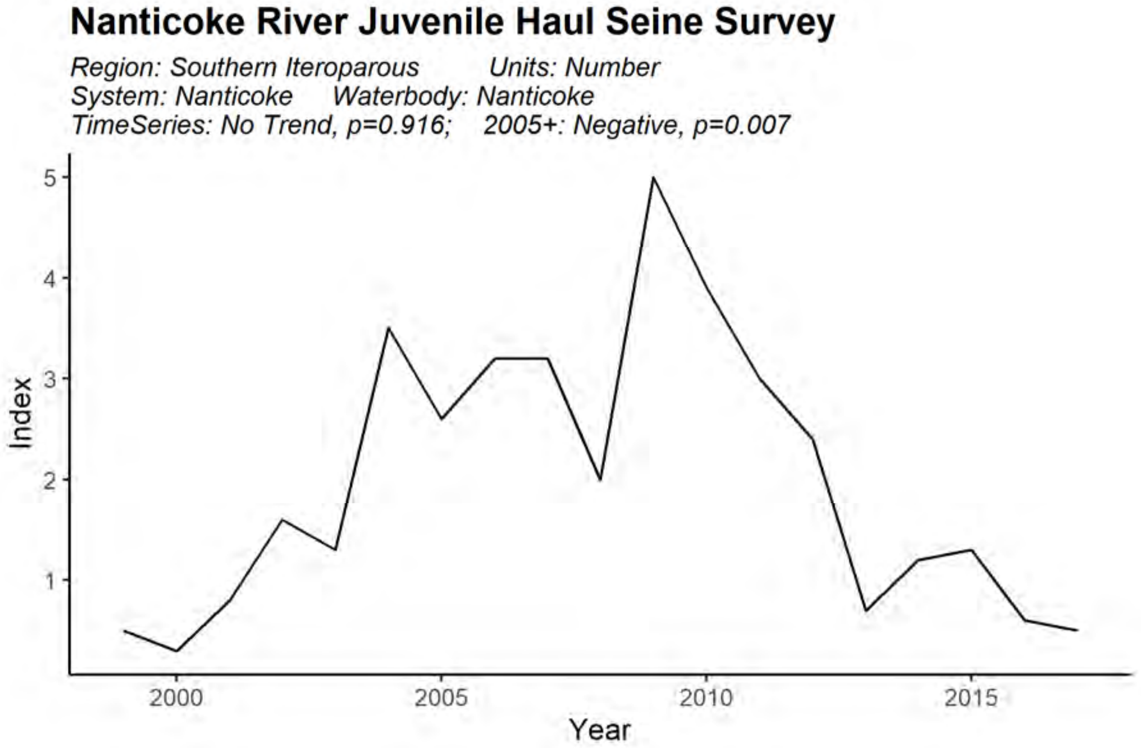


Figure 155. Nanticoke River Juvenile Haul Seine Survey index and Mann-Kendall results.

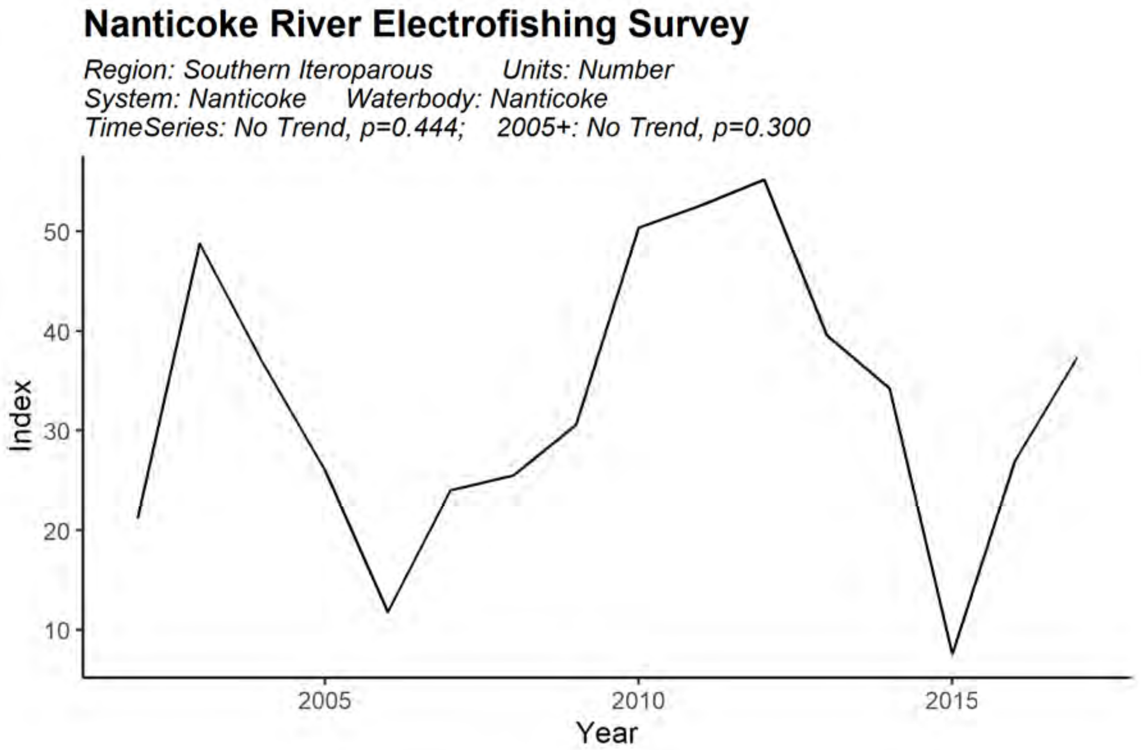


Figure 156. Nanticoke River Electrofishing Survey index and Mann-Kendall results.

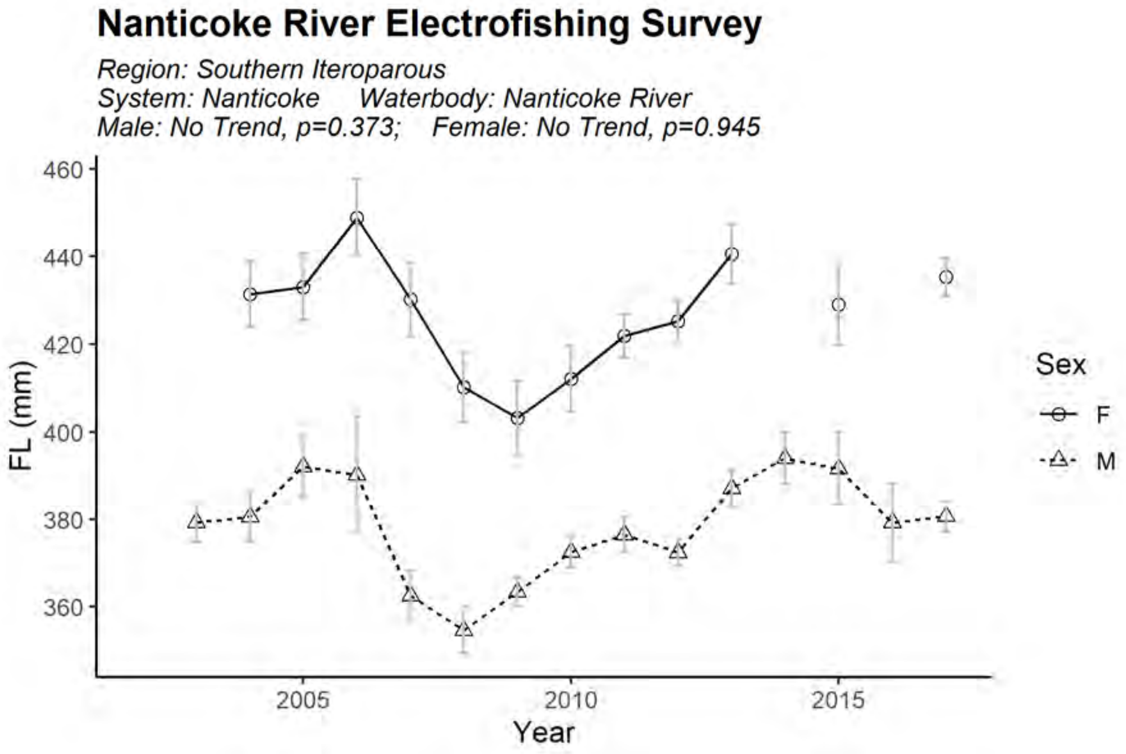


Figure 157. Annual mean length of male and female American shad collected by the Nanticoke River Electrofishing Survey and Mann-Kendall results.

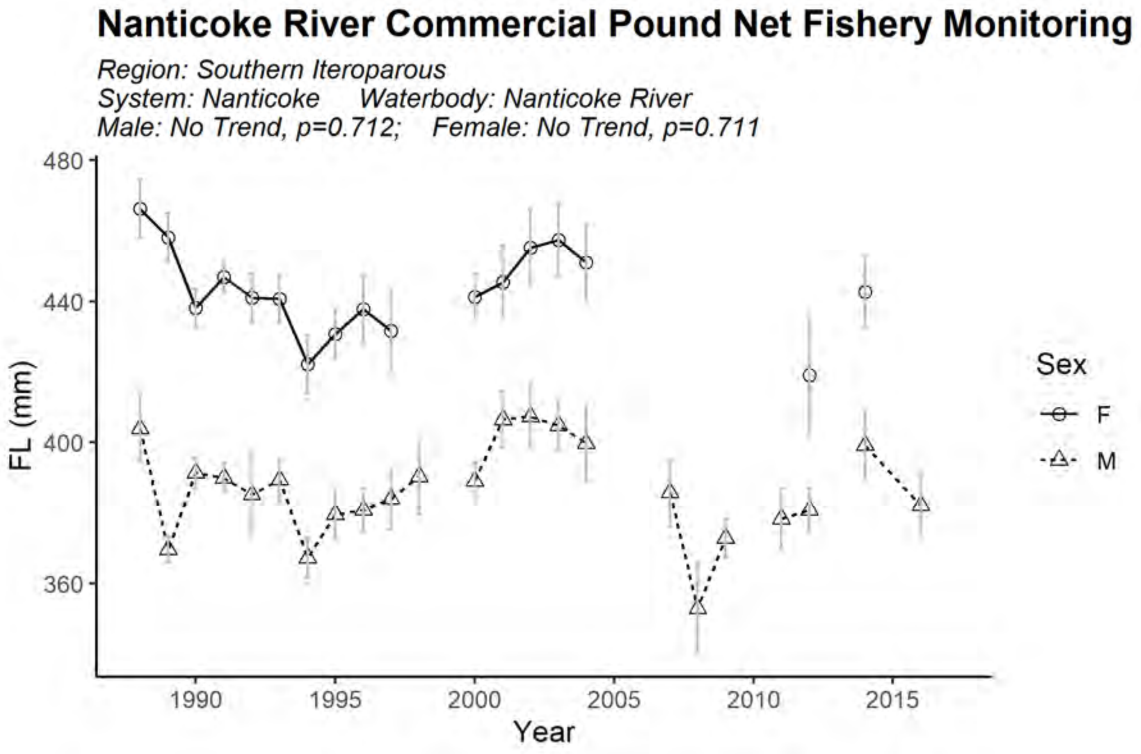


Figure 158. Annual mean length of male and female American shad collected by the Nanticoke River Commercial Pound Net Fishery Monitoring and Mann-Kendall results.

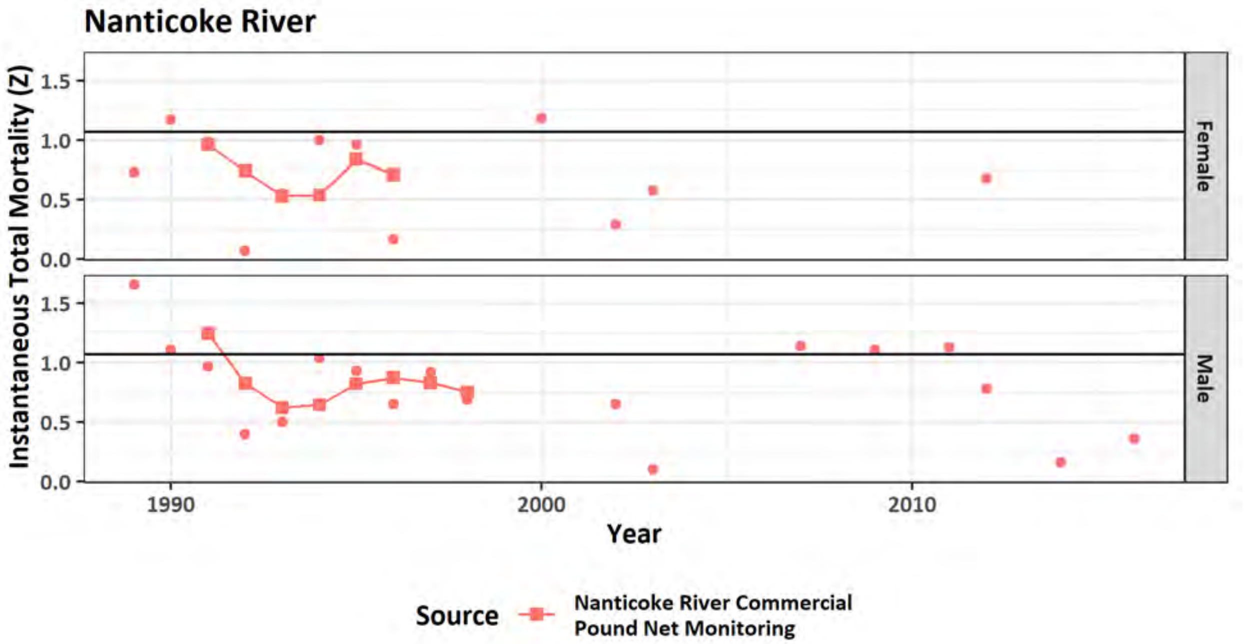


Figure 159. Three year average *Z* estimates via weighted linear regression by sex and monitoring program for the Nanticoke River System based on scale-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual *Z* estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).

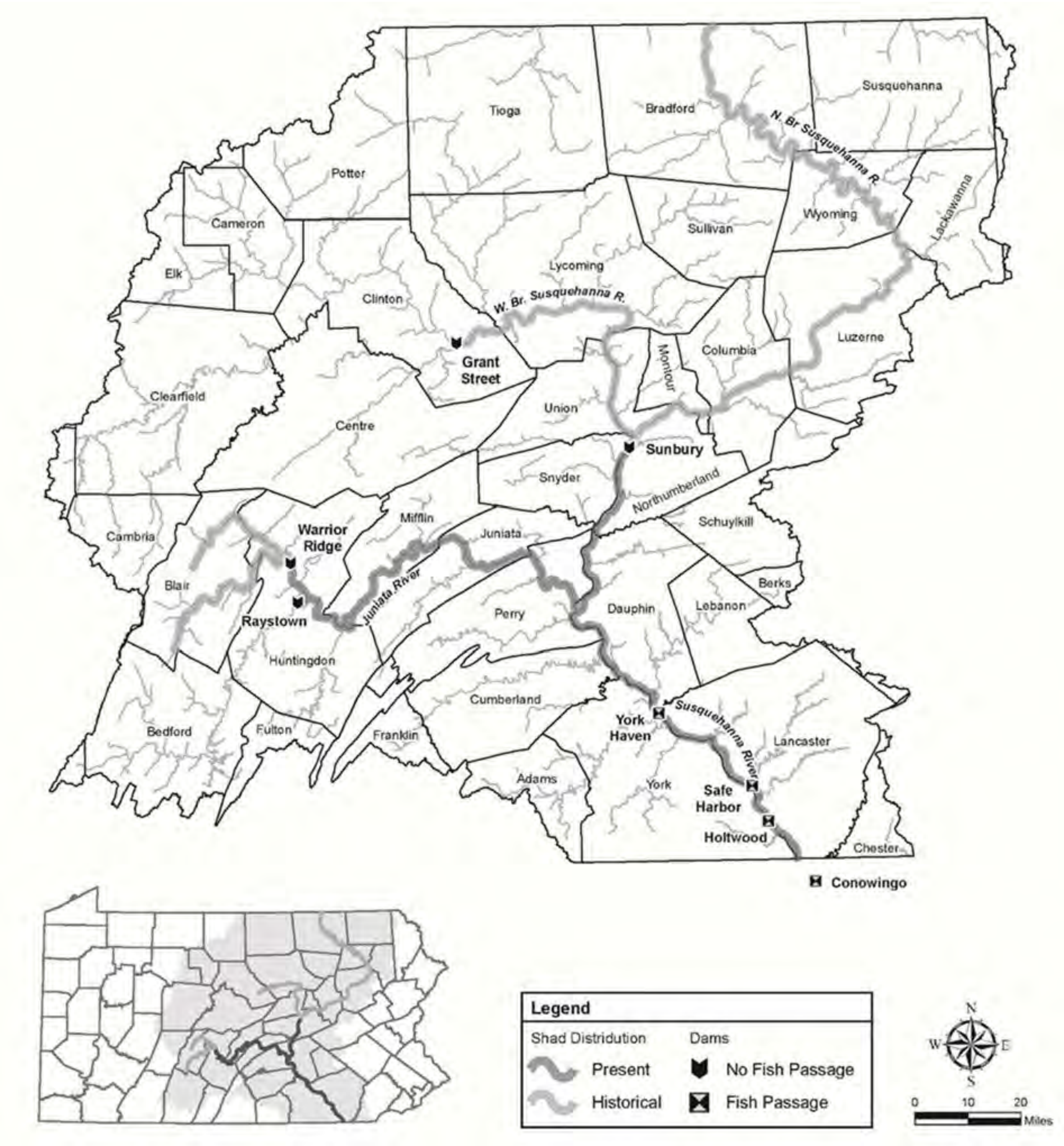


Figure 160. Map of Susquehanna River basin within Pennsylvania.

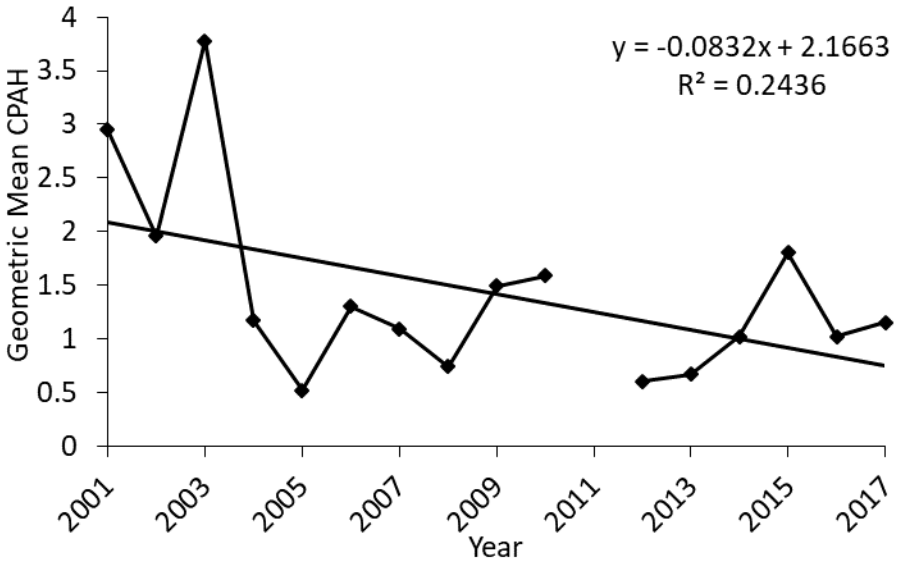


Figure 161. Geometric mean CPAH (catch-per-angler-hour) of American shad captured by recreational catch-and-release anglers in the Conowingo Dam tailrace, 2001-2017. P = 0.0520

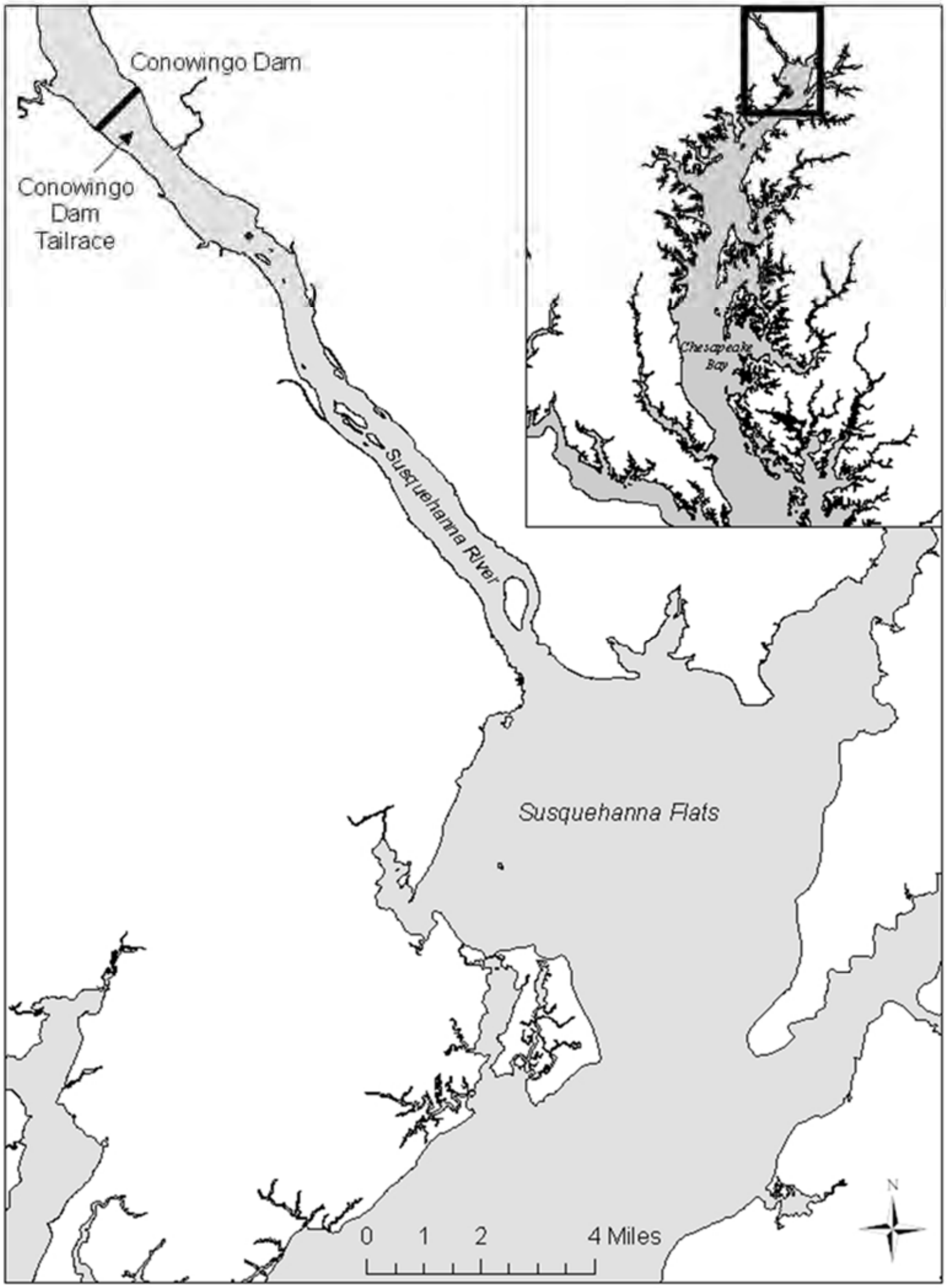


Figure 162. MD DNR Conowingo Dam tailrace (Susquehanna River) hook-and-line sampling location for American shad from 1982-2017.

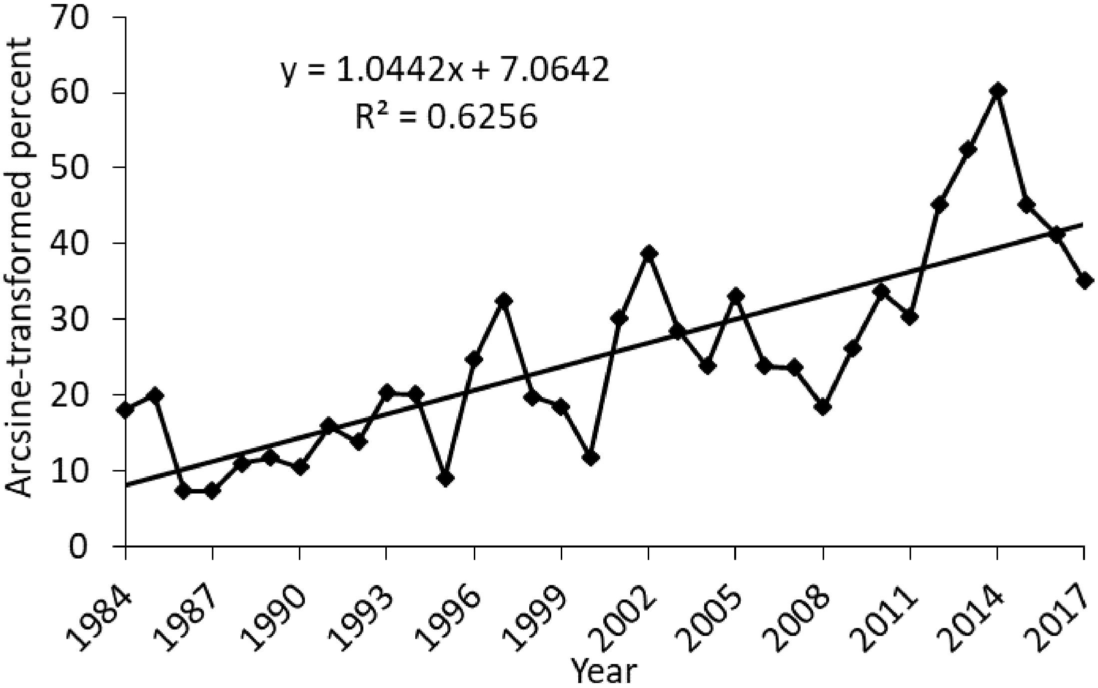


Figure 163. Arcsine-transformed percentage occurrence of repeat spawning American shad, sexes combined, captured by the MD DNR Susquehanna River hook-and-line survey, 1984-2017. P < 0.001

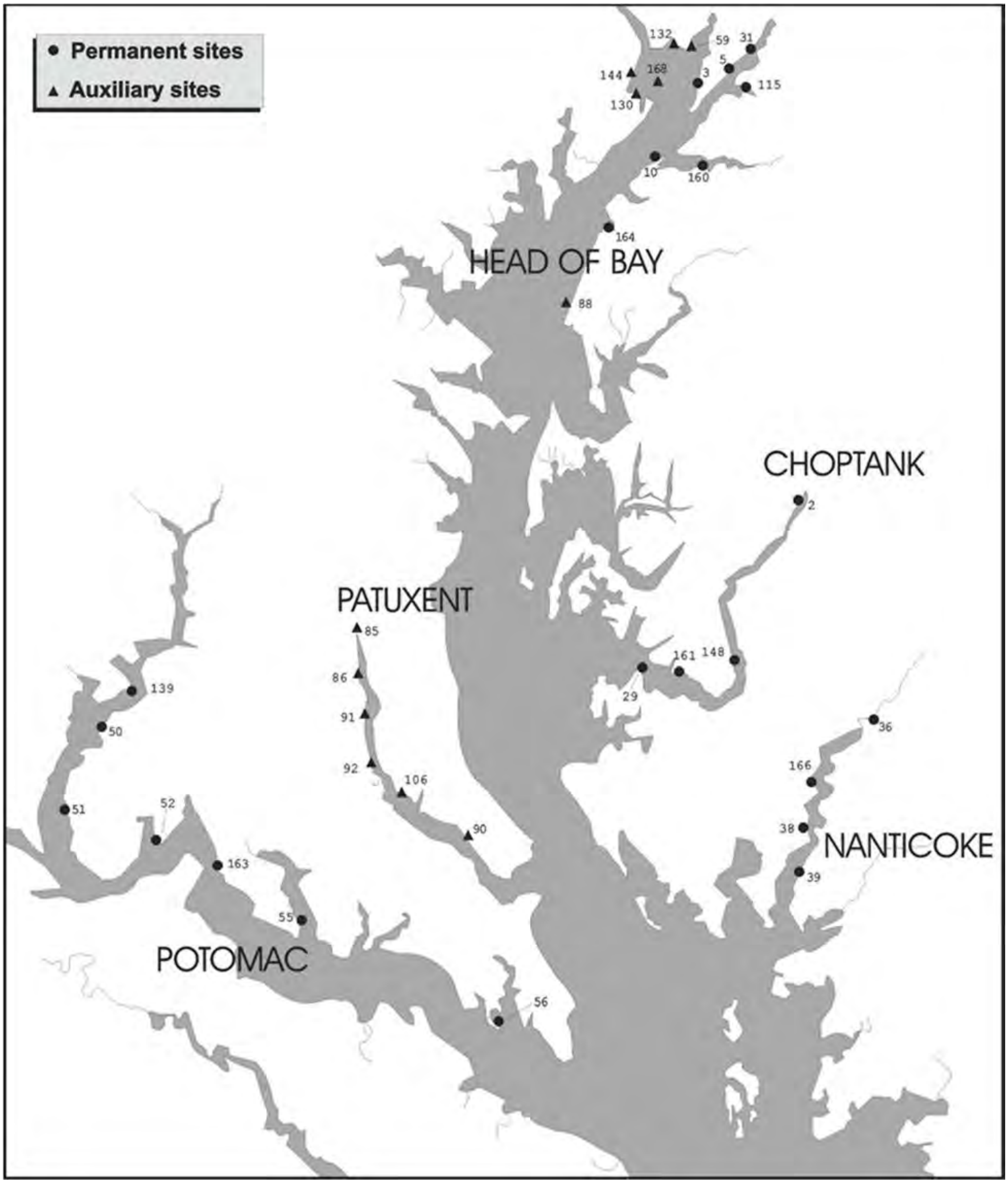


Figure 164. MD DNR Striped Bass Juvenile Seine Survey 2017 sampling sites.

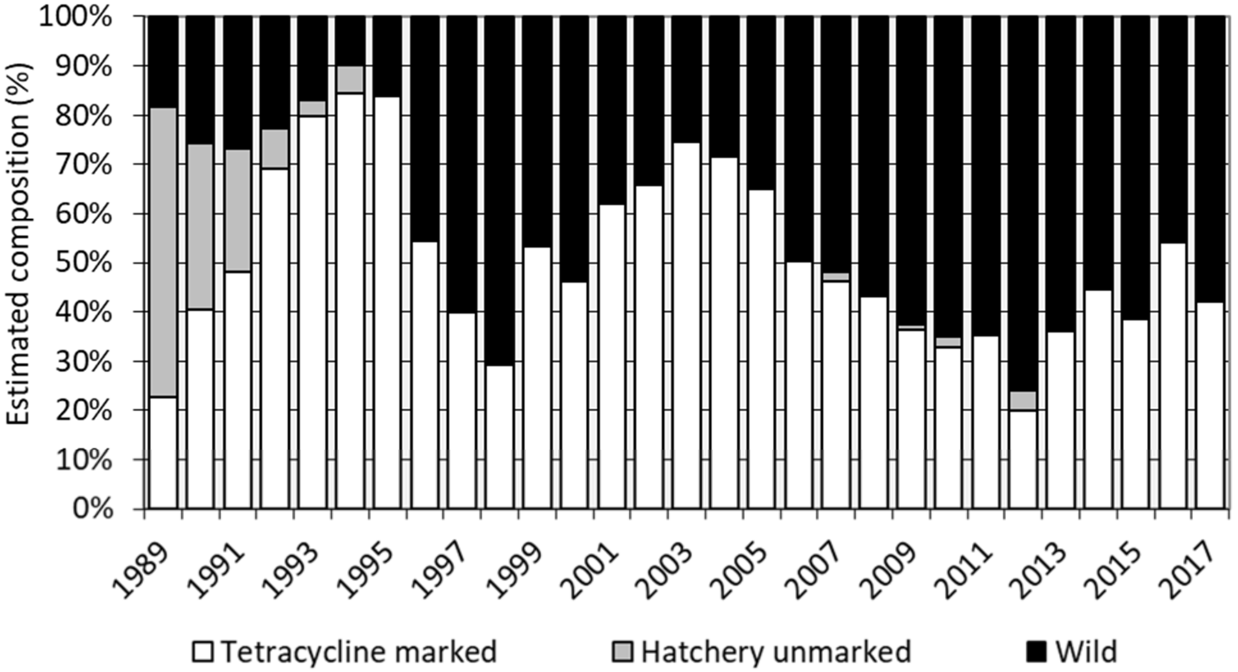


Figure 165. Estimated composition of adult American shad caught at Conowingo Dam, based on otolith microstructure and tetracycline marking.

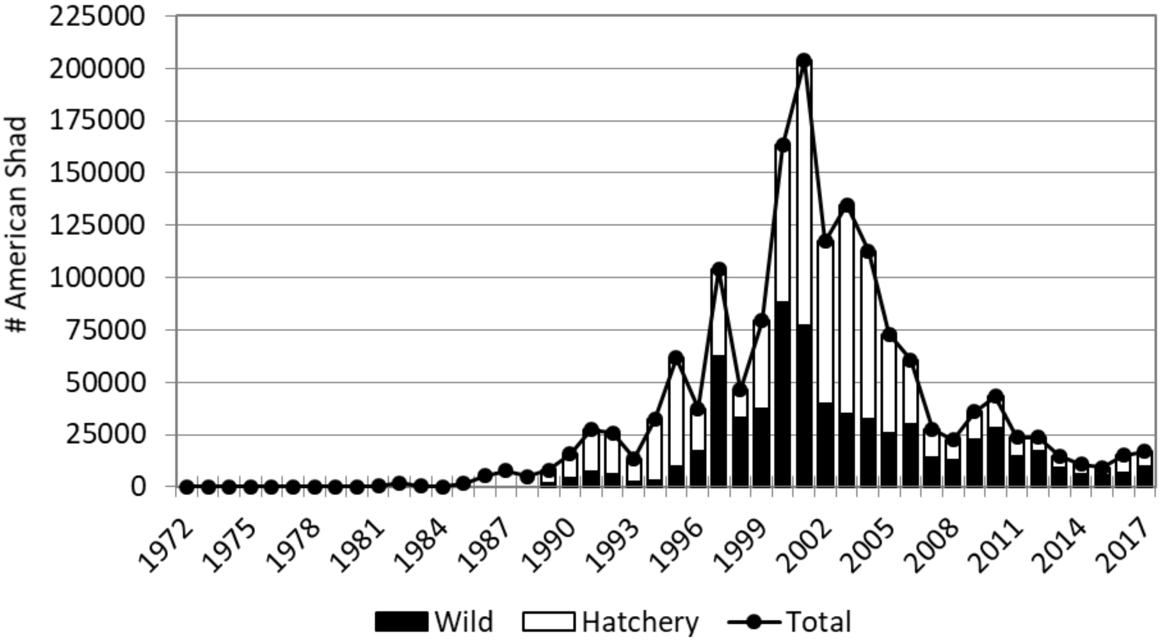


Figure 166. Number of American shad captured, by origin, at the Conowingo Dam fish-lifts, Susquehanna River, 1972-2017.

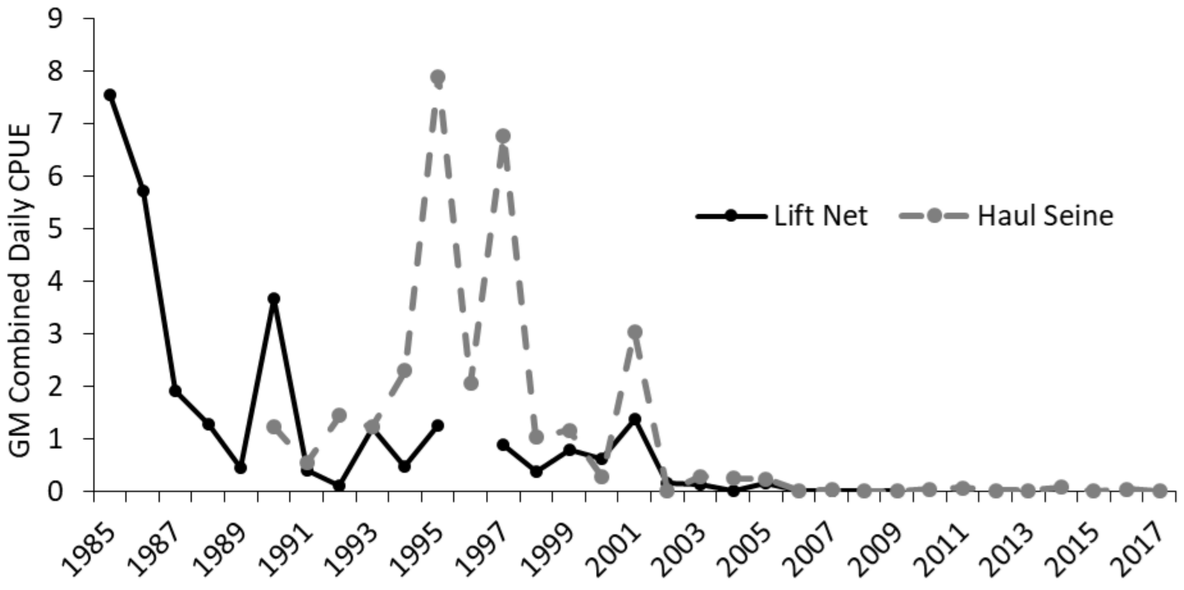


Figure 167. Geometric mean CPUE (combined daily catch) of juvenile American shad captured by lift net survey (Holtwood Dam forebay) and haul seine survey (Susquehanna River at Columbia-Wrightsville, PA).

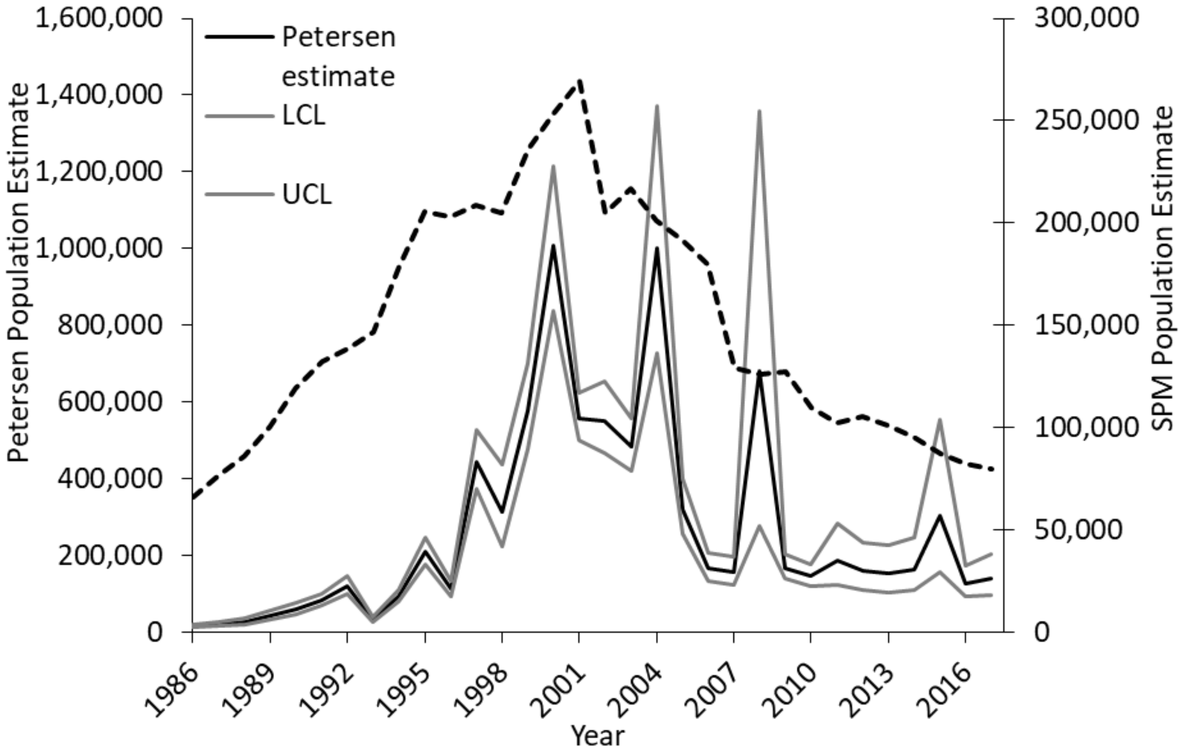


Figure 168. Conowingo dam tailrace American shad population estimates by two methods, the Petersen statistic and a biomass surplus production model (SPM), 1986-2017. Note differences in scale.

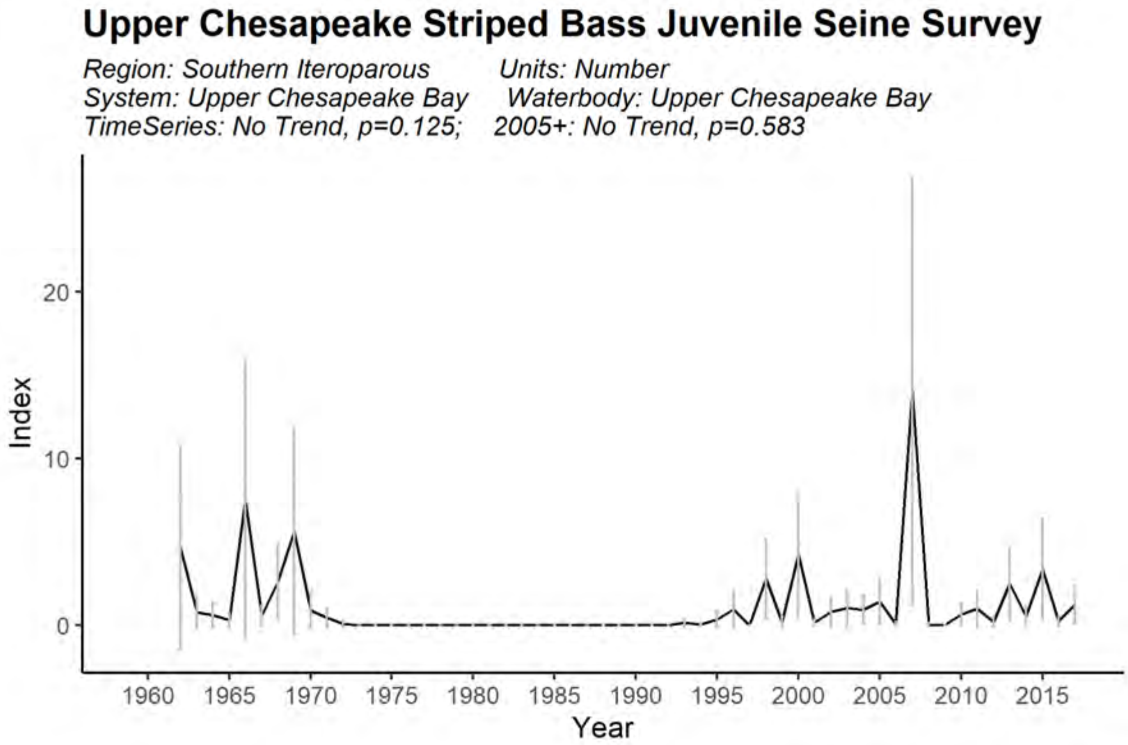


Figure 169. Upper Chesapeake Striped Bass Juvenile Seine Survey abundance index and Mann-Kendall results.

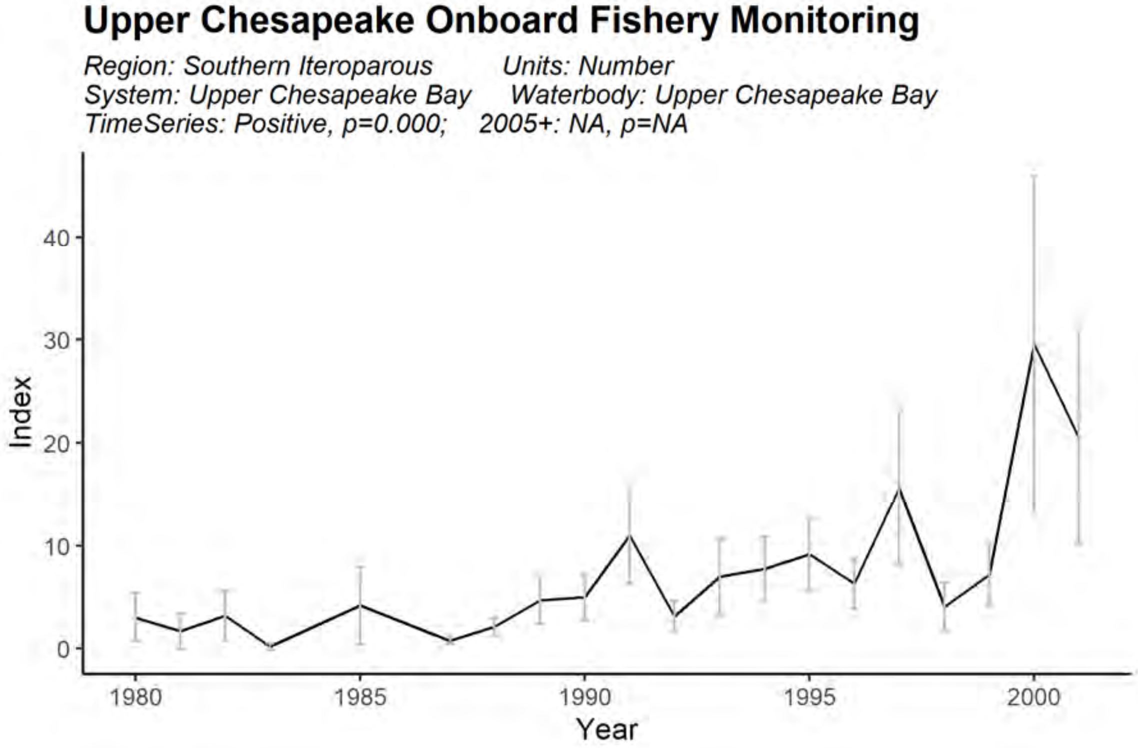


Figure 170. Upper Chesapeake Onboard Fishery Monitoring index and Mann-Kendall results.

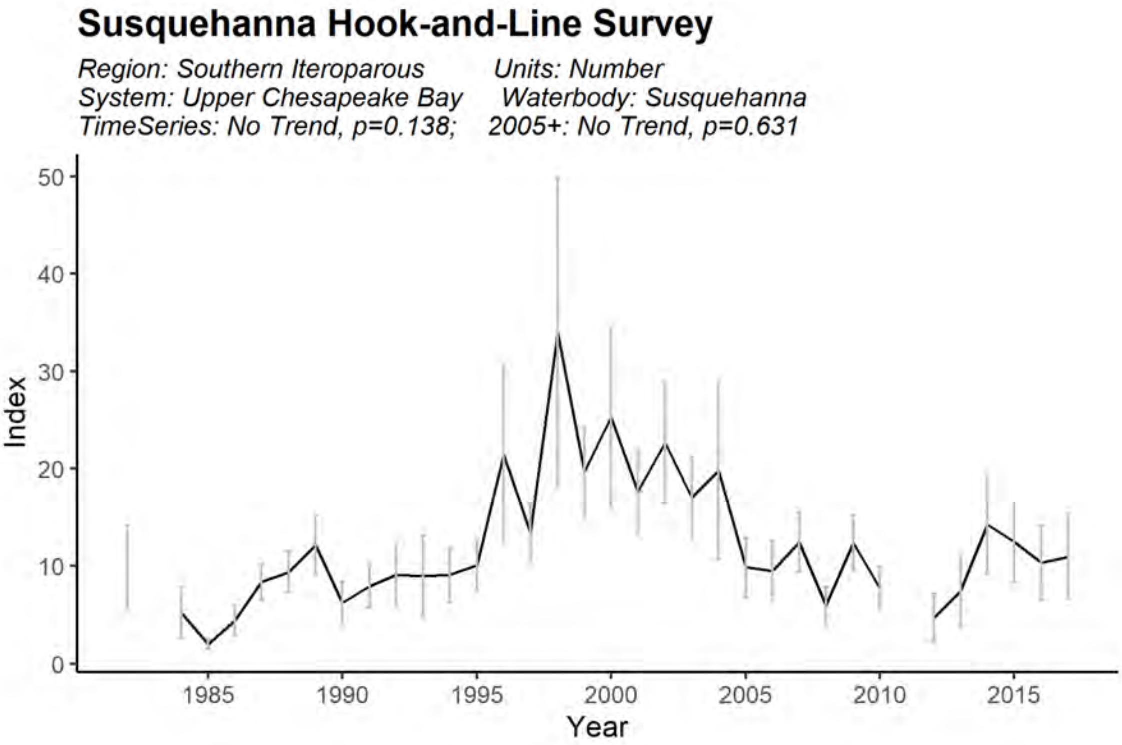


Figure 171. Susquehanna Hook-and-Line Survey abundance index and Mann-Kendall results.

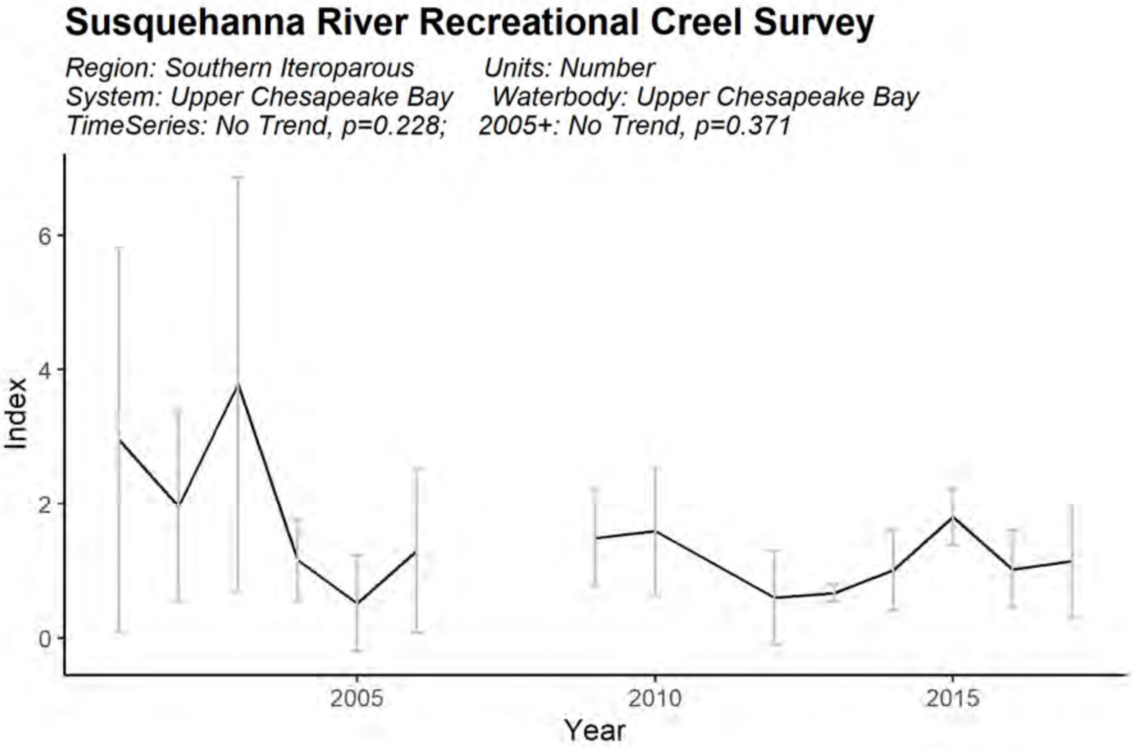


Figure 172. Susquehanna River Recreational Creel Survey abundance index and Mann-Kendall results.

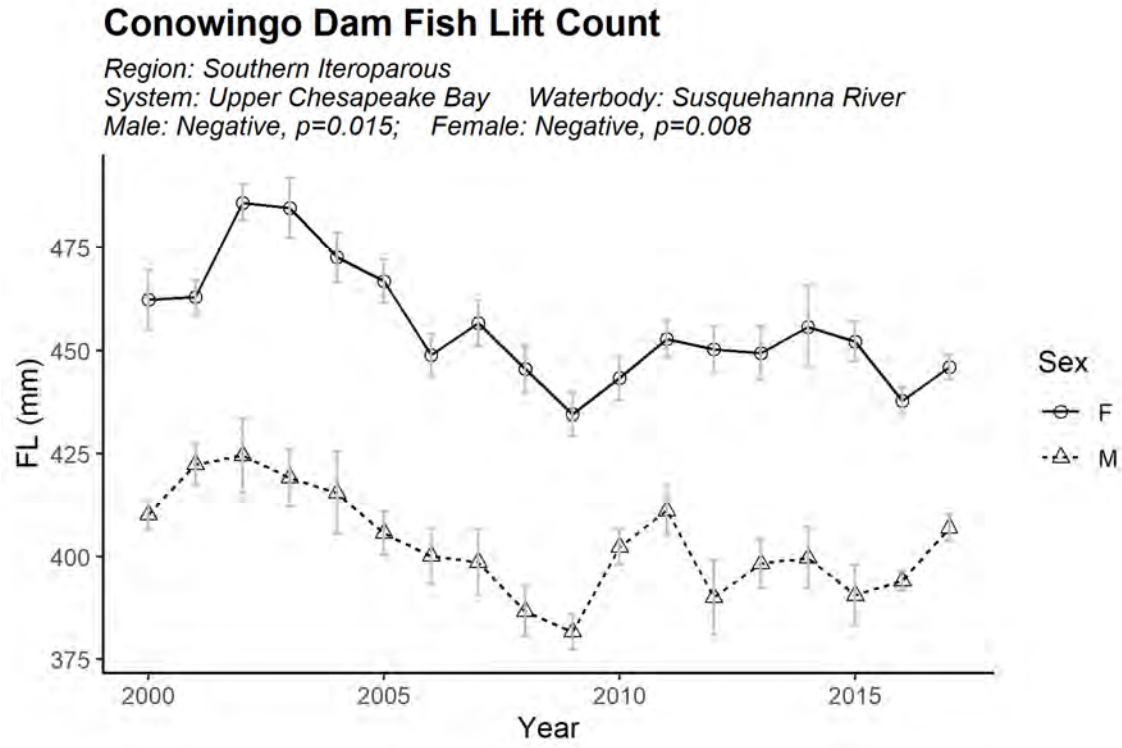


Figure 173. Mean fork length over time from the Conowingo Dam Fish Lift Count and Mann-Kendall results.

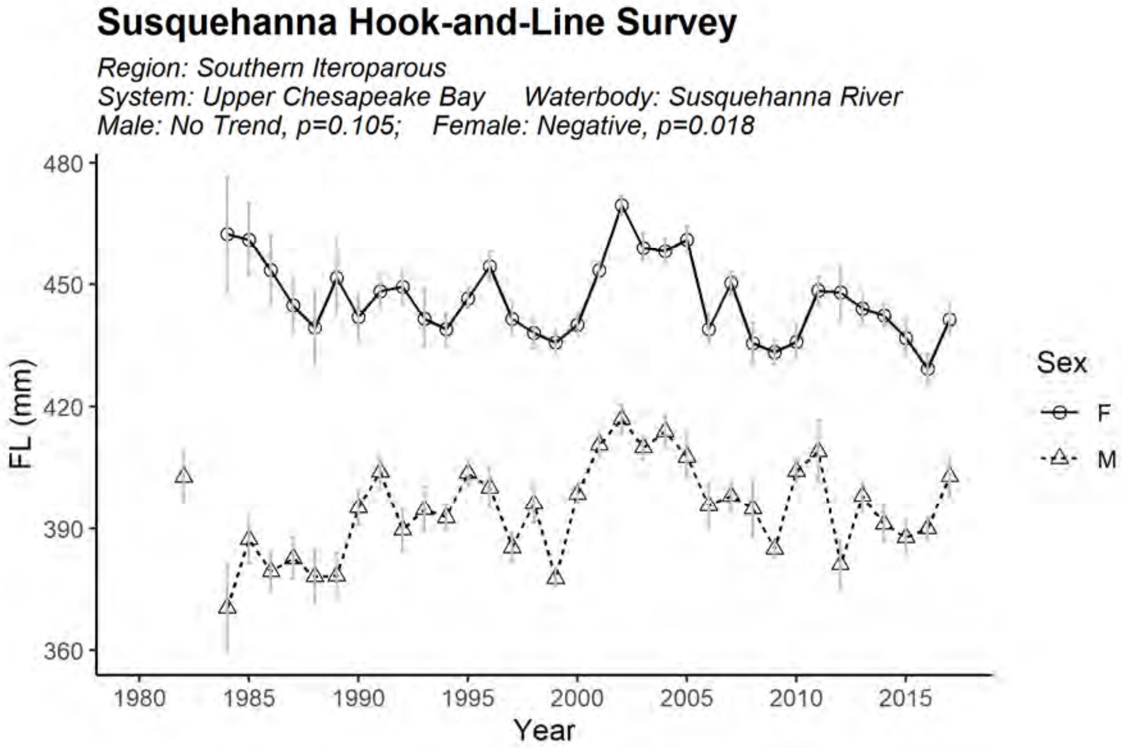


Figure 174. Mean fork length over time for the Susquehanna River Hook-and-Line Survey and Mann-Kendall results.

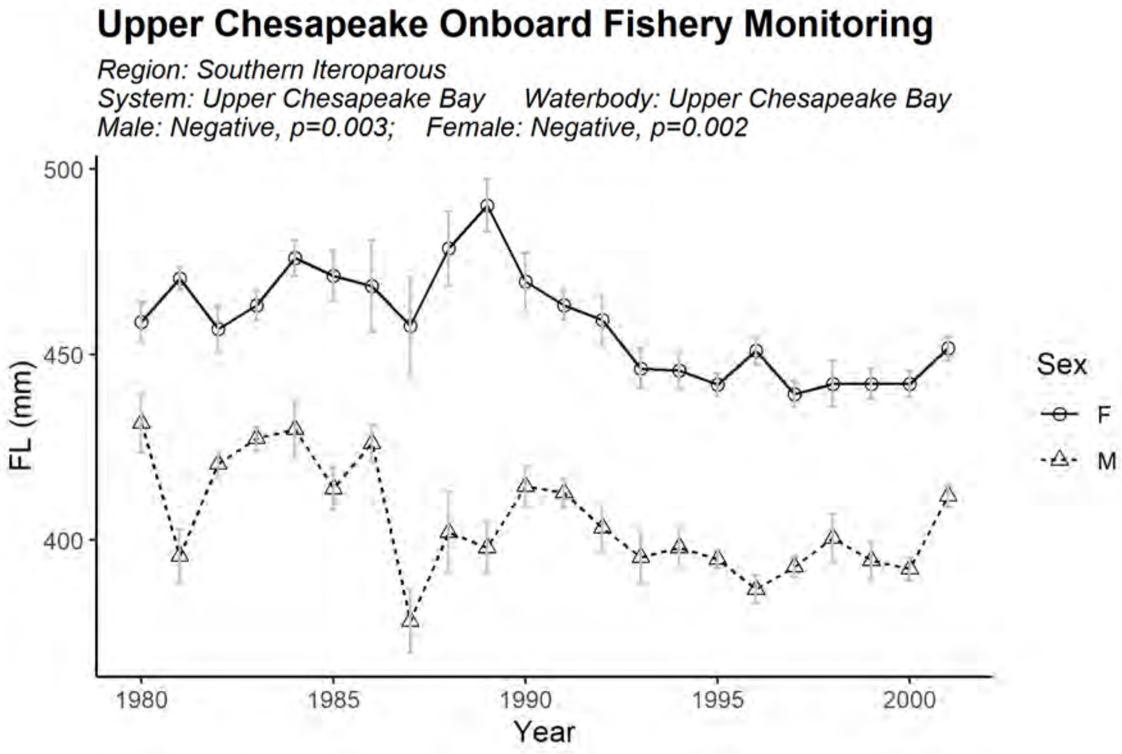


Figure 175. Mean fork length over time for the Upper Chesapeake Onboard Fishery Monitoring and Mann-Kendall results.

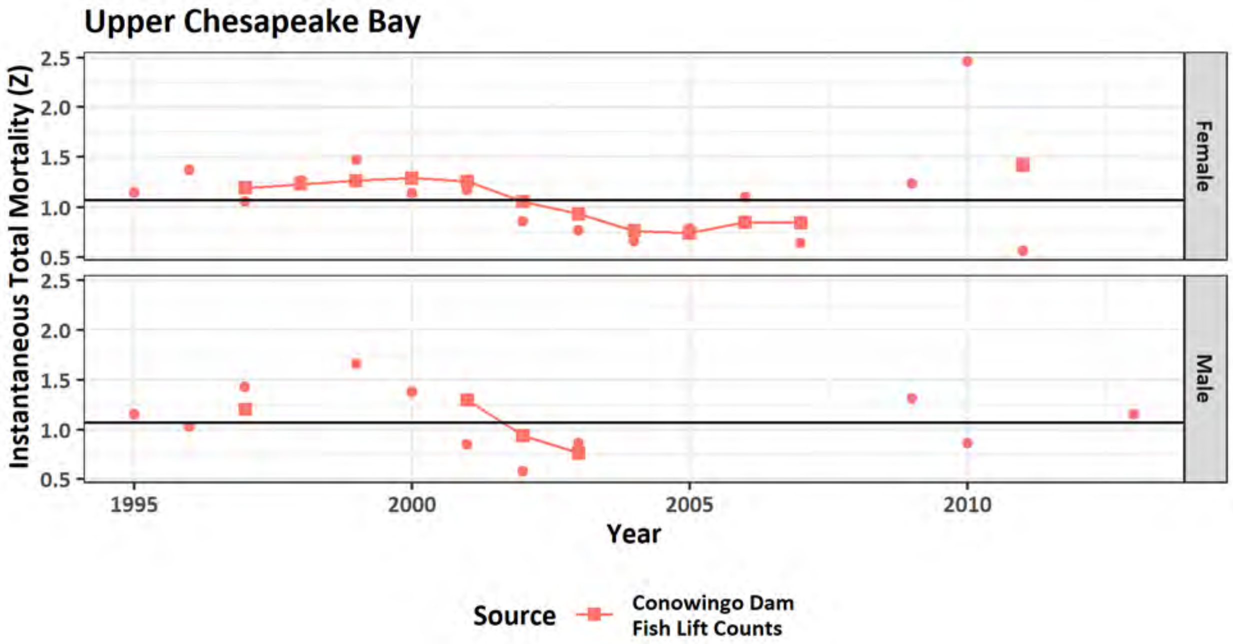


Figure 176. Three year average *Z* estimates via weighted linear regression by sex and monitoring program for the Upper Chesapeake Bay System based on otolith-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual *Z* estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).

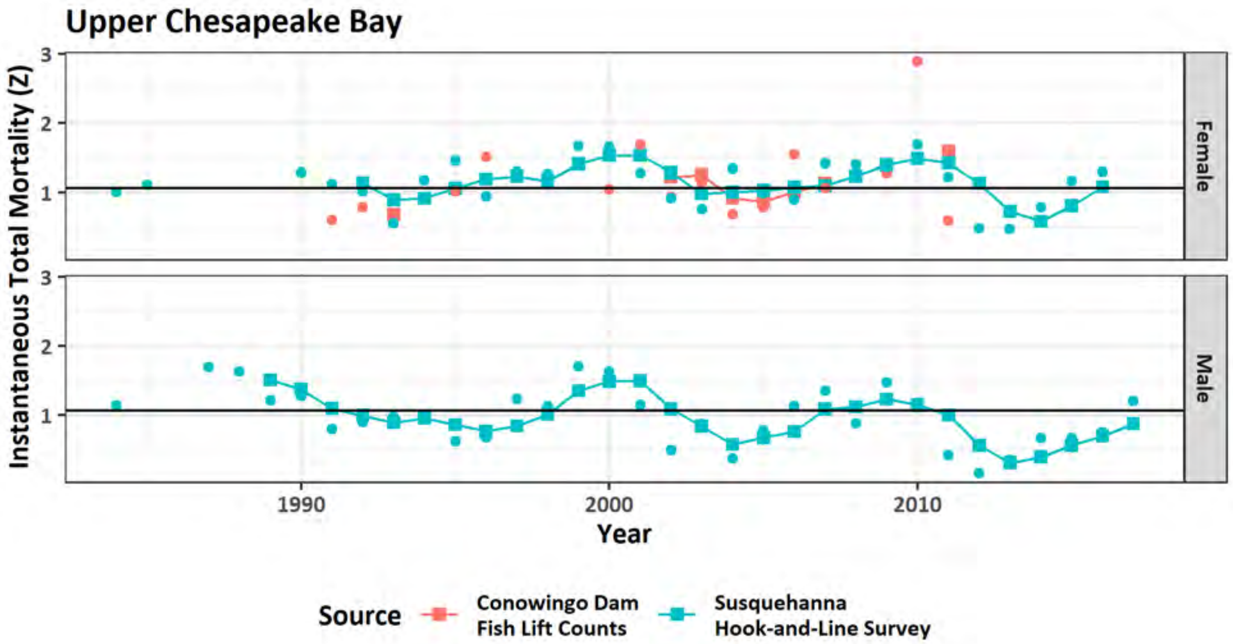


Figure 177. Three year average *Z* estimates via weighted linear regression by sex and monitoring program for the Upper Chesapeake Bay System based on scale-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual *Z* estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).

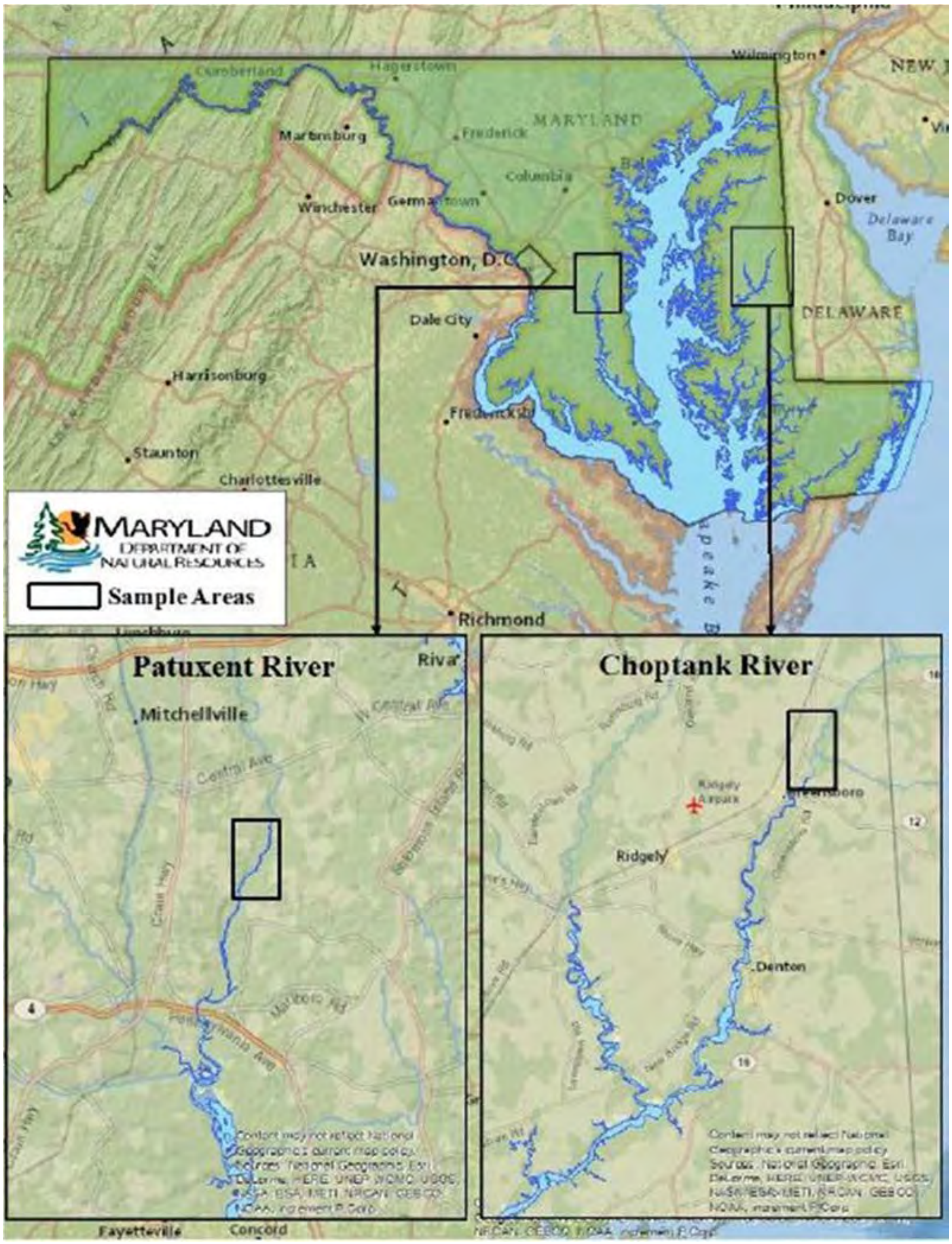


Figure 178. American shad electrofishing sampling areas (from Stence et al. 2017).

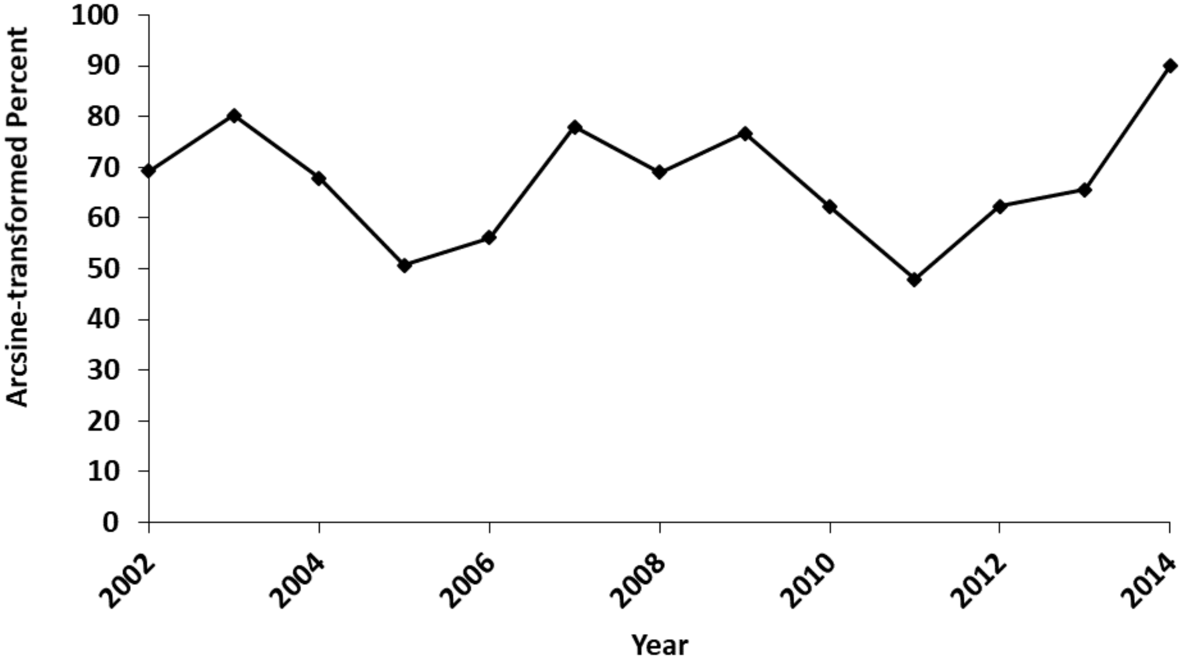


Figure 179. Arcsine-transformed percentage occurrence of repeat spawning American shad, sexes combined, captured in the Patuxent River electrofishing survey, 2002-2014.

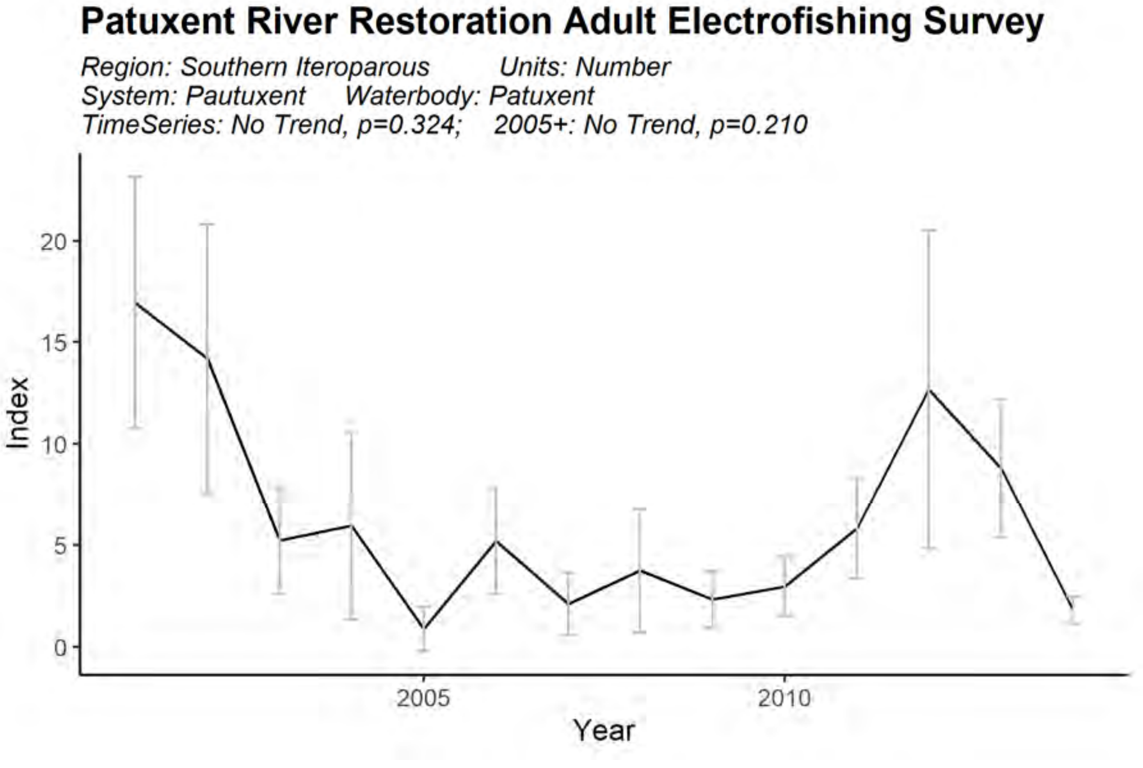


Figure 180. Patuxent River Restoration Adult Electrofishing Survey abundance index and Mann-Kendall results.

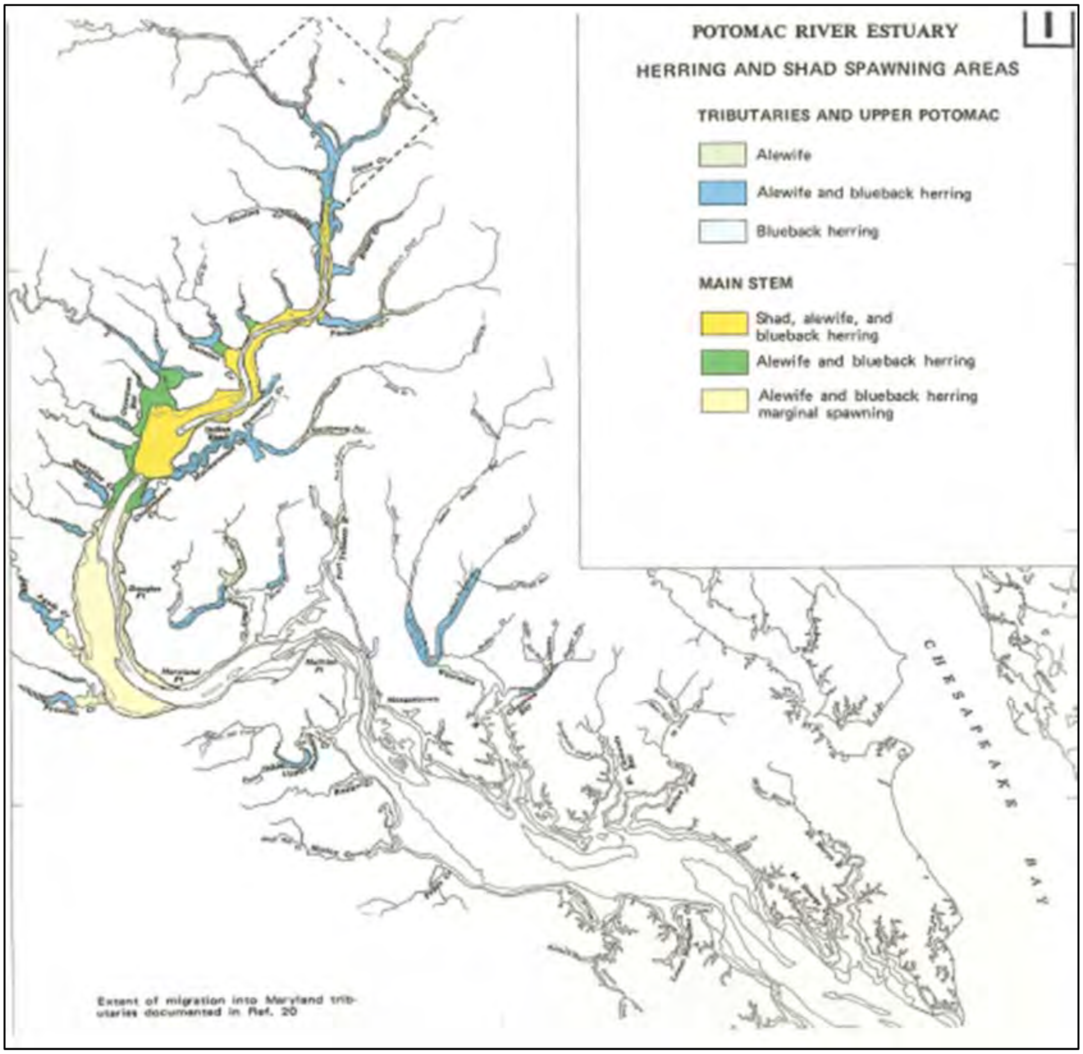


Figure 181. **Potomac River herring and shad spawning areas from Lippson et al.'s *Environmental Atlas of the Potomac Estuary* Herring and Shad Spawning Areas.**

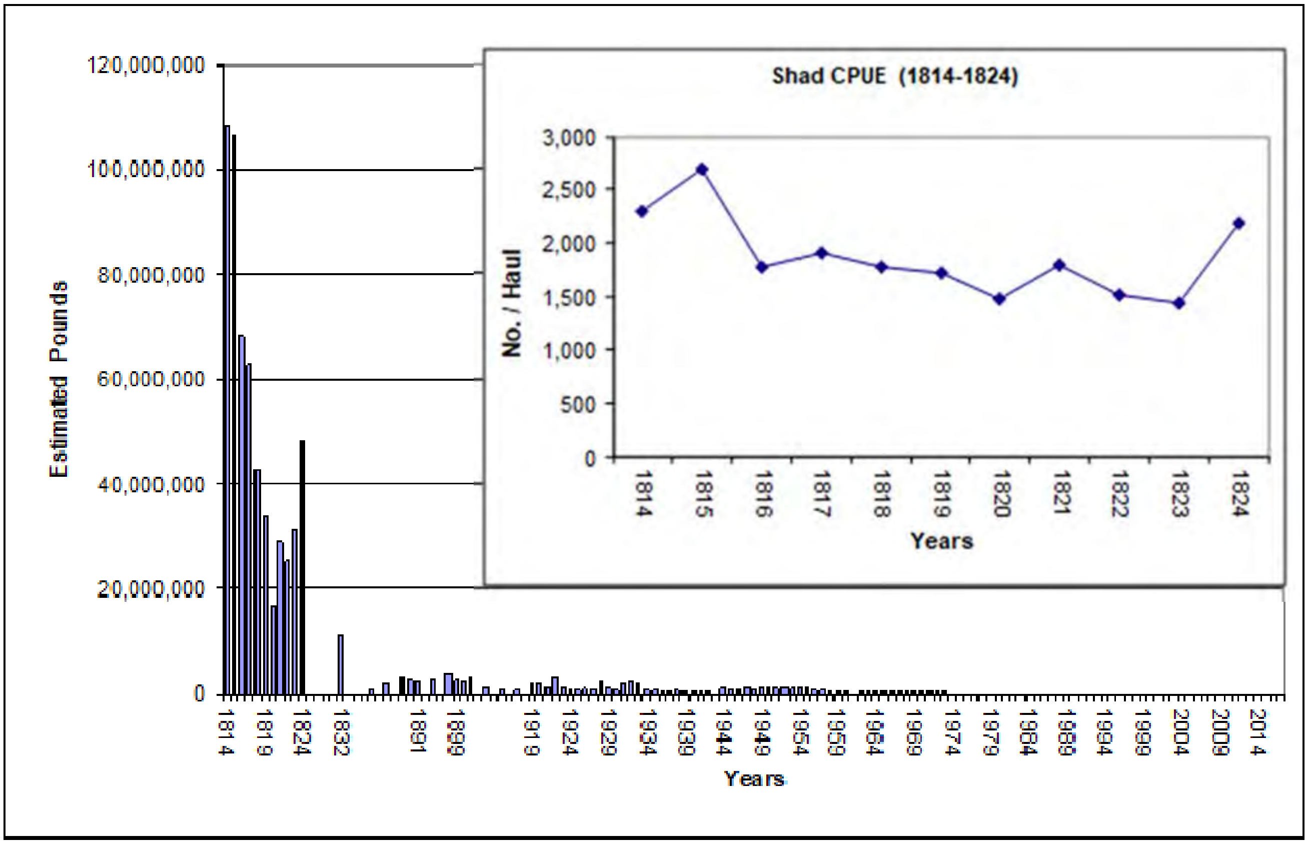


Figure 182. Historical American shad landings (lbs) and CPUE (inset) in the Potomac River, 1814-2017. The 1814-1818 landings are only a representative estimate based on an expansion of the detailed records of one haul seine fishery. The CPUE inset is from the same records (Massman 1961). Numbers of fish were converted to pounds for the 1932 data. The 1898-1900 data come from *This Was Potomac* by Tilp (1978).

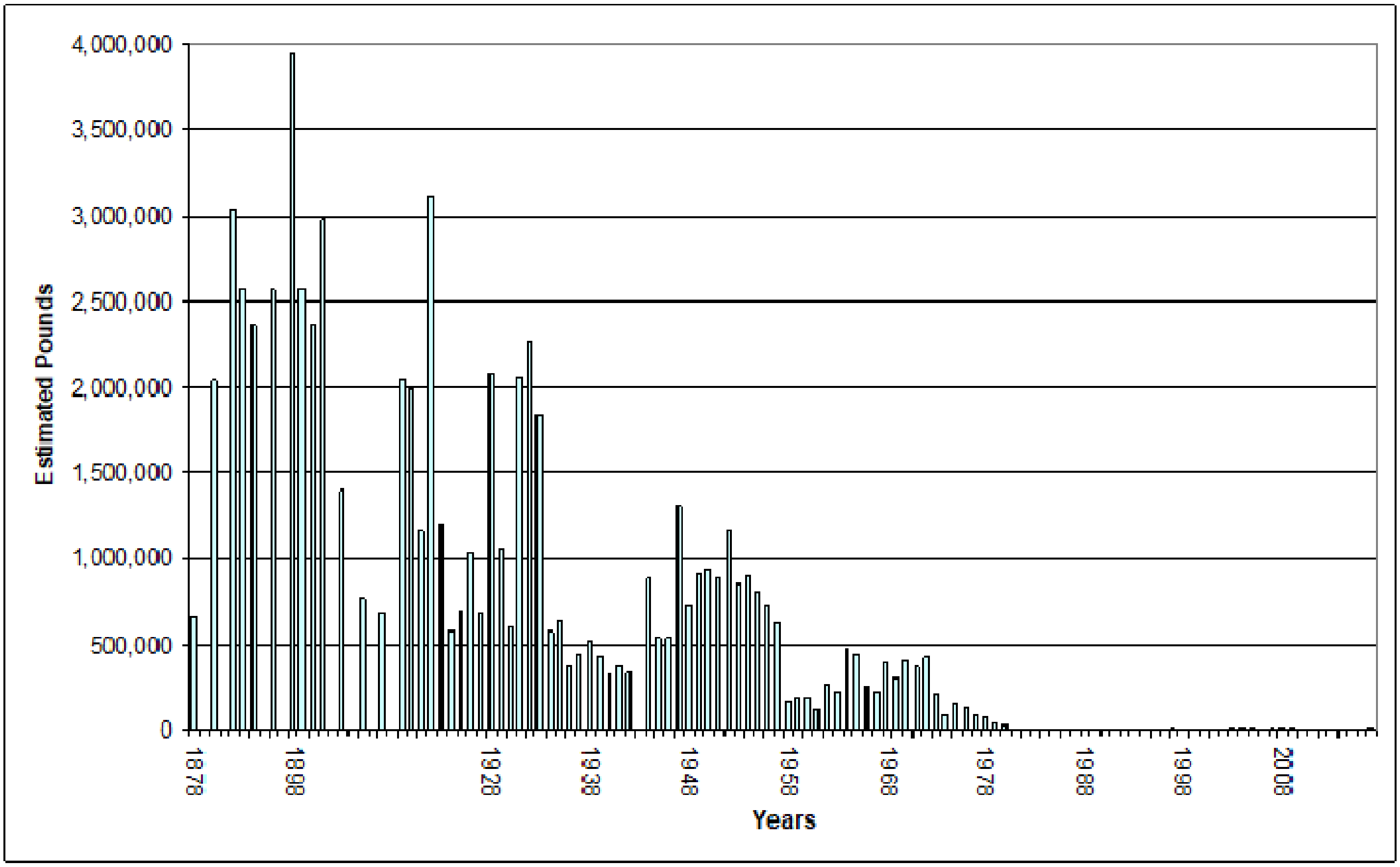


Figure 183. Historical American shad landings (lbs) from the Potomac River, 1878-2017. The 1878-1963 landings are from the *U.S. Commission of Fish* & *Fisheries*. The 1964-2017 harvest data are from PRFC.

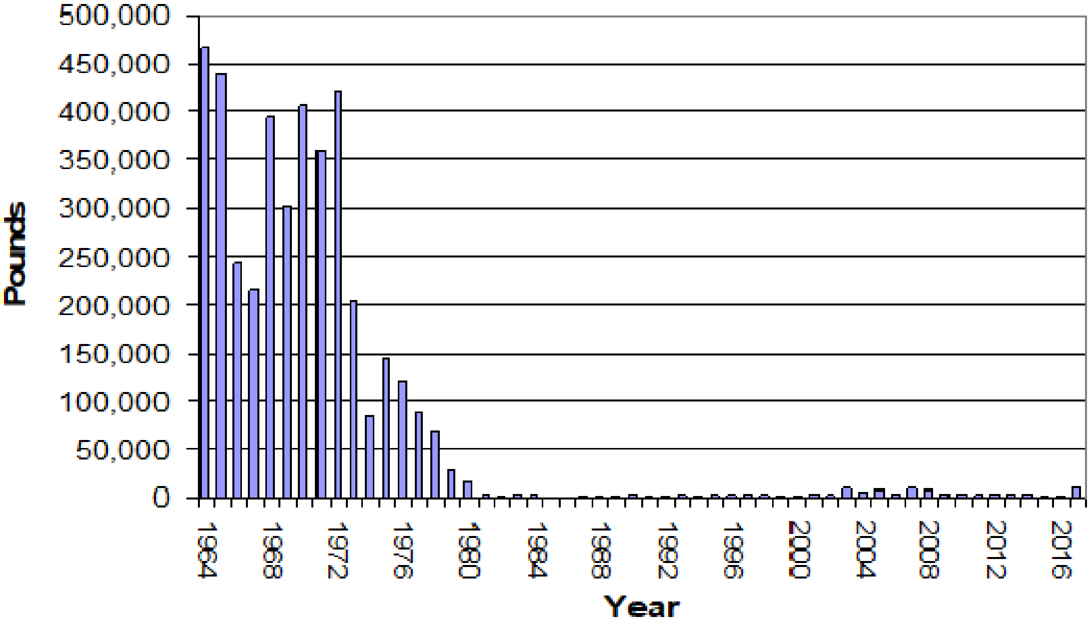


Figure 184. Potomac River American shad commercial harvest data, 1964-2017. (Source: PRFC)

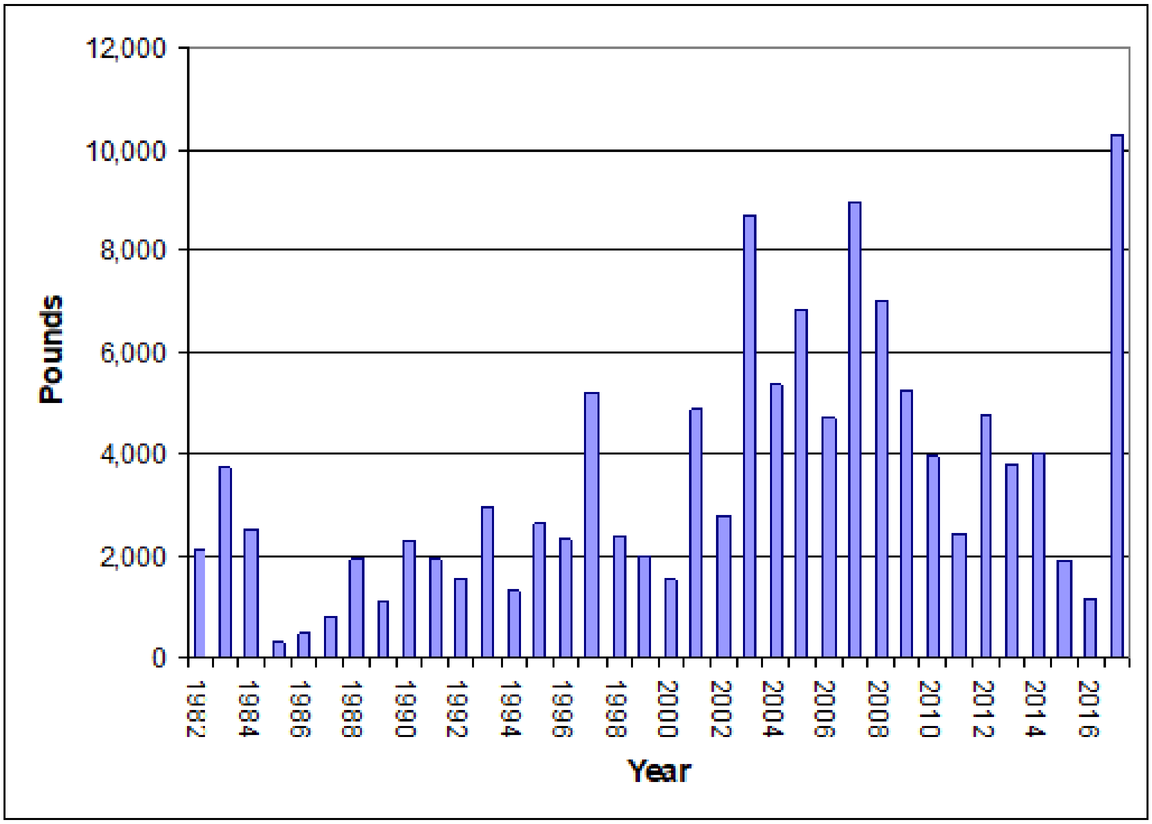


Figure 185. **Potomac River American shad commercial bycatch harvest data, 1982-2017.(Source: PRFC)**

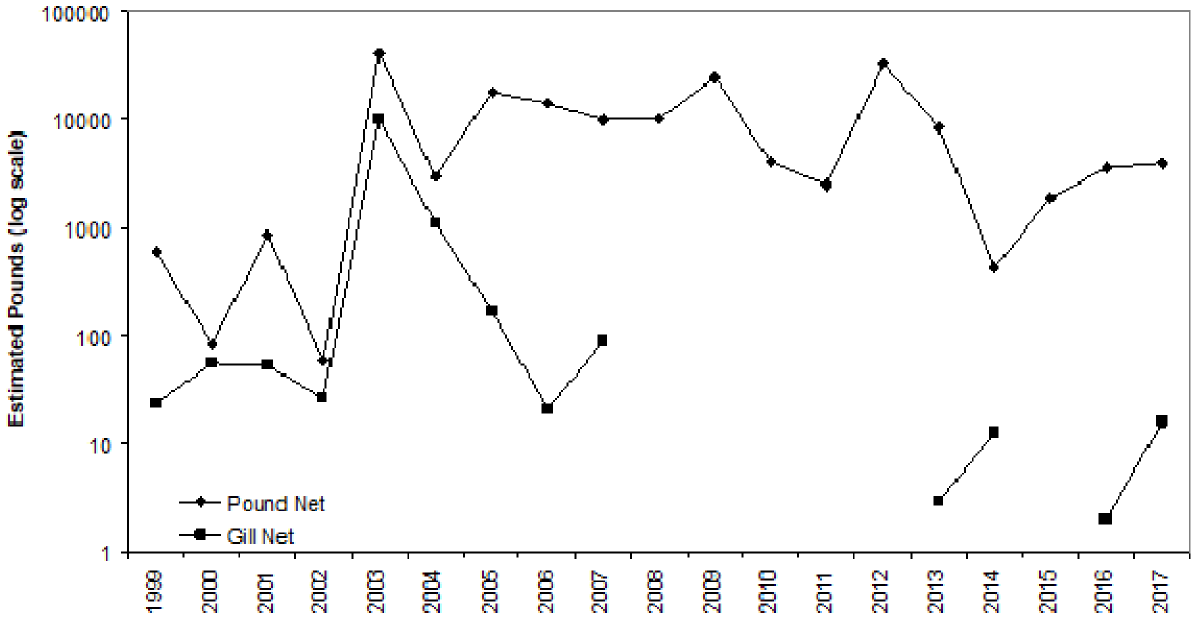


Figure 186. Potomac River American shad commercial discard/release (lbs) data (log scale), 1999-2017. (Source: PRFC)

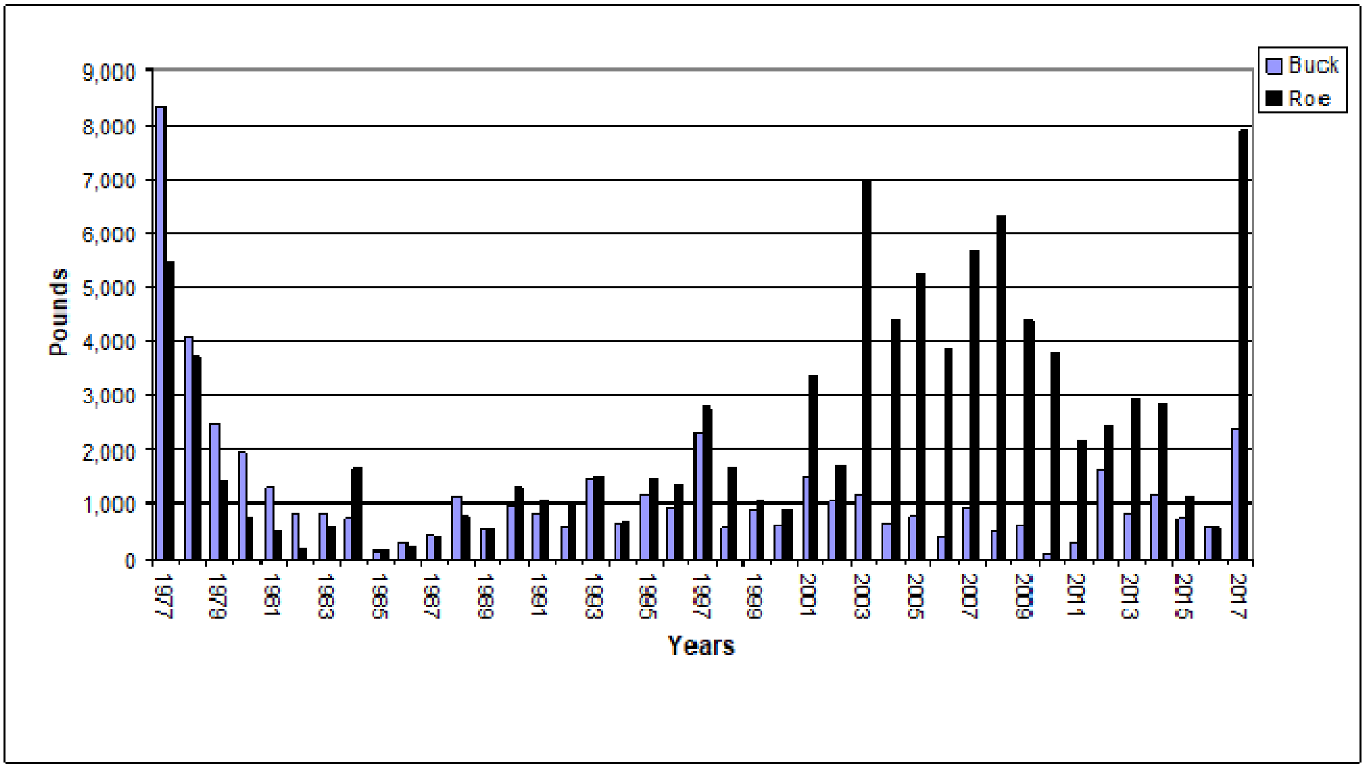


Figure 187. Potomac River American shad commercial pound net harvest (lbs) by sex, 1976-2017. Harvest from 1982 forward are bycatch. (Source: PRFC)

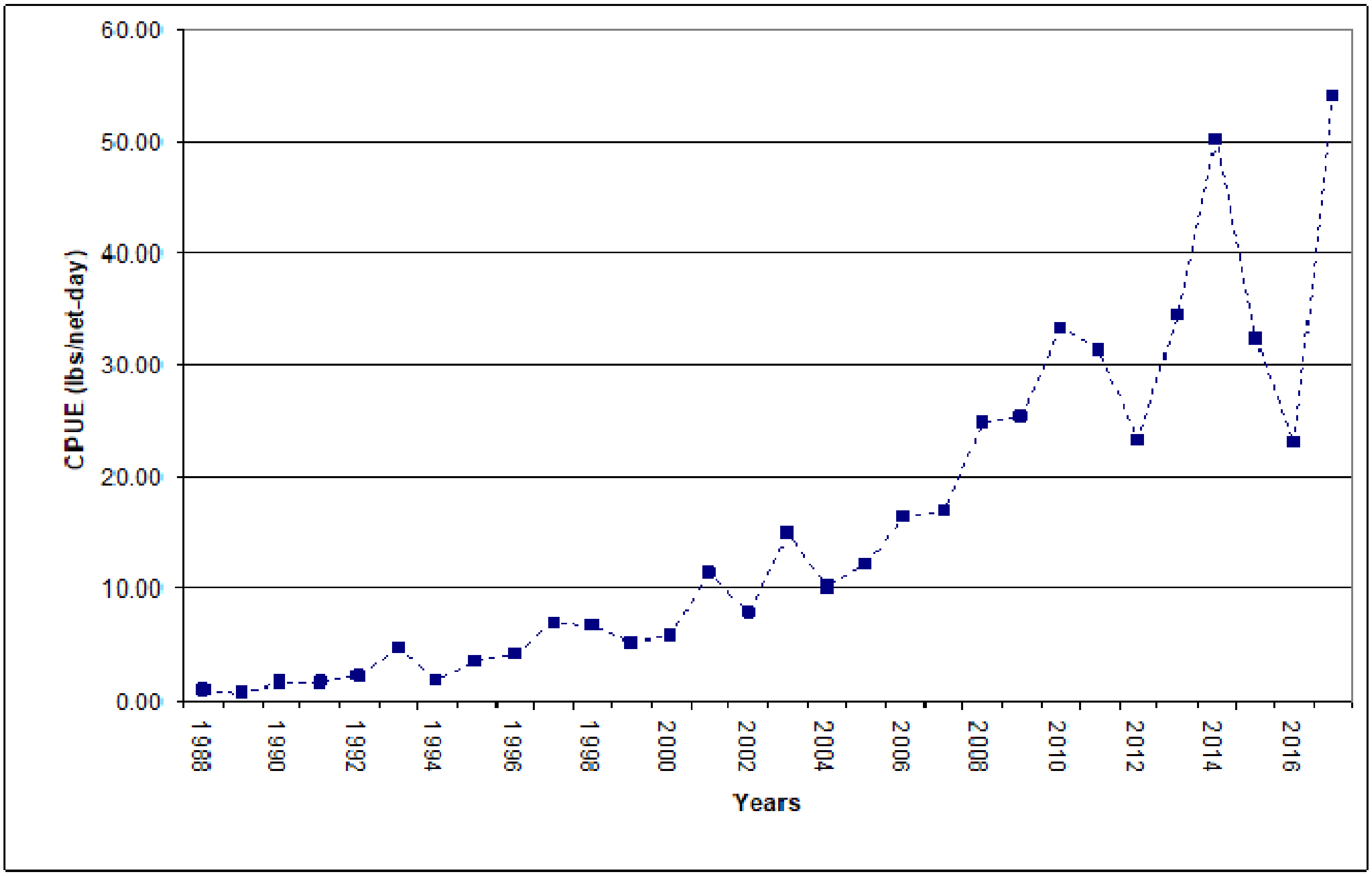


Figure 188. Potomac River American shad commercial pound net bycatch only index (pounds/net-day), 1988-2017. (Source: PRFC)

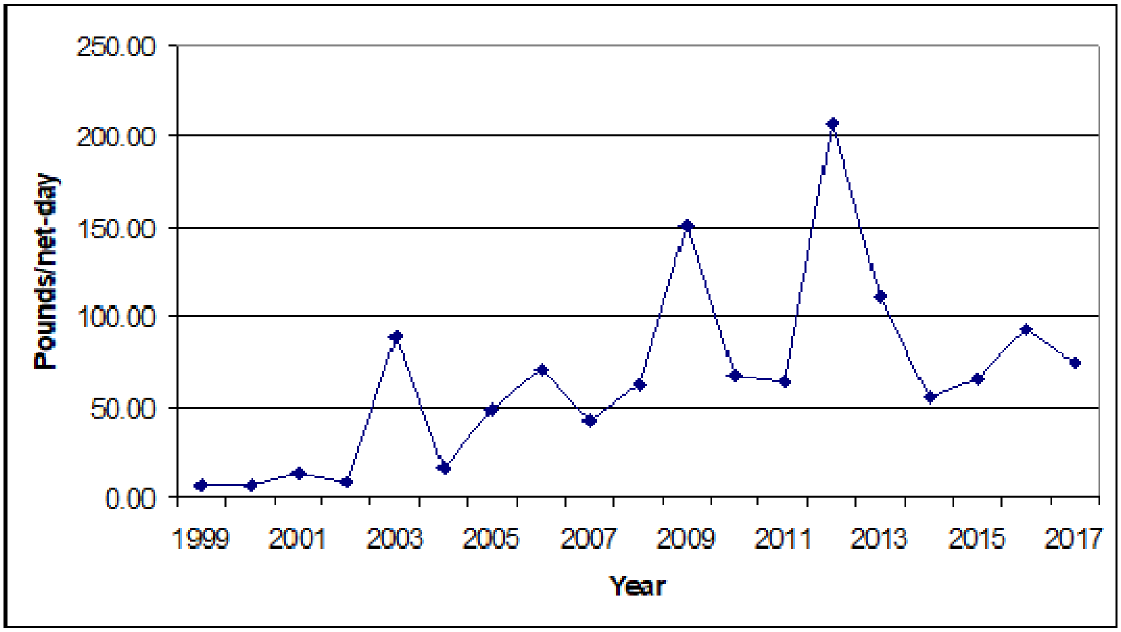


Figure 189. Potomac River Commercial Pound Net CPUE (bycatch plus discards) index, 1999-2017. (Source: PRFC)

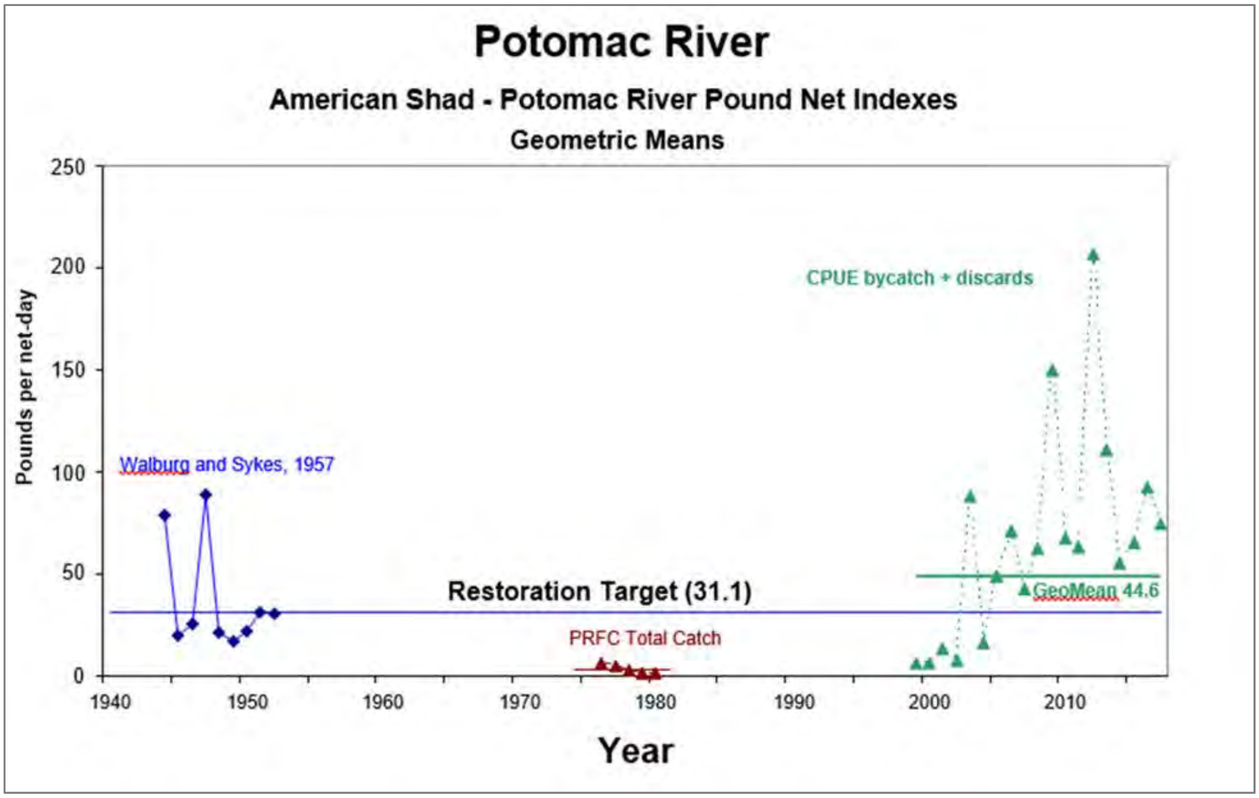


Figure 190. Catch indices of historic pound net data from the 1940s through 1950s (Walburg and Sykes), 1970s (PRFC), and current monitoring (PRFC). Horizontal lines are the geometric means of each data set.

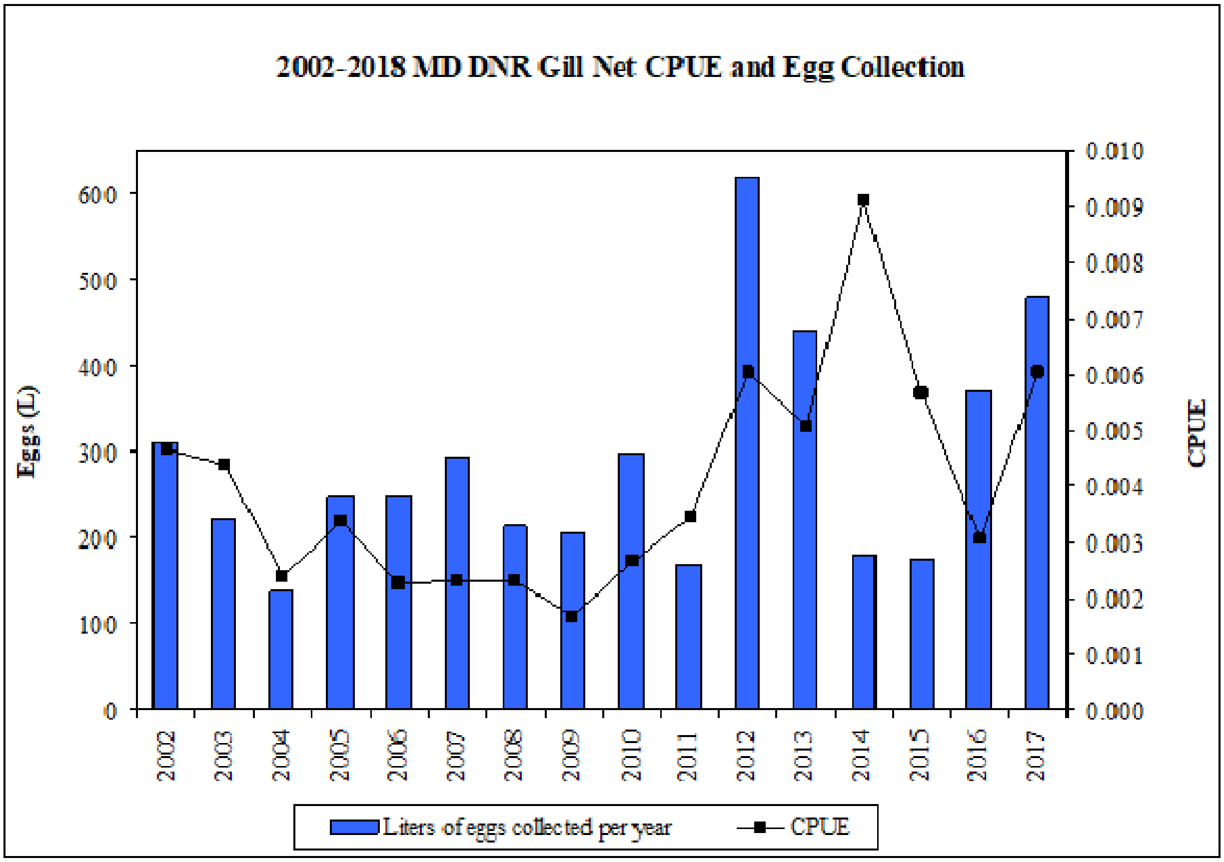


Figure 191. MD DNR American shad gill net CPUE (fish per day per net square footage) and American shad egg collection data, 2002-2017. (Source: MD DNR)

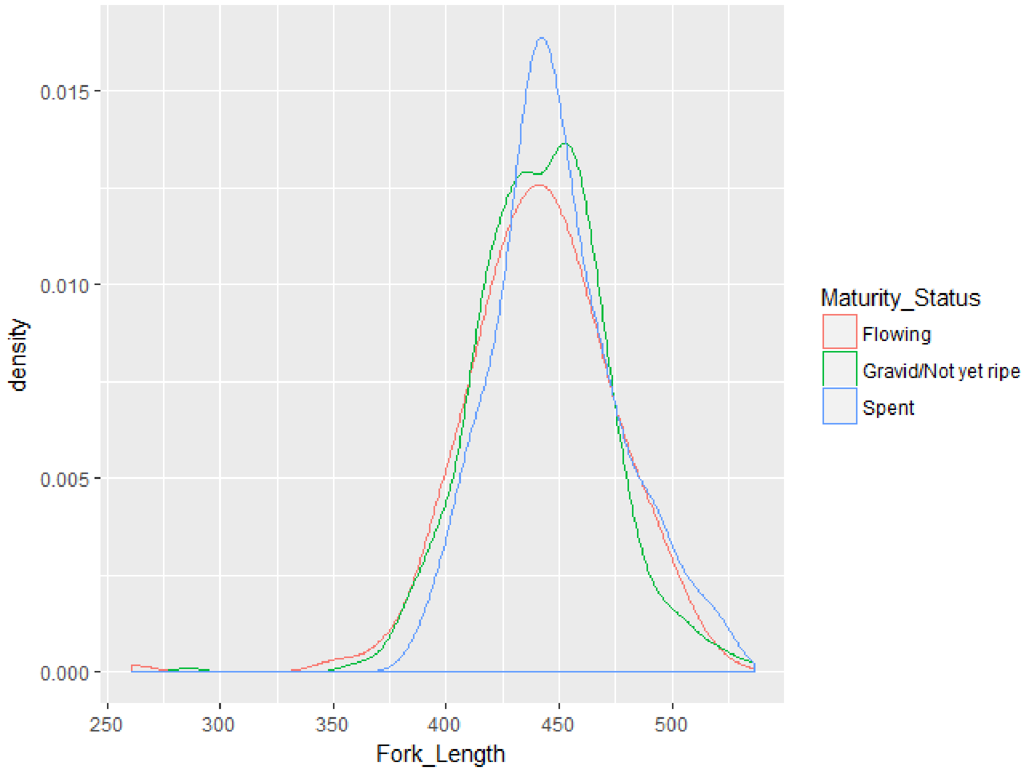


Figure 192. Potomac River Female American shad length distributions by maturity status.

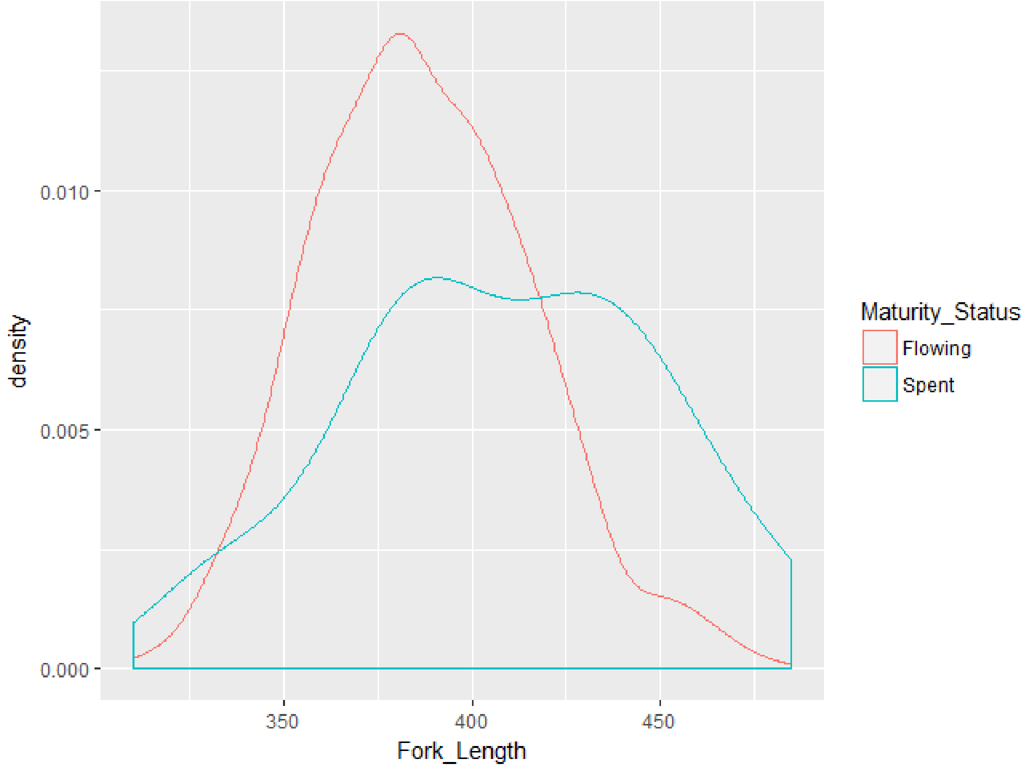


Figure 193. Potomac River Male American shad length distributions by maturity status.

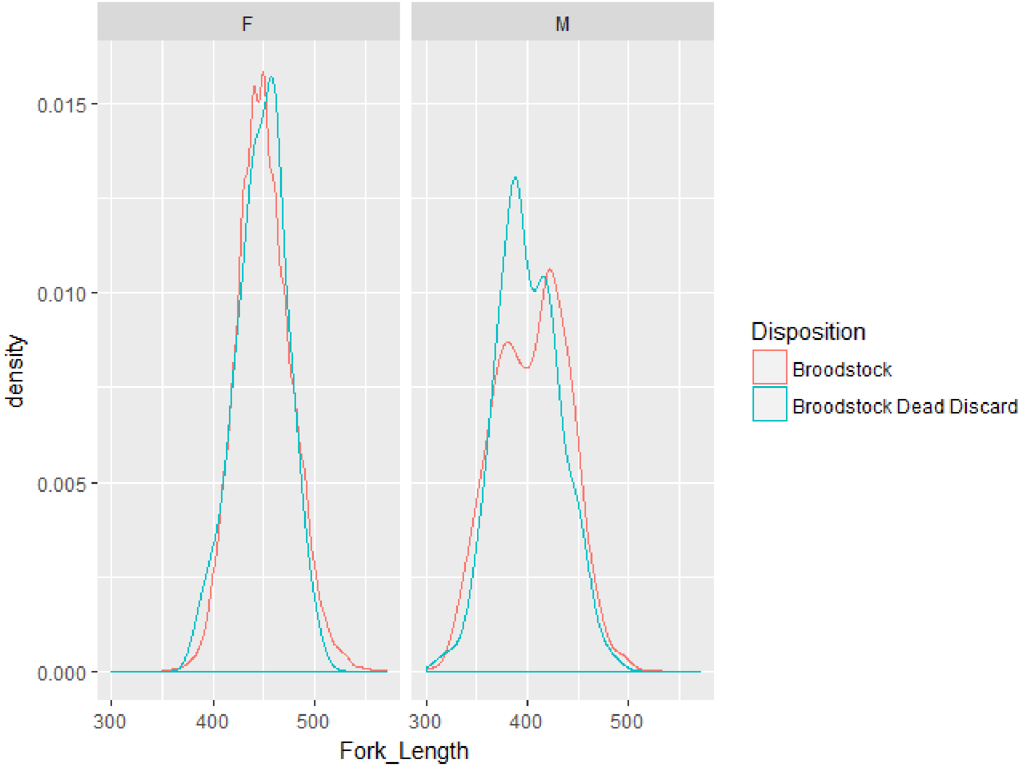


Figure 194. Potomac River broodstock American shad length distributions by sex and disposition.

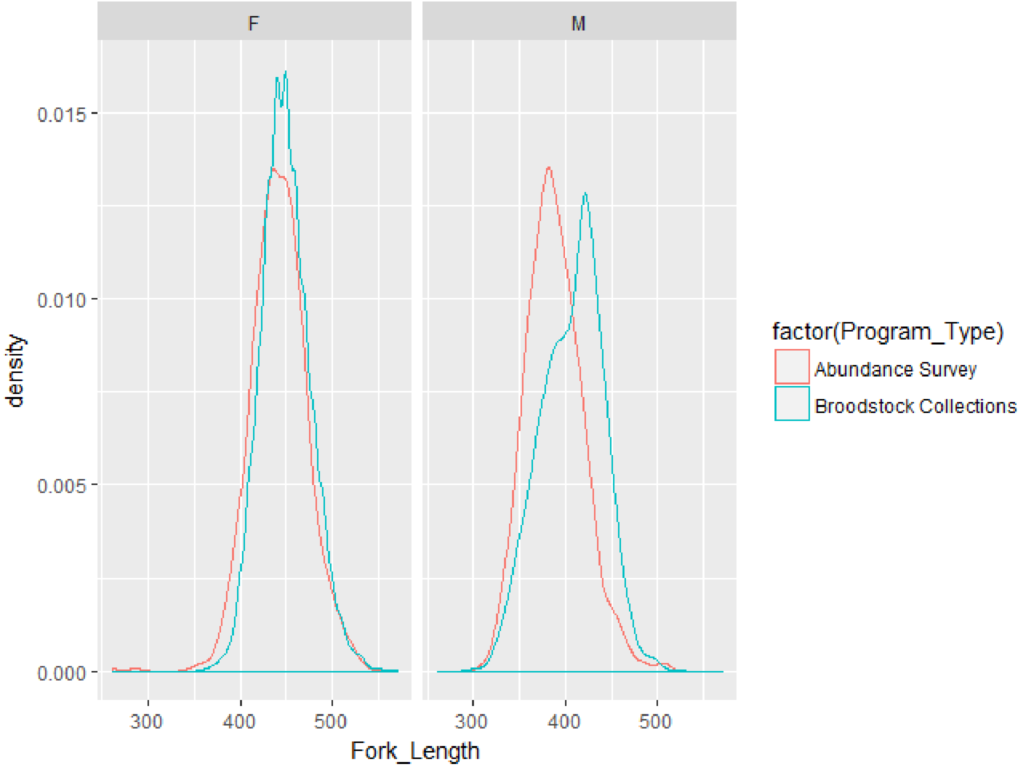


Figure 195. Potomac River American shad length distributions by sex and monitoring program type.

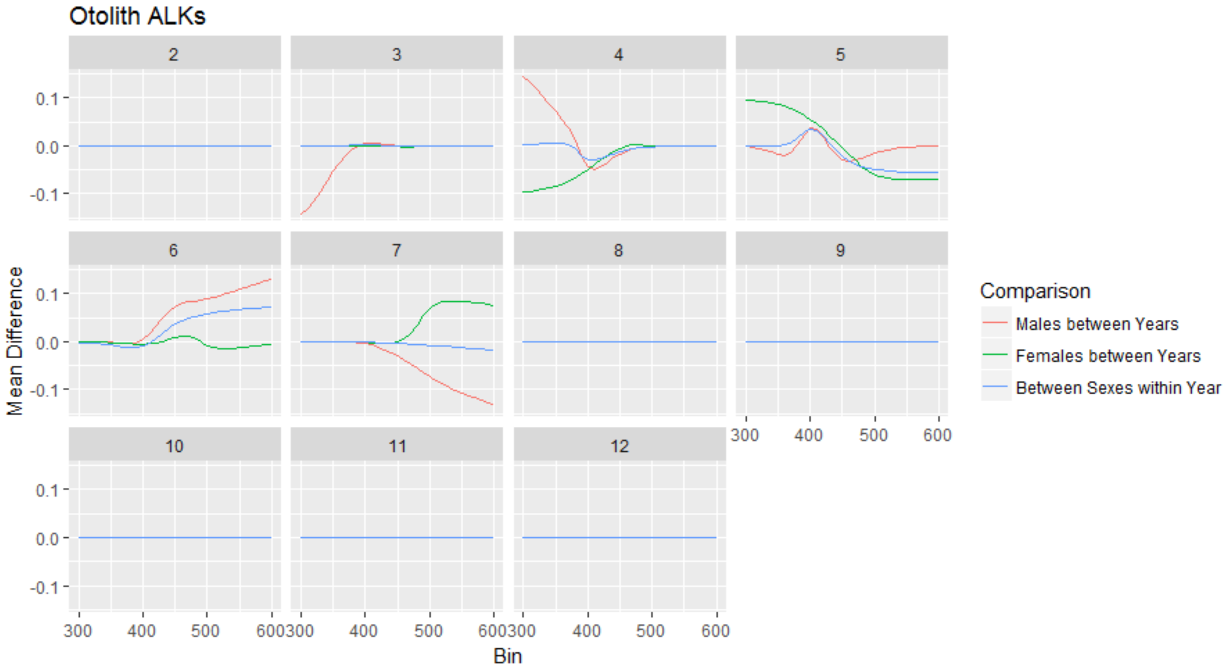


Figure 196. Mean differences of Potomac River American shad otolith age-length keys compared between years within sexes and between sexes within years.

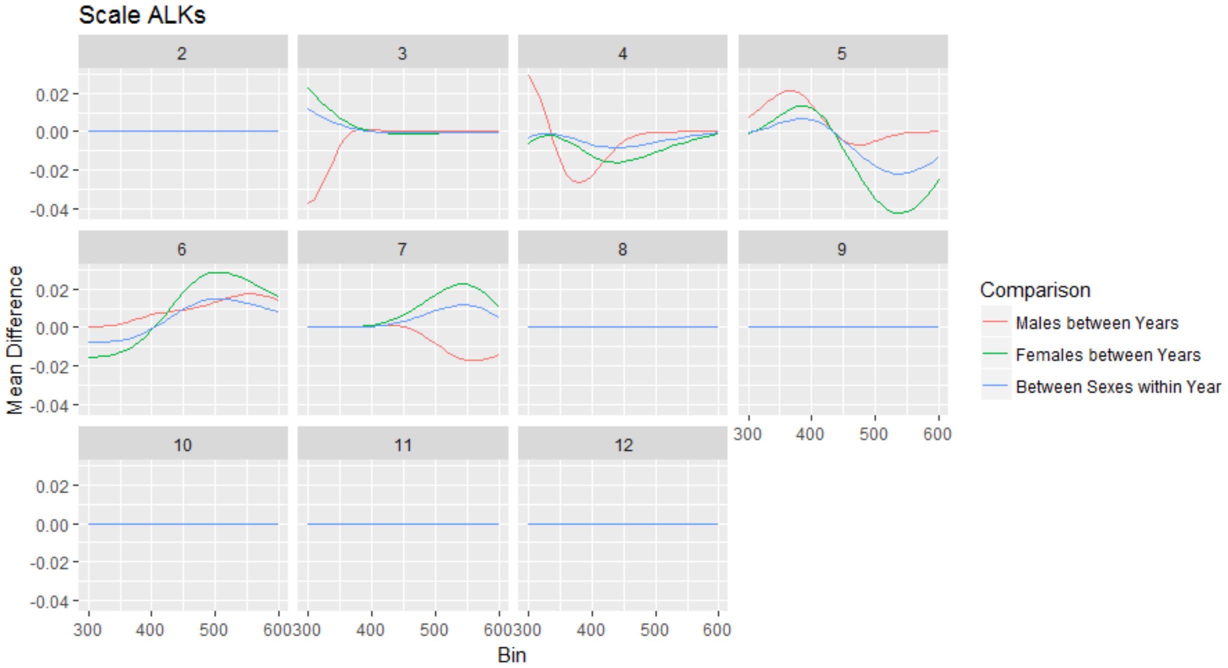


Figure 197. Mean differences of Potomac River American shad scale age-length keys compared between years within sexes and between sexes within years.

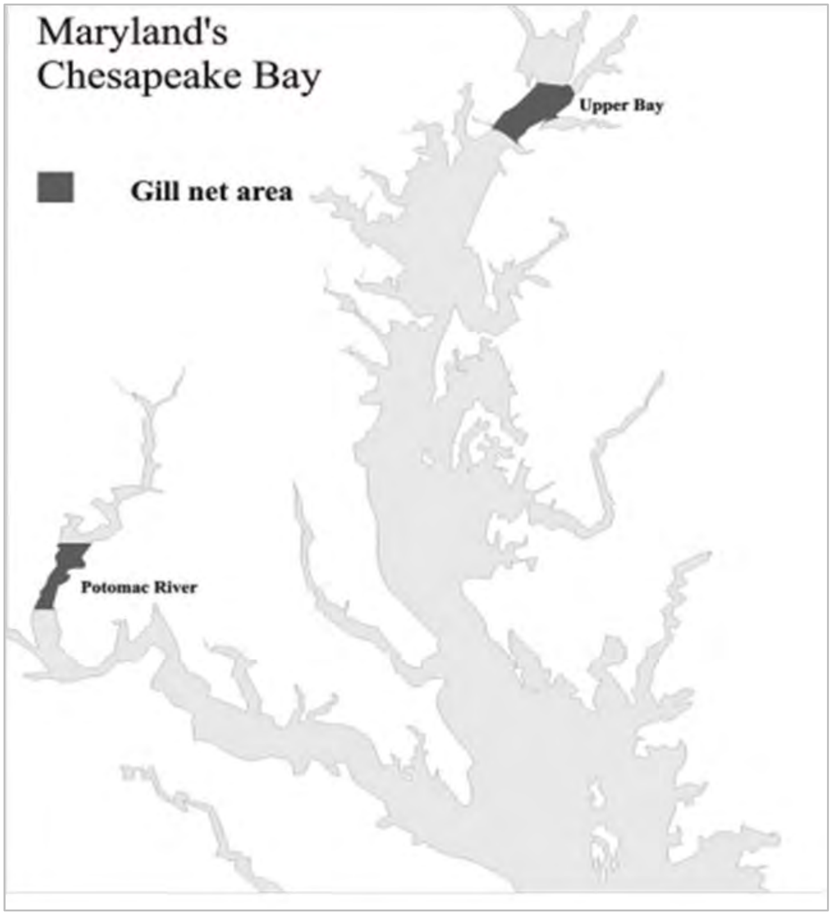


Figure 198. MD DNR Potomac River Striped Bass Spawning Stock Survey drift gill net sampling locations in the spawning areas of the Upper Chesapeake Bay and the Potomac River, late March-May.

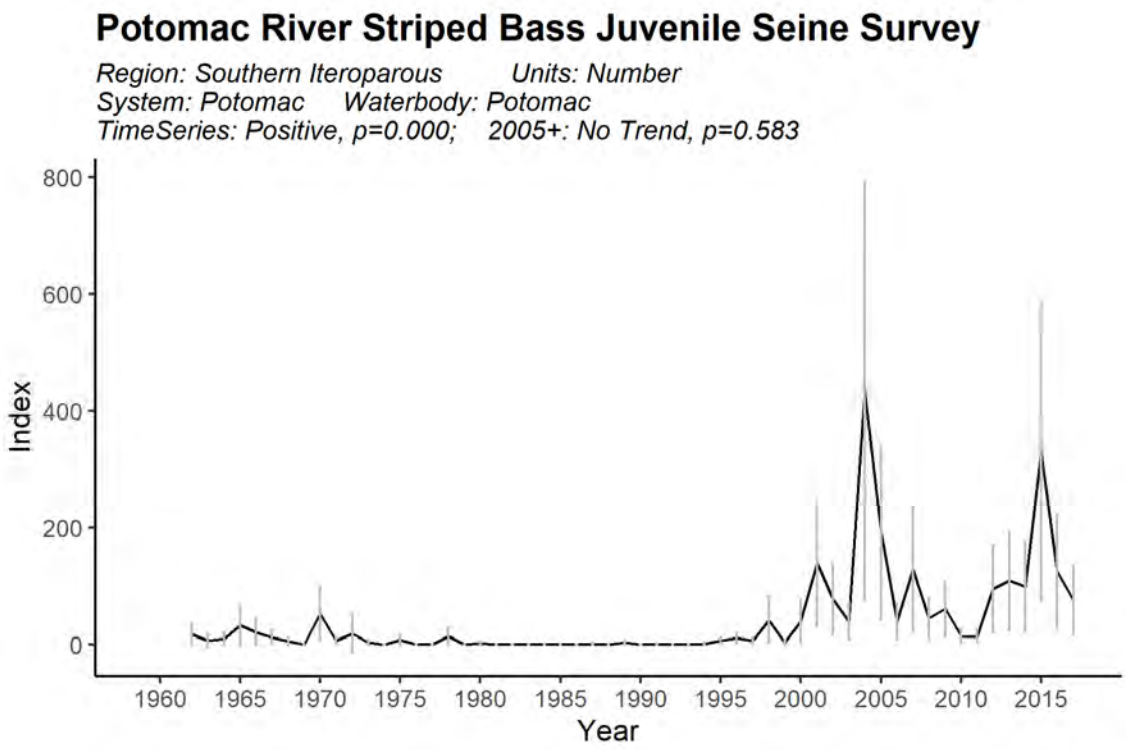


Figure 199. Potomac River Striped Bass Juvenile Seine Survey index and Mann-Kendall results.

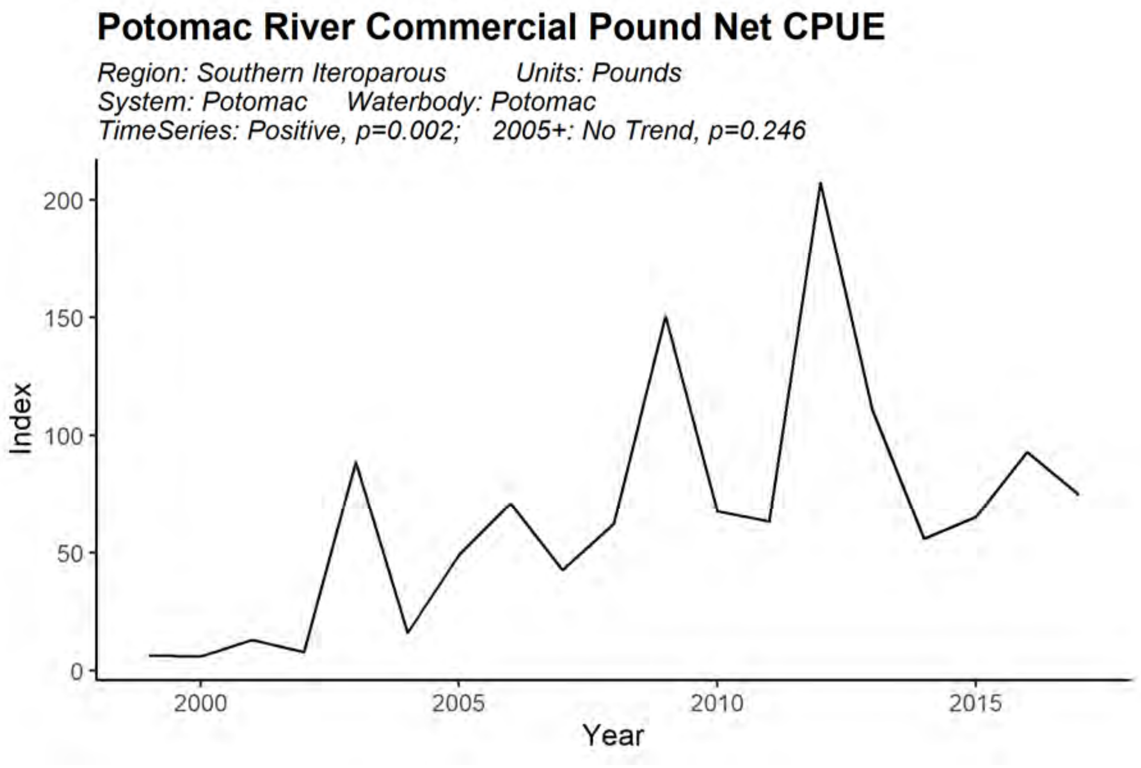


Figure 200. Potomac River Commercial Pound Net CPUE and Mann-Kendall results.

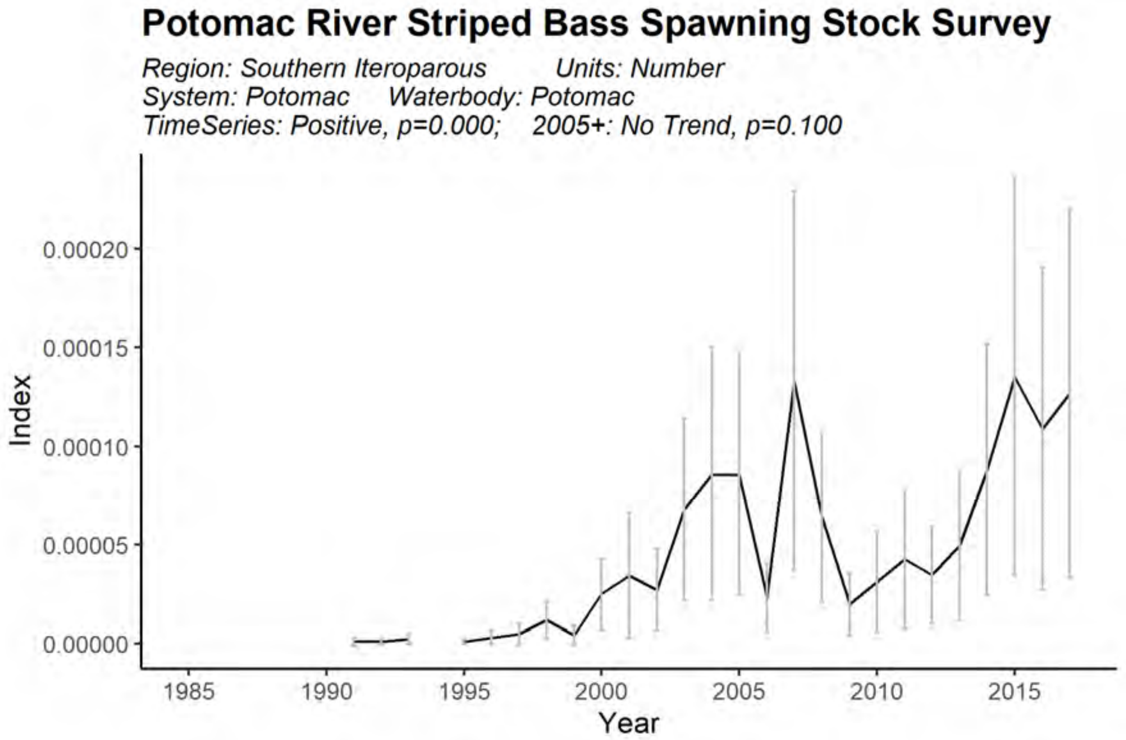


Figure 201. Potomac River Striped Bass Spawning Stock Survey index and Mann-Kendall results.

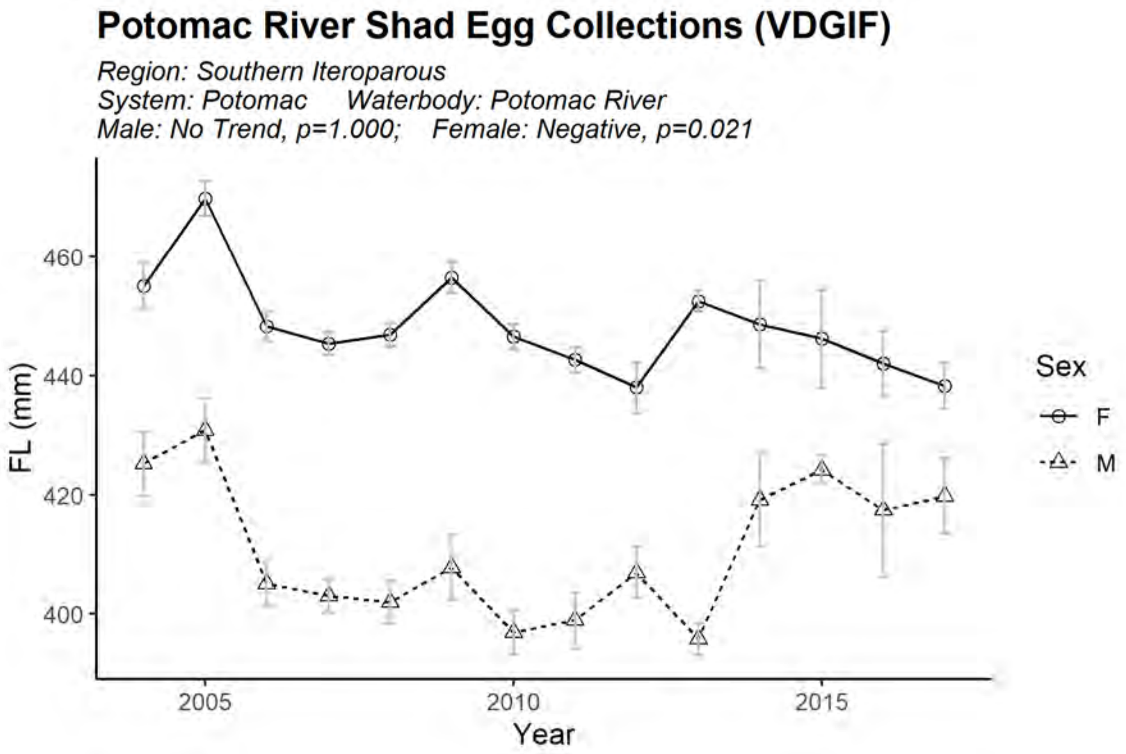


Figure 202. Mean length over time by sex for American shad sampled during Potomac River Shad Egg Collections (VDGIF) and Mann-Kendall results.

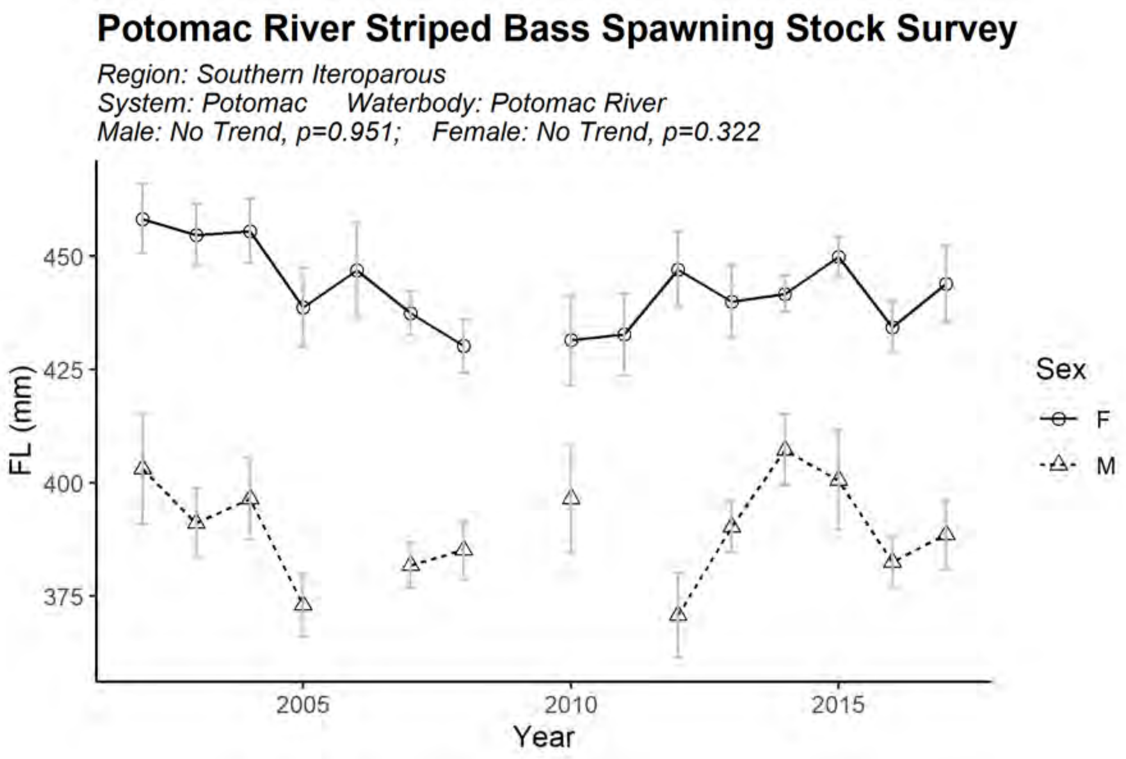


Figure 203. Mean length over time by sex of American shad sampled by the Potomac River Striped Bass Spawning Stock Survey and Mann Kendall results.

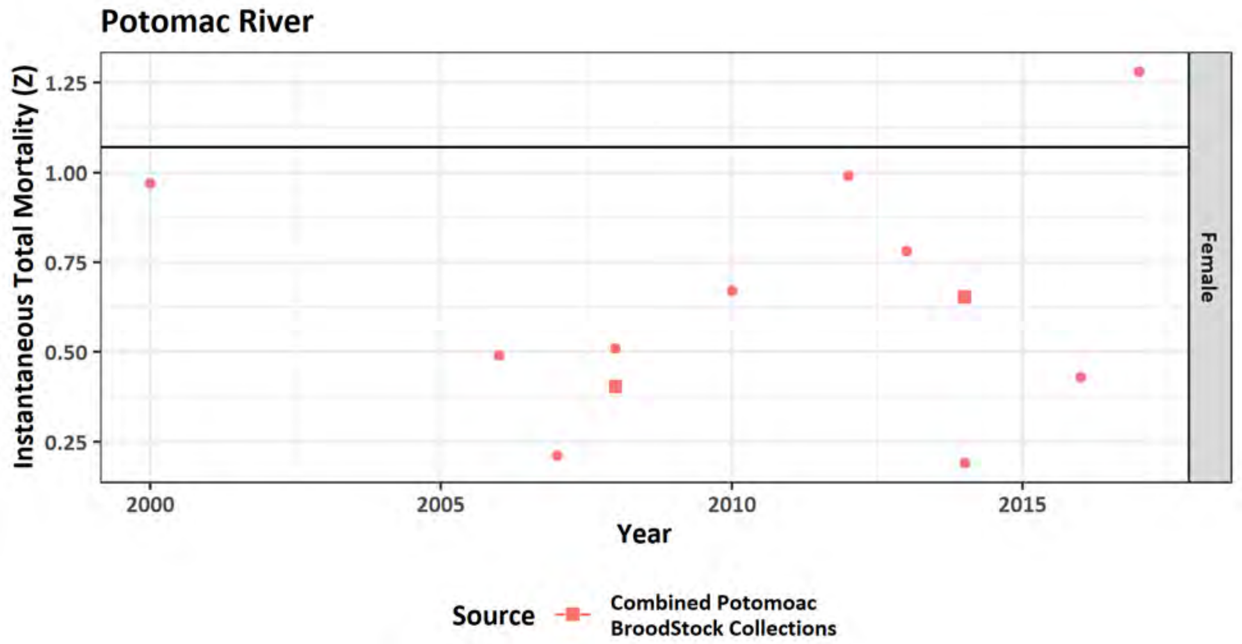


Figure 204. Three year average Z estimates via weighted linear regression by sex and monitoring program for the Potomac River System based on otolith-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual Z estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).

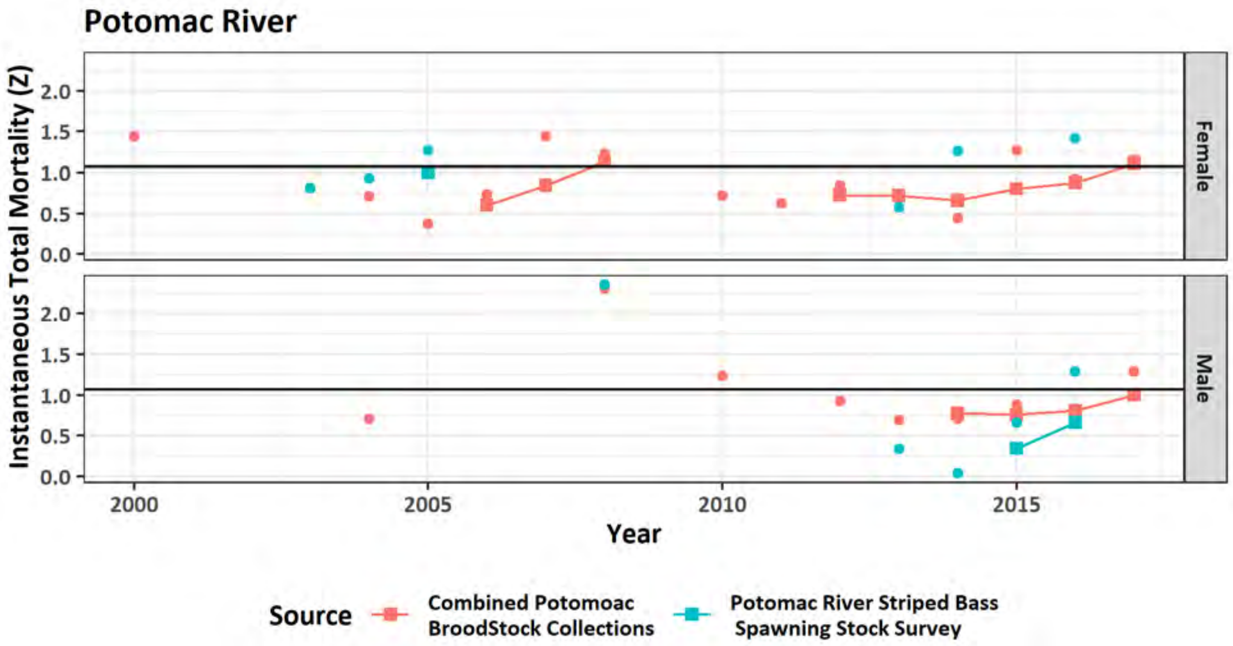


Figure 205. Three year average Z estimates via weighted linear regression by sex and monitoring program for the Potomac River System based on scale-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual Z estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).

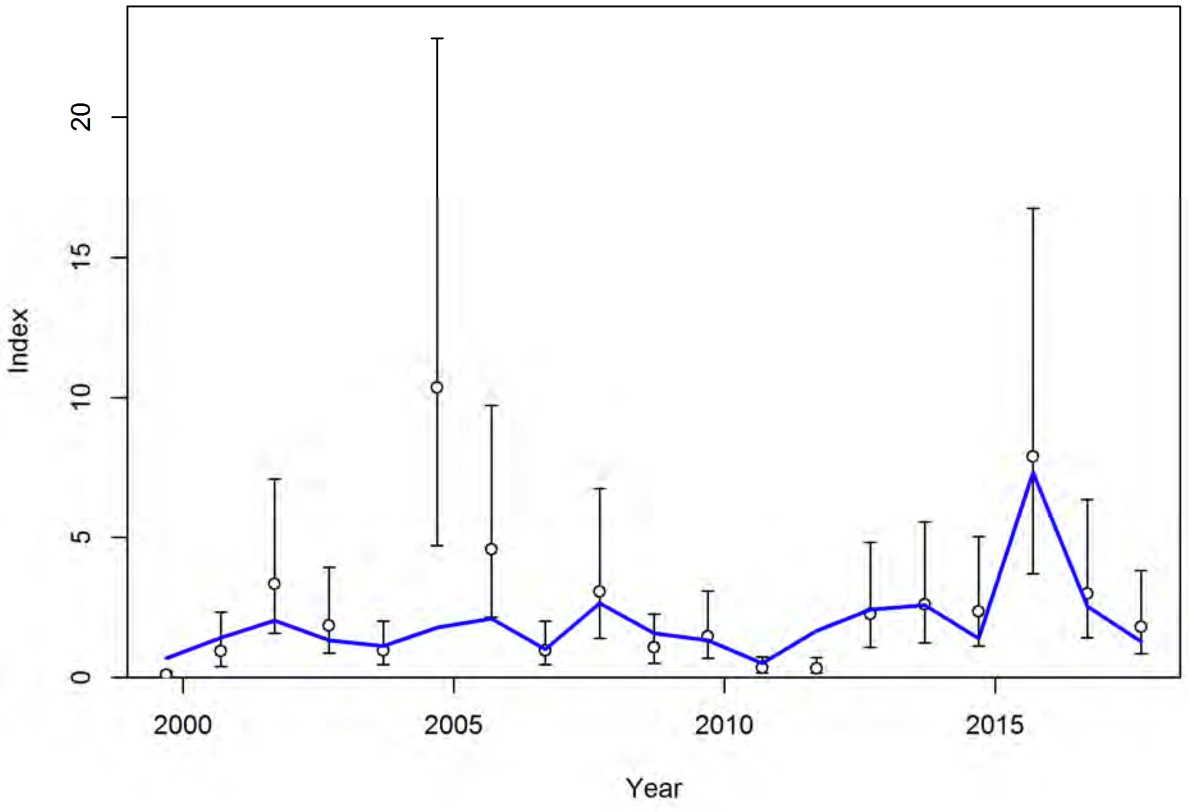


Figure 206. **Observed (circles) and Potomac SCAA model-predicted (blue line) index of abundance from the MD DNR Potomac River Striped Bass Juvenile Seine Survey. Error bars indicate input standard errors.**

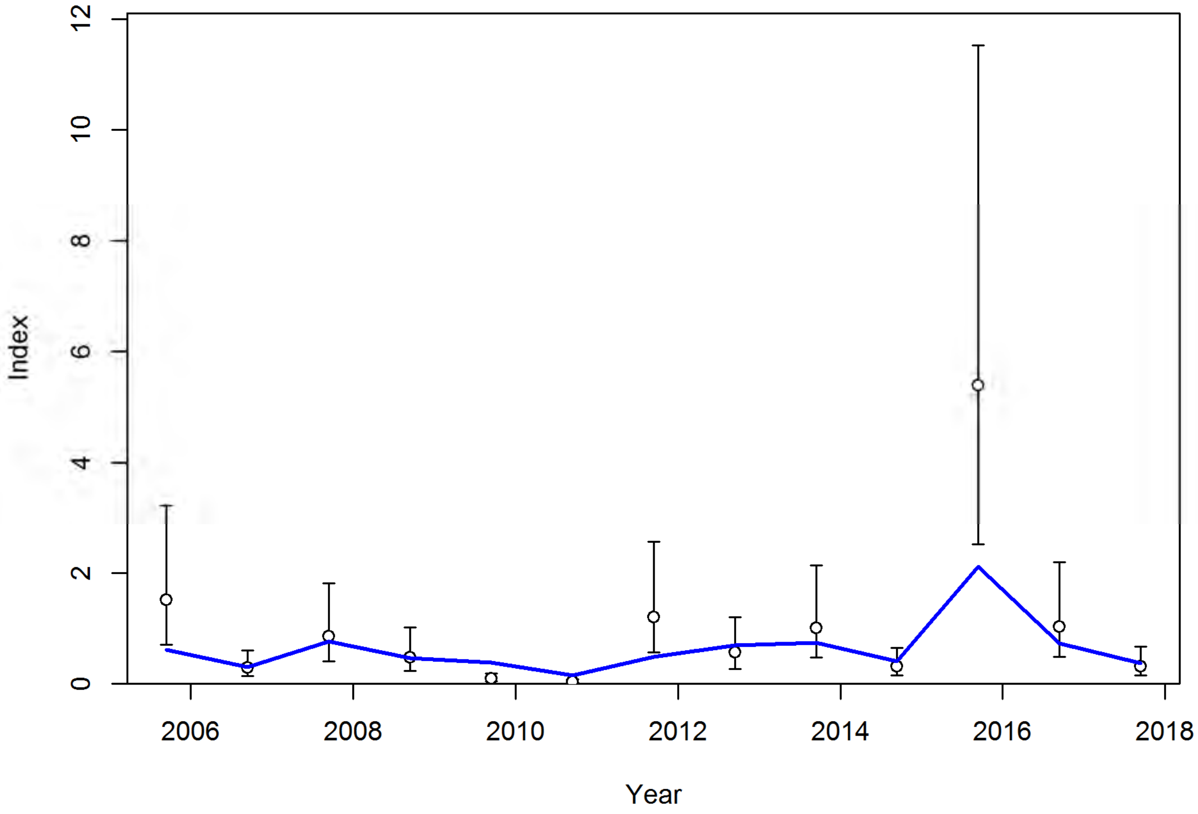


Figure 207. Observed (circles) and Potomac SCAA model-predicted (blue line) index of abundance from the DC DOEE Potomac River Juvenile Pushnet Survey. Error bars indicate input standard errors.

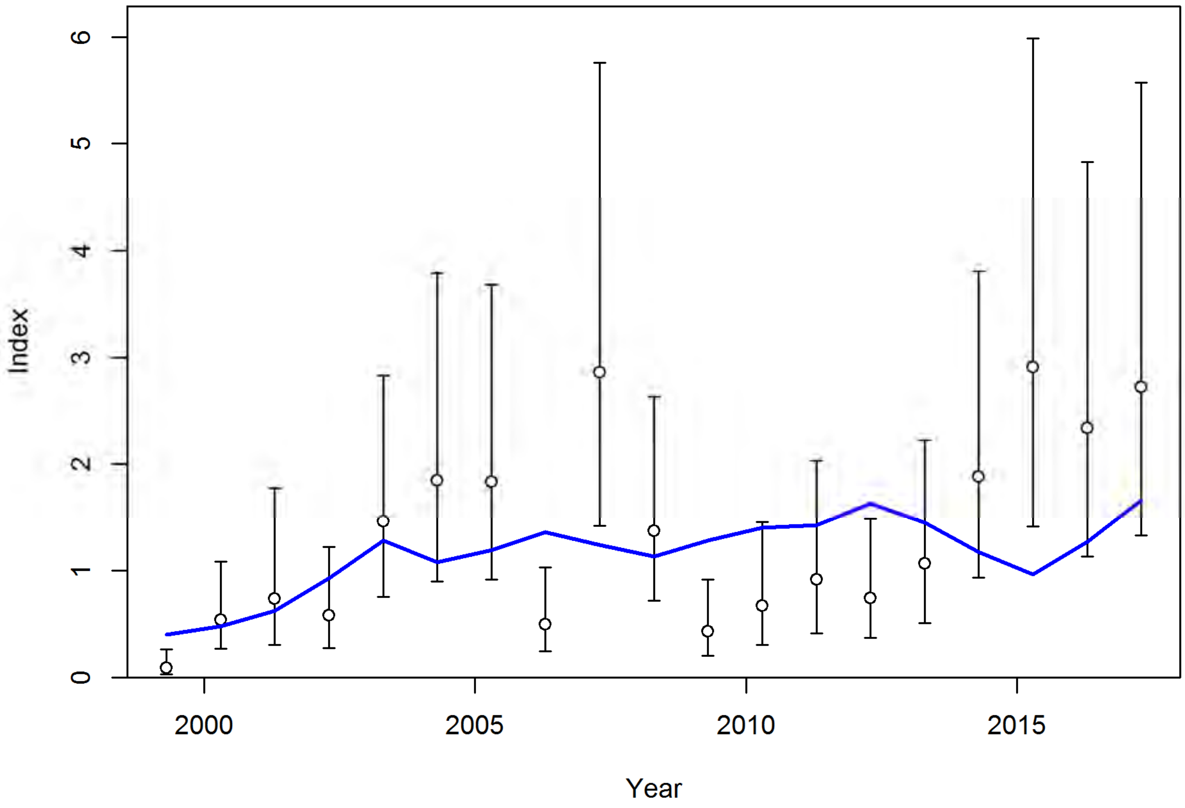


Figure 208. Observed (circles) and Potomac SCAA model-predicted (blue line) index of abundance from the MD DNR Potomac River Striped Bass Spawning Stock Survey. Error bars indicate input standard errors.

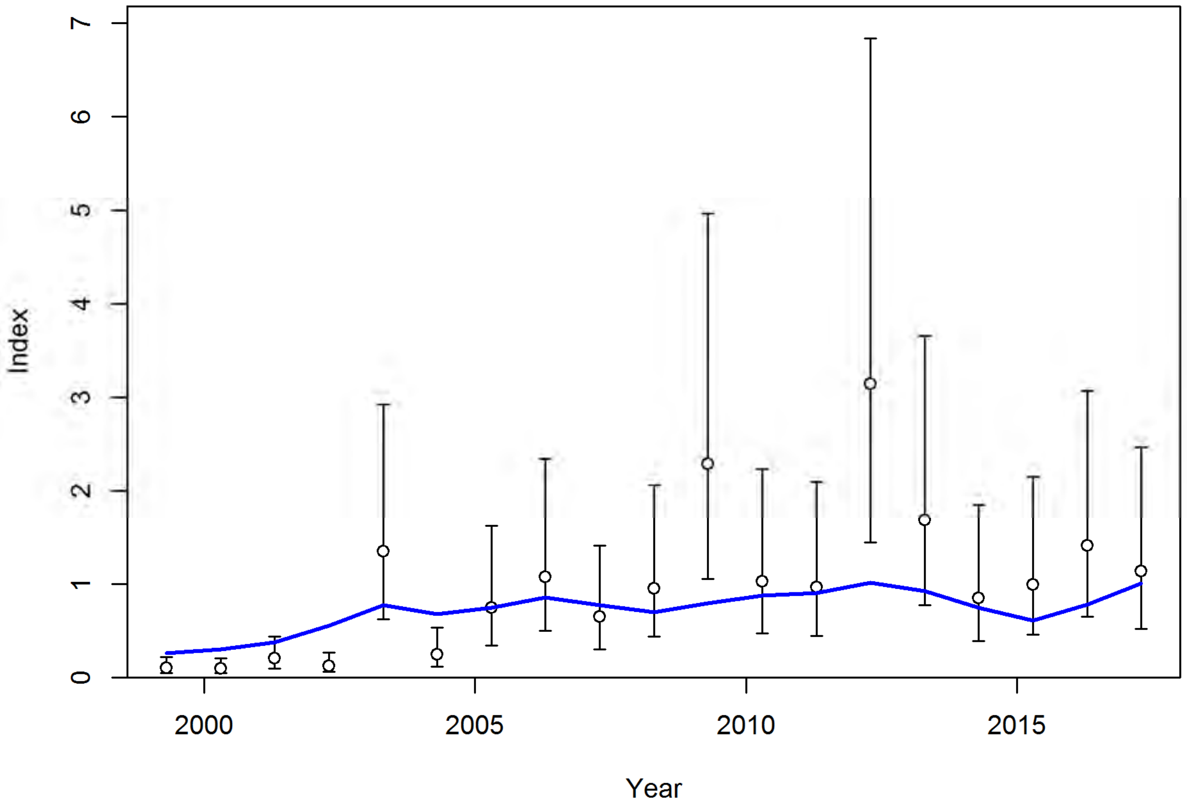


Figure 209. Observed (circles) and Potomac SCAA model-predicted (blue line) PRFC Potomac River Commercial Pound Net CPUE. Error bars indicate input standard errors.

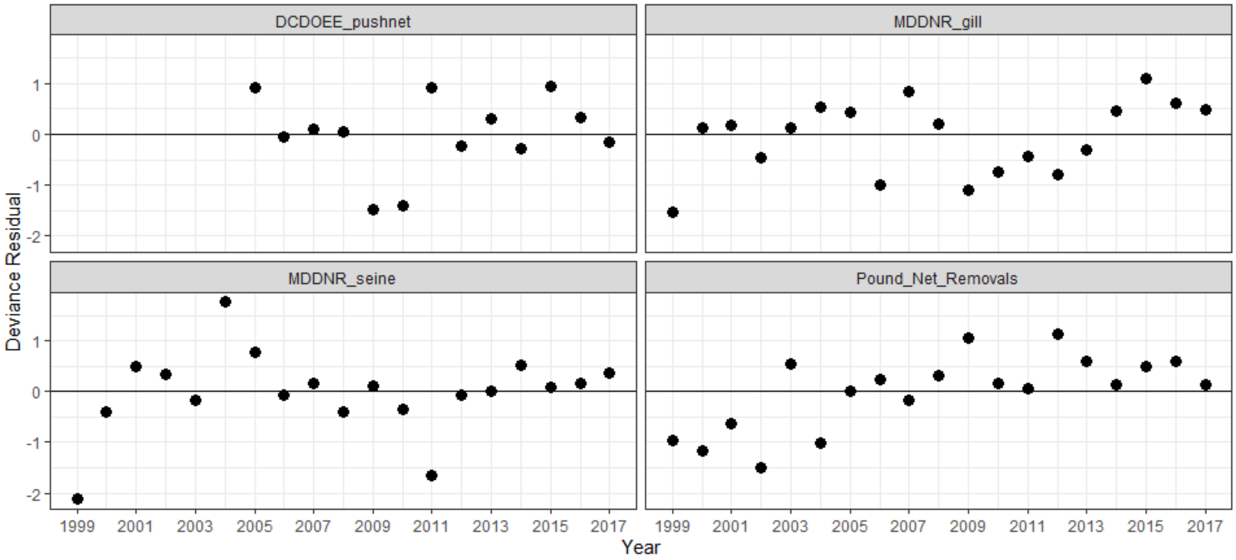


Figure 210. Deviance residuals from Potomac SCAA model fits to indices of abundance.

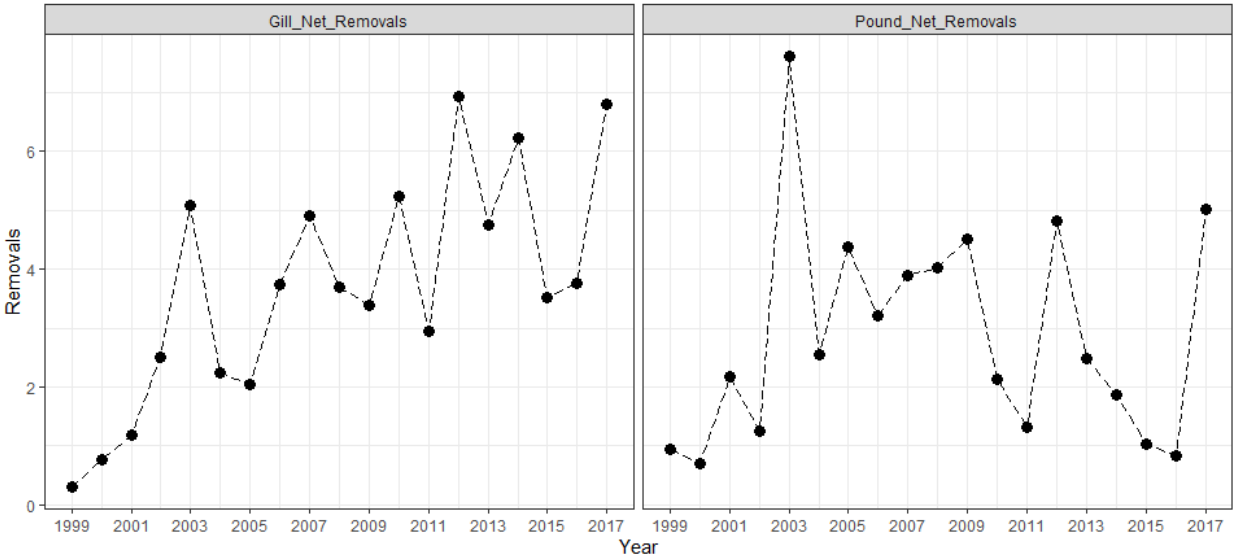


Figure 211. Observed (circles) and Potomac SCAA model-predicted (blue line) removals.

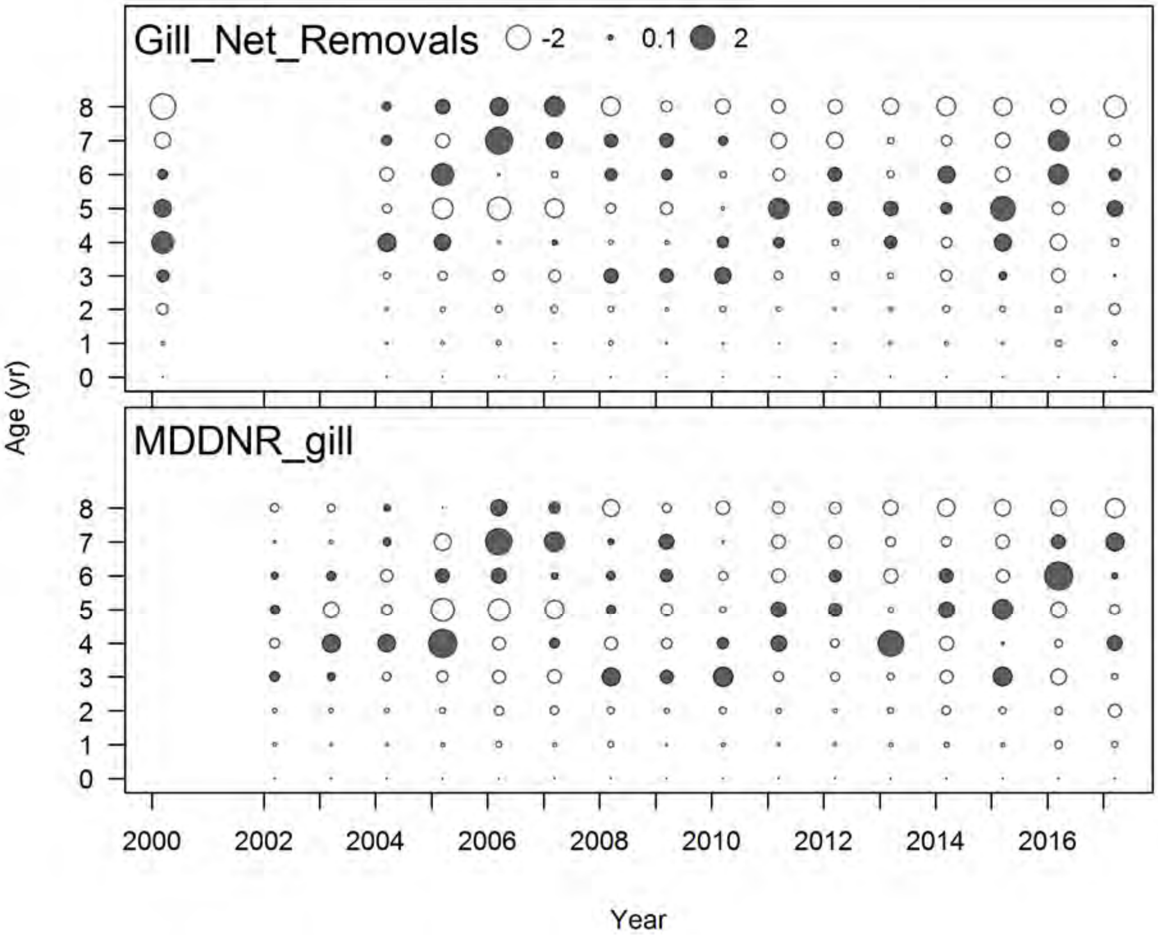


Figure 212. Pearson residuals from Potomac SCAA model fits to age composition data.

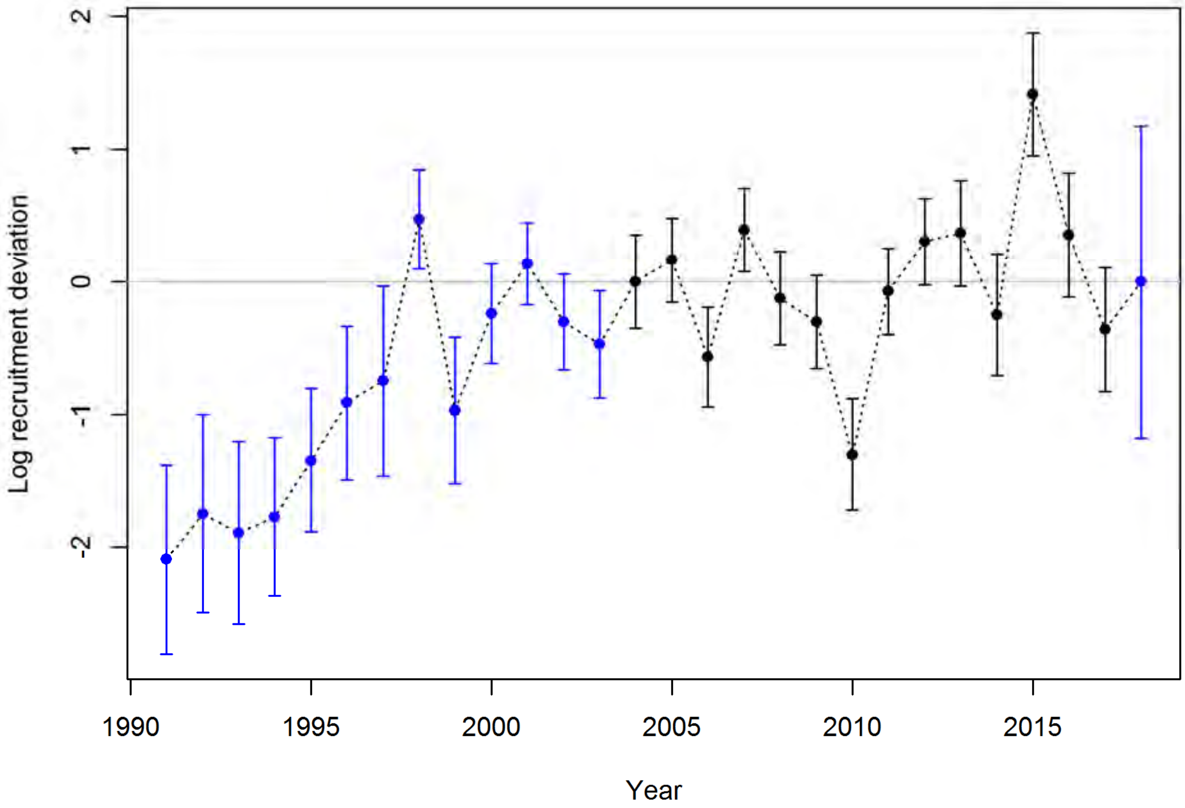


Figure 213. Potomac SCAA model recruitment deviations. Error bars indicate ± 1.96 asymptotic standard errors.

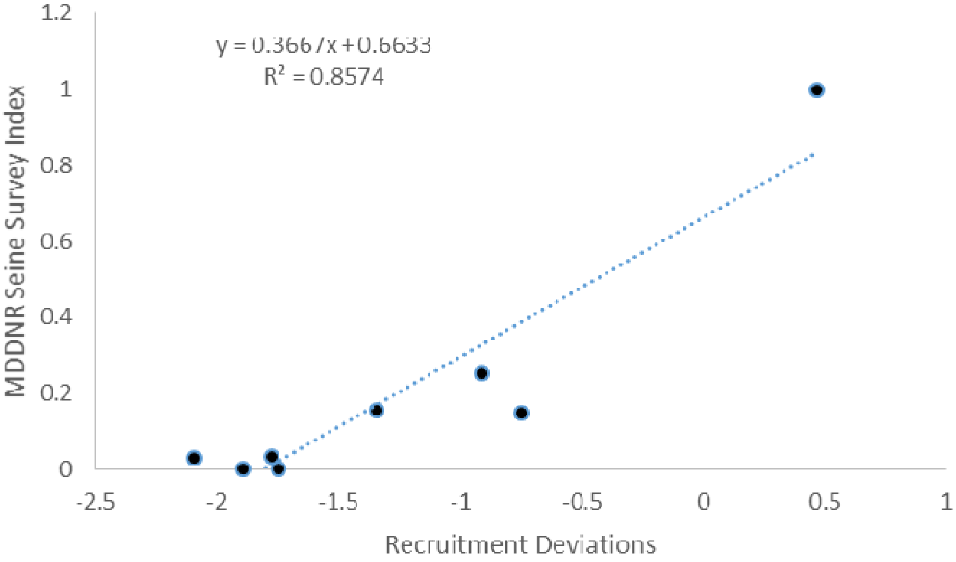


Figure 214. Results of regression between MDDNR Potomac River Striped Bass Juvenile Seine Survey index and Potomac SCAA model recruitment deviations.

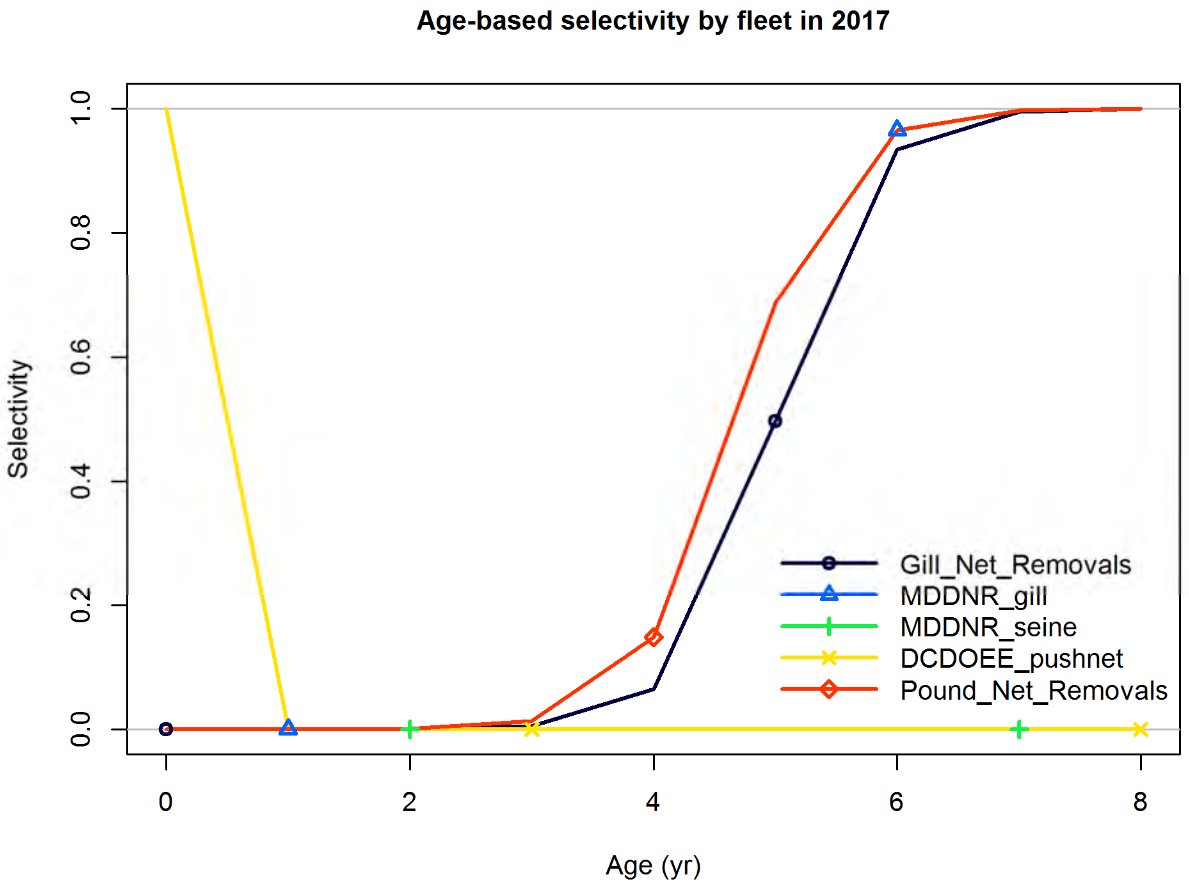


Figure 215. Potomac SCAA model selectivity estimates. Selectivity for the DC DOEE Potomac River Juvenile Pushnet Survey and MDDNR Potomac River Striped Bass Juvenile Seine Survey is fixed at one for age-0 and zero for all other ages.

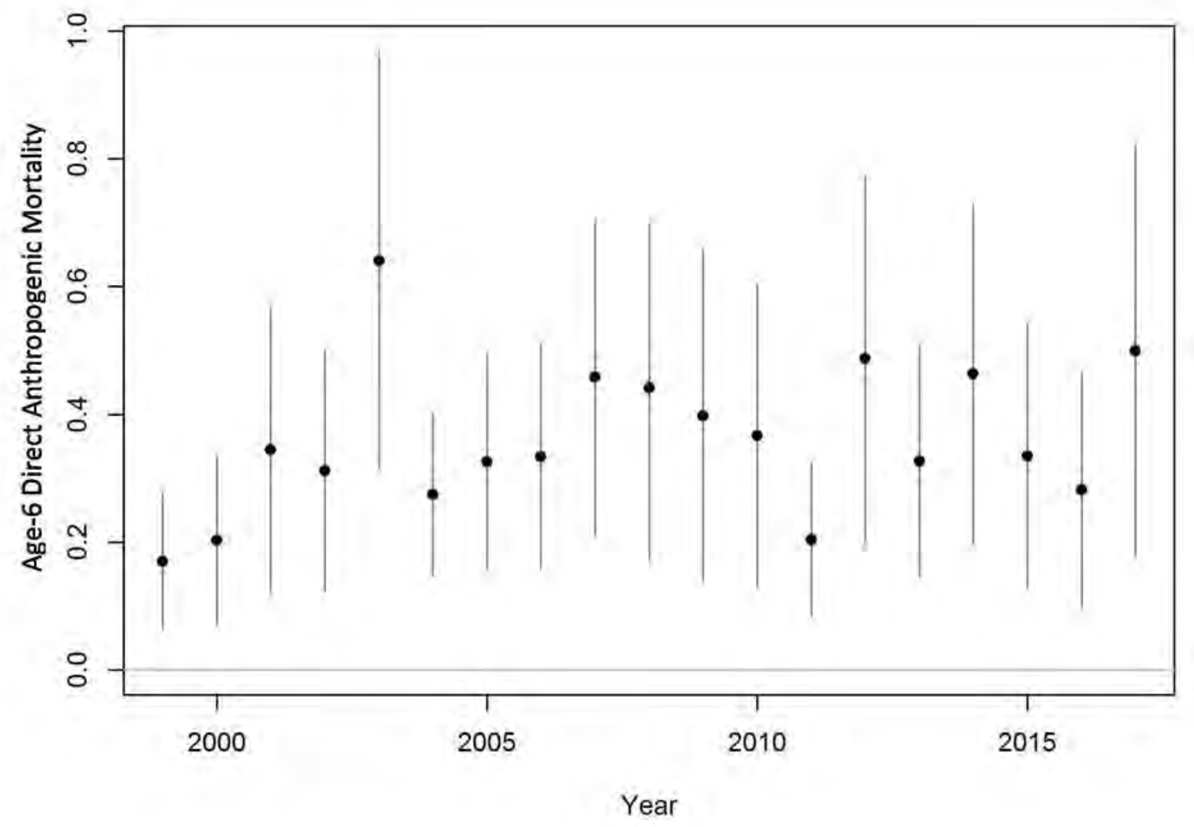


Figure 216. Potomac SCAA model age-6 direct anthropogenic mortality estimates. Error bars indicate + 1.96 asymptotic standard errors.

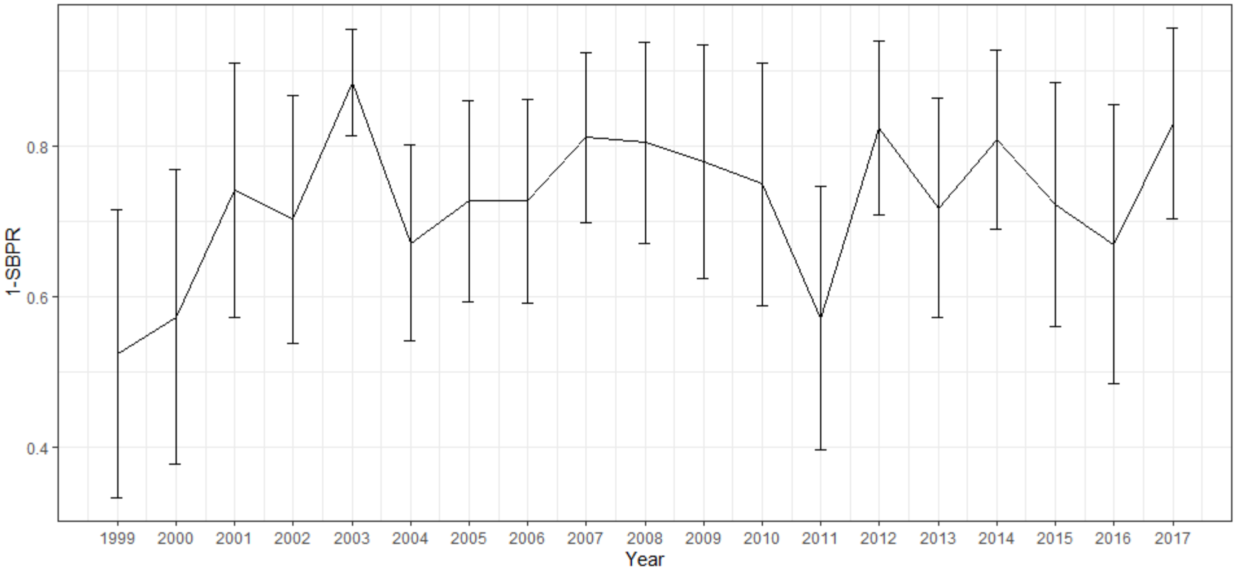


Figure 217. Potomac SCAA model 1-SBPR estimates. Error bars indicate + 1.96 asymptotic standard errors.

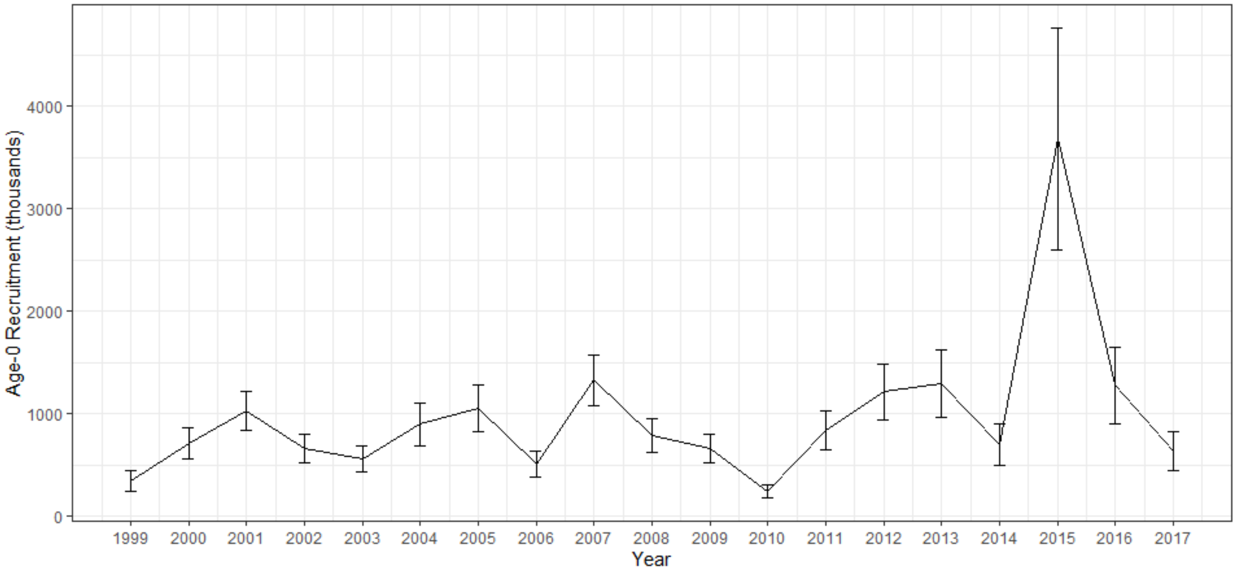


Figure 218. Potomac SCAA model age-0 recruitment estimates. Error bars indicate ± 1.96 asymptotic standard errors.

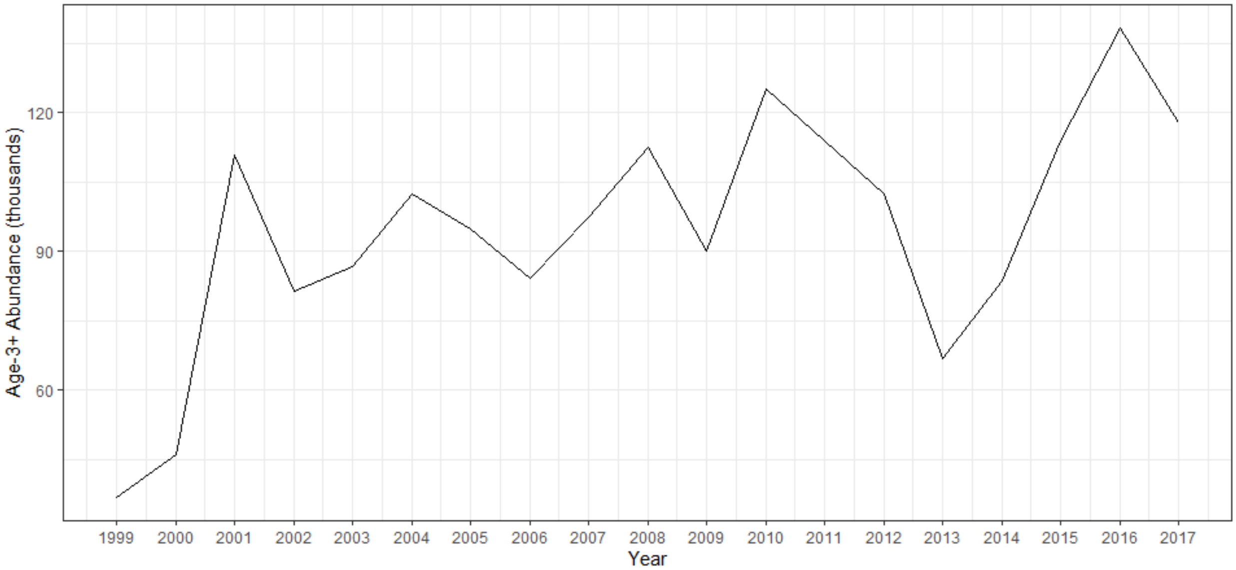


Figure 219. Potomac SCAA model age-3+ abundance estimates (thousands of fish).

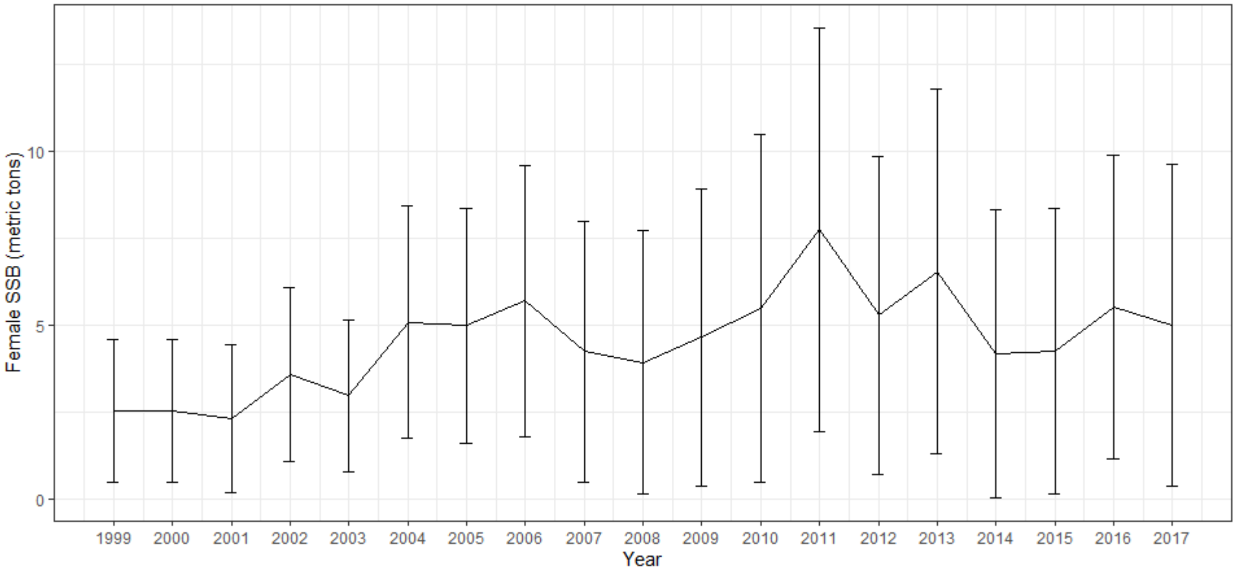


Figure 220. Potomac SCAA model female spawning stock biomass estimates (metric tons).

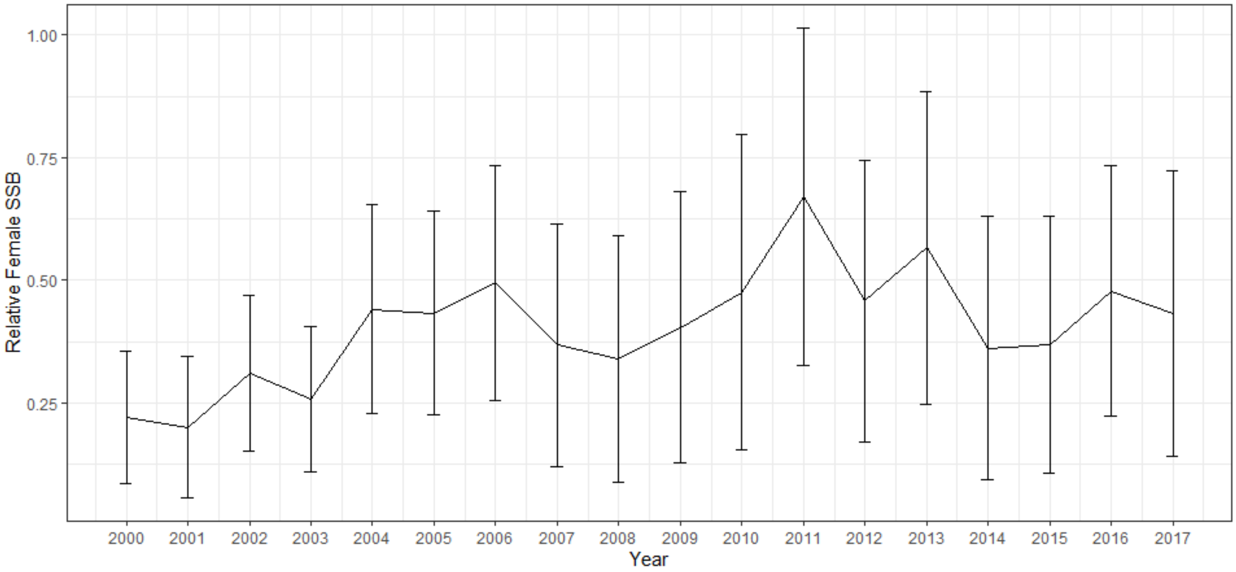


Figure 221. Potomac SCAA model relative female spawning stock biomass estimates (metric tons).

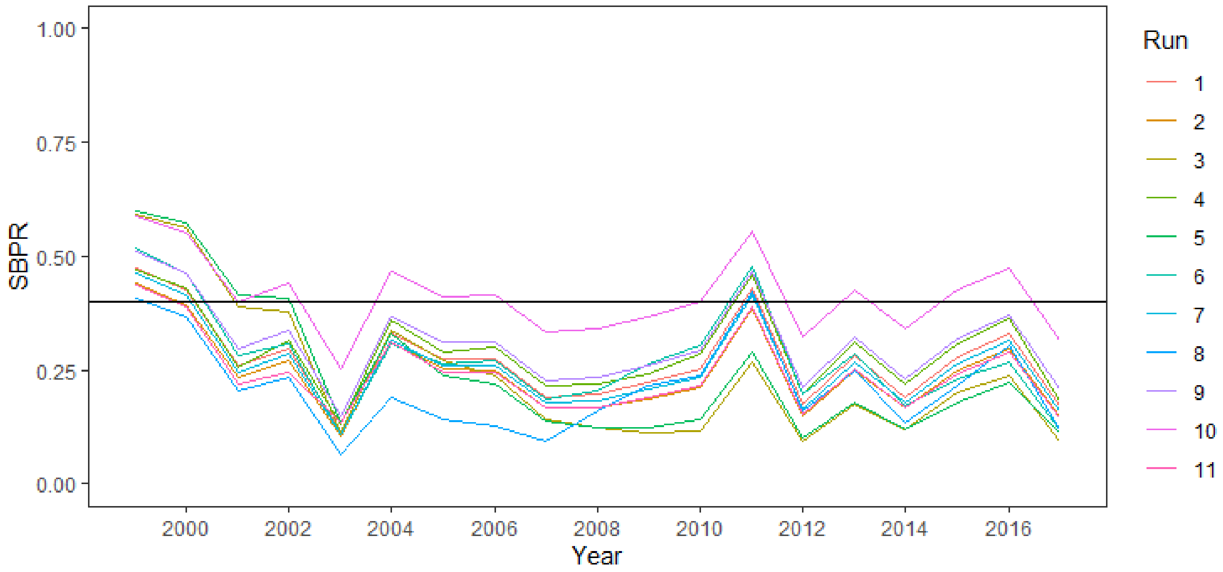


Figure 222. Potomac SCAA model spawning stock biomass per-recruit estimates from the base model (run 1) and sensitivity model runs (see Section 3.10.8.5.3 for description of sensitivity runs).

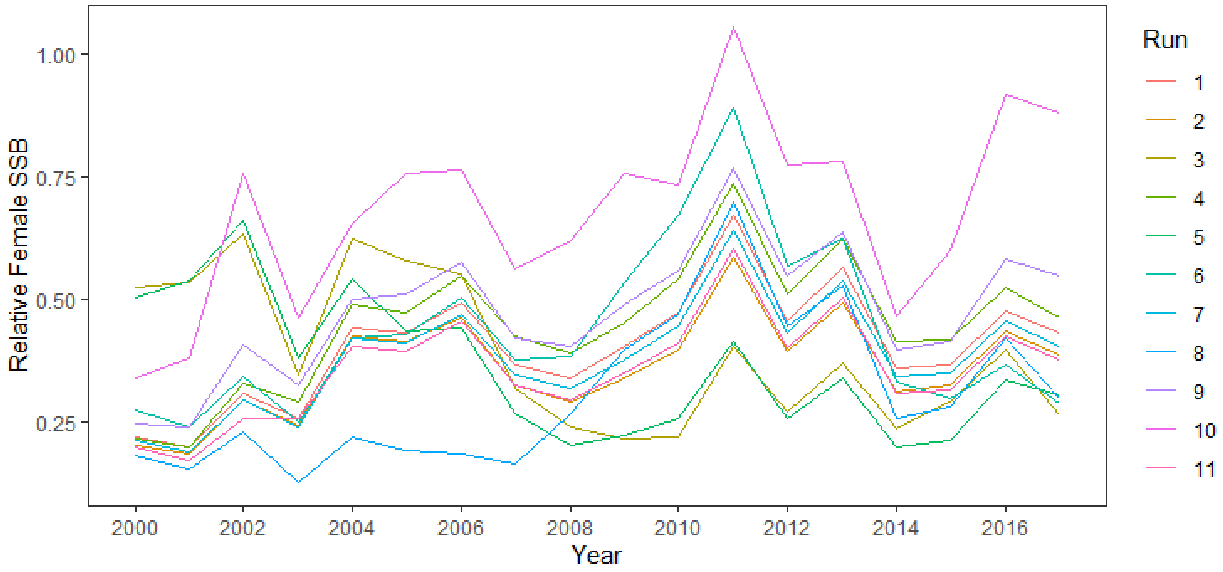


Figure 223. Potomac SCAA model relative female spawning stock biomass estimates from the base model (run 1) and sensitivity model runs (see Section 3.10.8.5.3 for description of sensitivity runs).

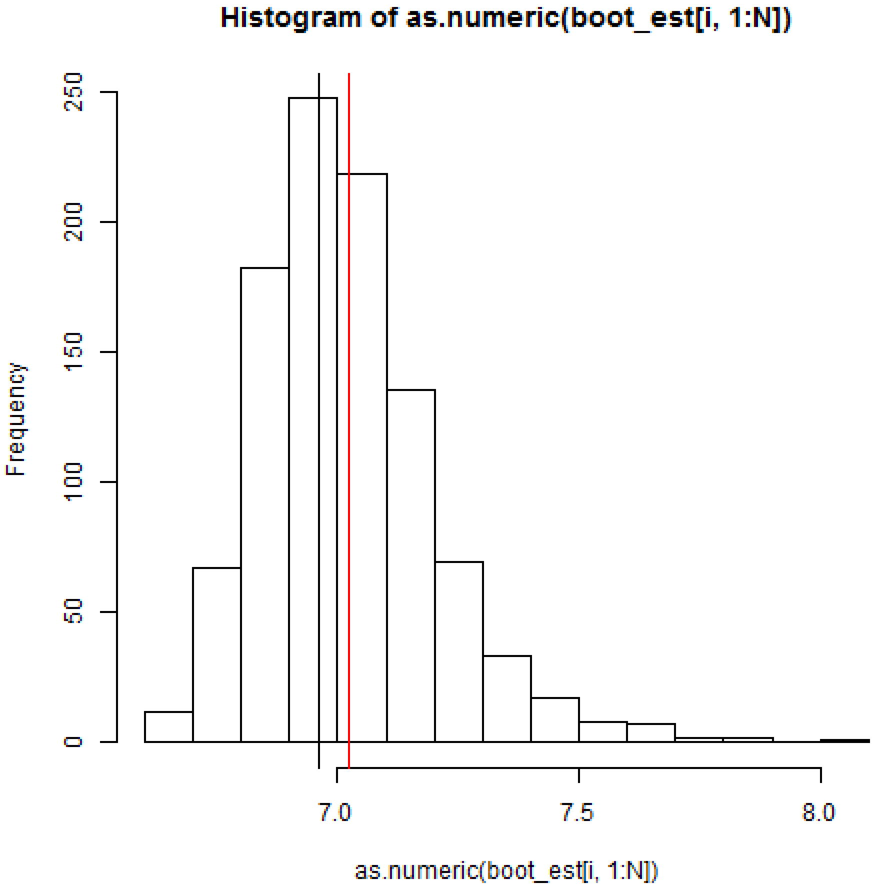


Figure 224. Potomac SCAA model average recruitment (R0) parameter estimate from base model (vertical black line) compared to distribution and mean (vertical red line) of estimates form 1,000 bootstrap model runs.

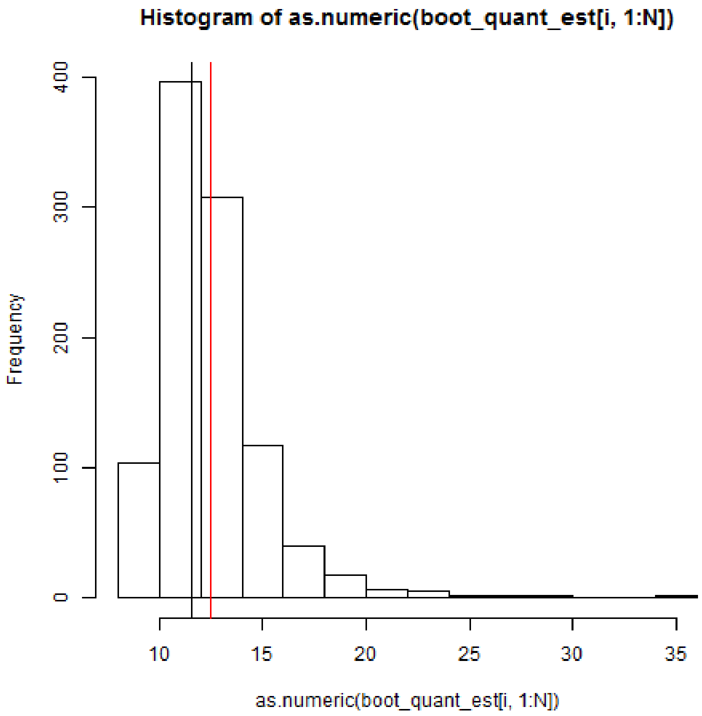


Figure 225. Potomac SCAA model spawning stock biomass reference point estimate from base model (vertical black line) compared to distribution and mean (vertical red line) of estimates form 1,000 bootstrap model runs.

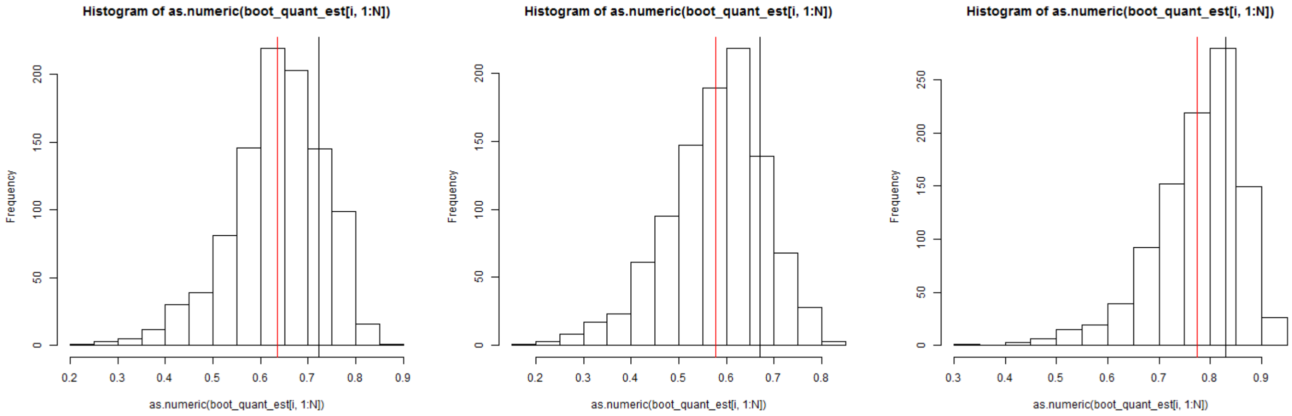


Figure 226. Potomac SCAA model 2015 (left), 2016 (center), and 2017 (right) 1-spawning stock biomass per-recruit estimates from base model (vertical black line) compared to distribution and mean (vertical red line) of estimates form 1,000 bootstrap model runs.

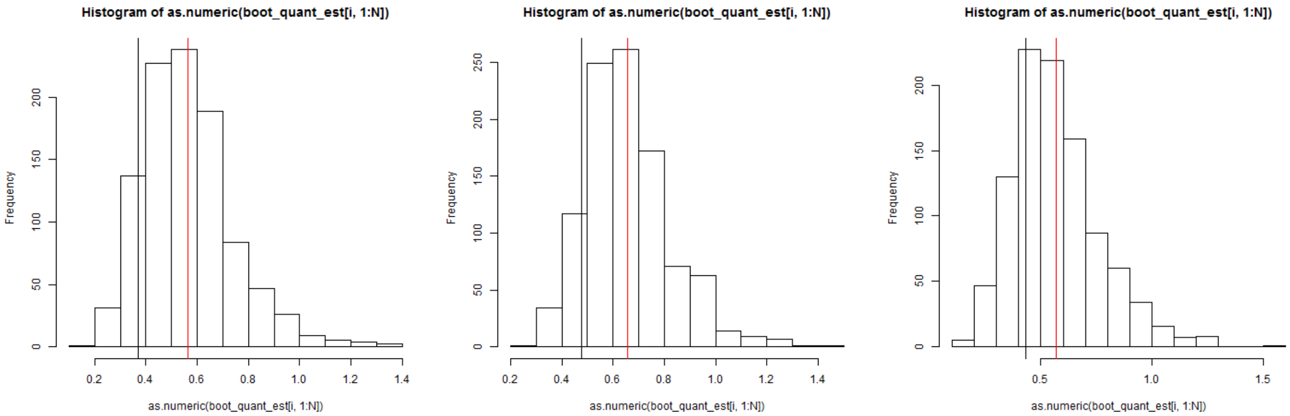


Figure 227. Potomac SCAA model 2015 (left), 2016 (center), and 2017 (right) relative female spawning stock biomass estimates from base model (vertical black line) compared to distribution and mean (vertical red line) of estimates form 1,000 bootstrap model runs.

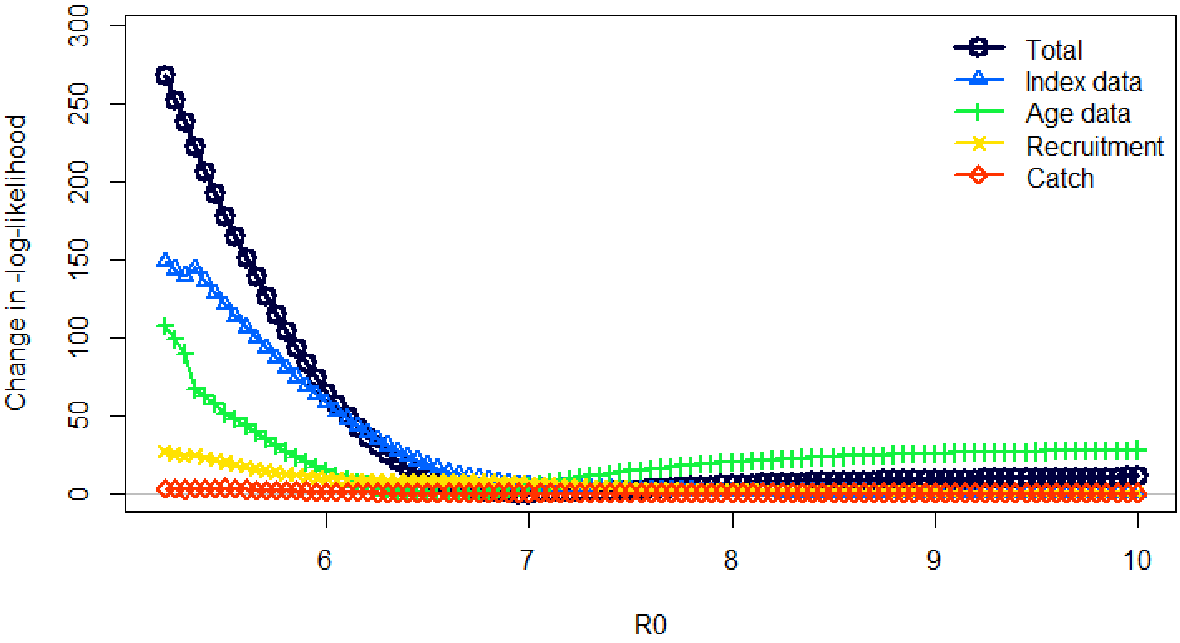


Figure 228. Potomac SCAA model likelihood profile for the average recruitment (R0) parameter. The y-axis shows the change in negative log likelihood for each fixed parameter value on the x-axis relative to the minimum negative log likelihood across the parameter range.

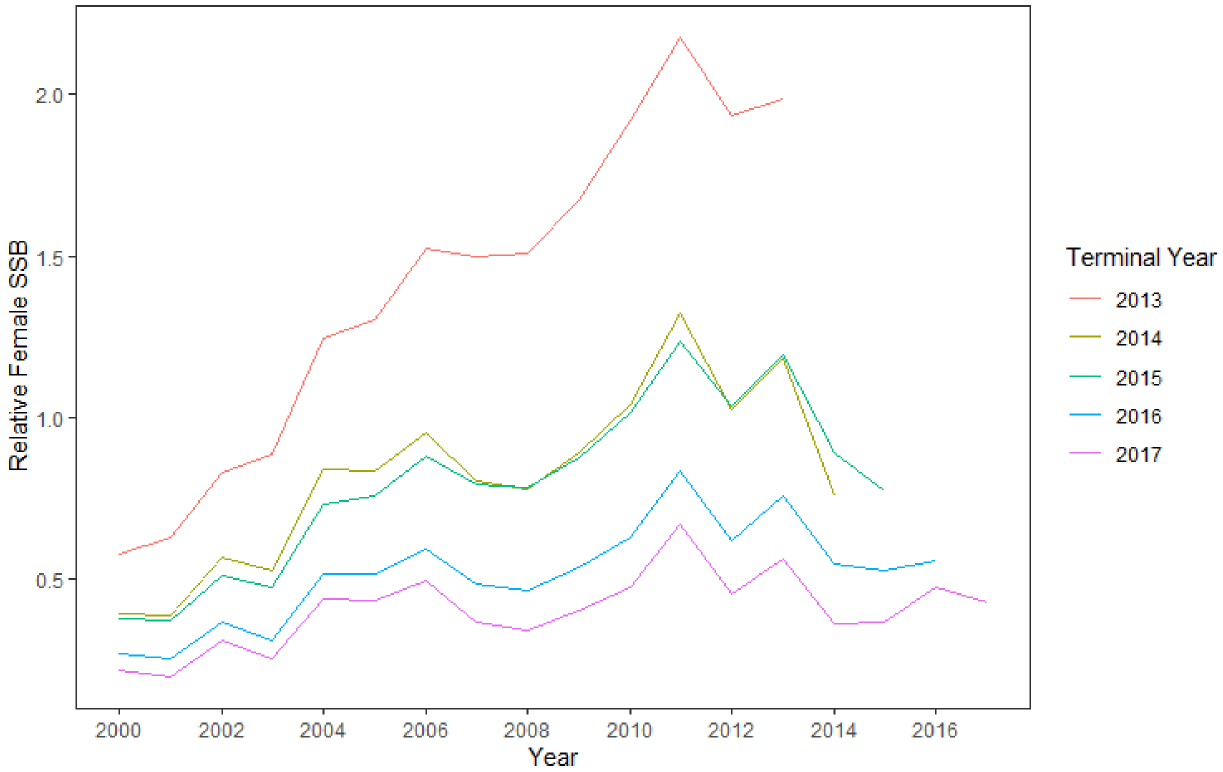


Figure 229. Potomac SCAA relative spawning stock biomass estimates from four year retrospective analysis.

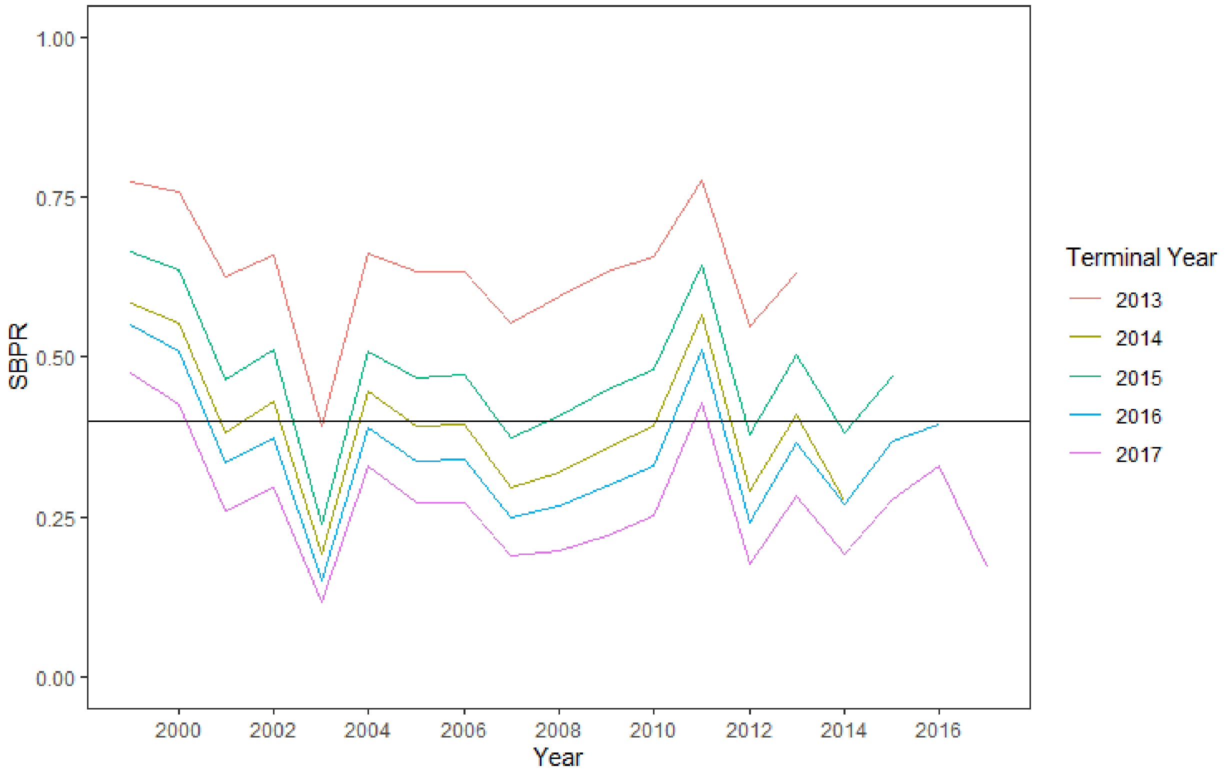


Figure 230. Potomac SCAA spawning stock biomass per-recruit estimates from four year retrospective analysis.

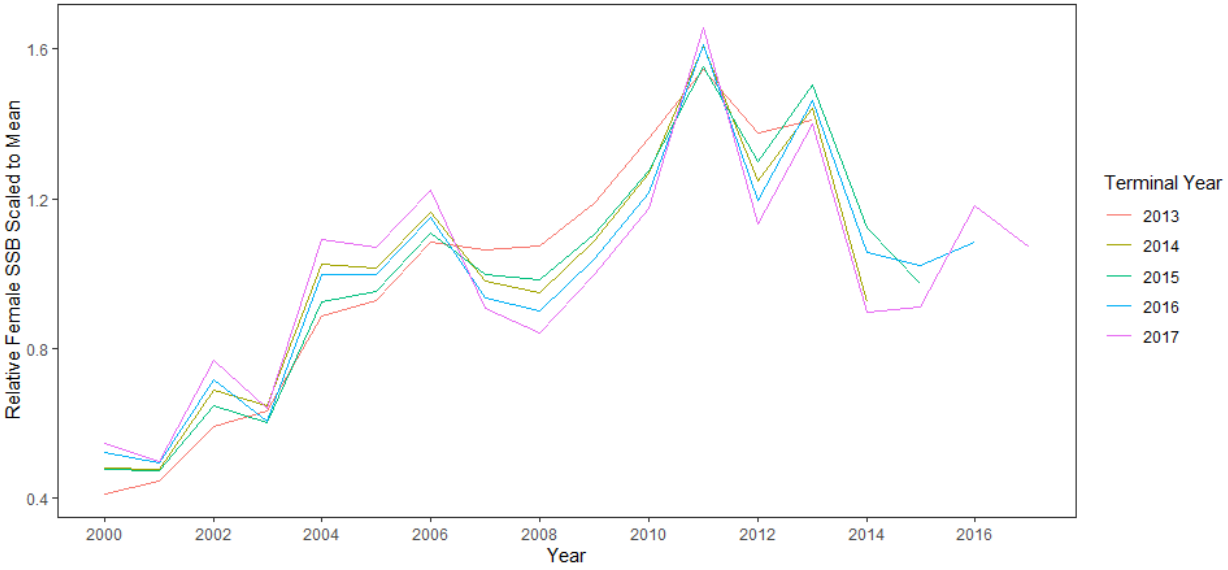


Figure 231. Potomac SCAA relative spawning stock biomass estimates from four year retrospective analysis scaled to time series means.

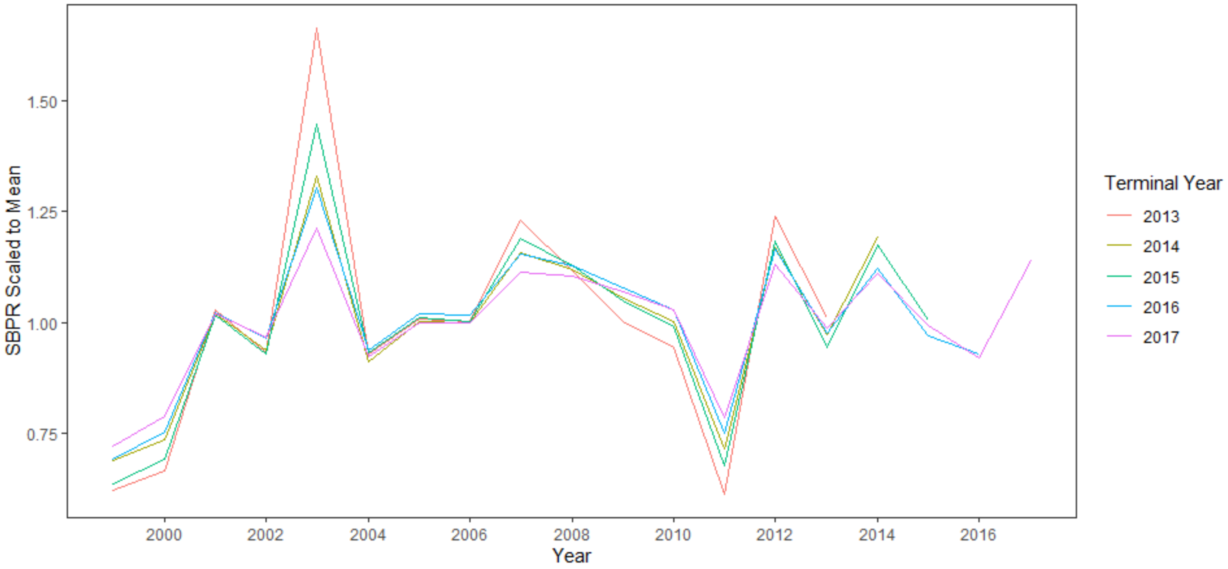


Figure 232. Potomac SCAA spawning stock biomass per-recruit estimates from four year retrospective analysis scaled to time series means.

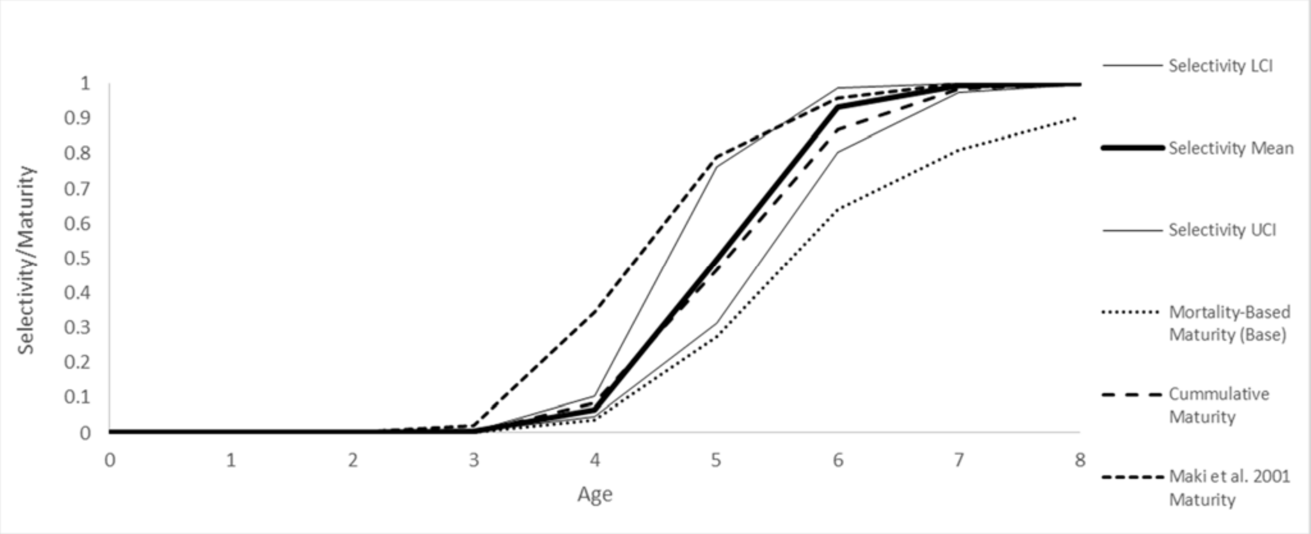


Figure 233. Comparison of various female maturity ogives considered in the assessment to Potomac SCAA base model selectivity estimates (mean and 95% CI from asymptotic standard errors) for the Gill Net Fleet.

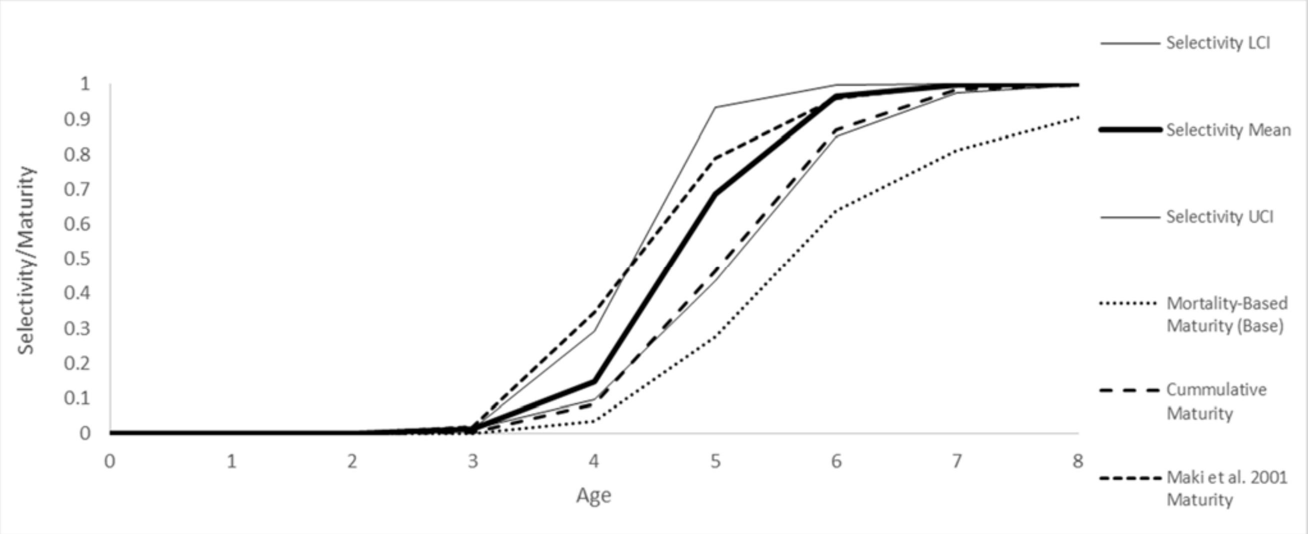


Figure 234. Comparison of various female maturity ogives considered in the assessment to Potomac SCAA base model selectivity estimates (mean and 95% CI from asymptotic standard errors) for the MD DNR Potomac River Striped Bass Spawning Stock Survey.

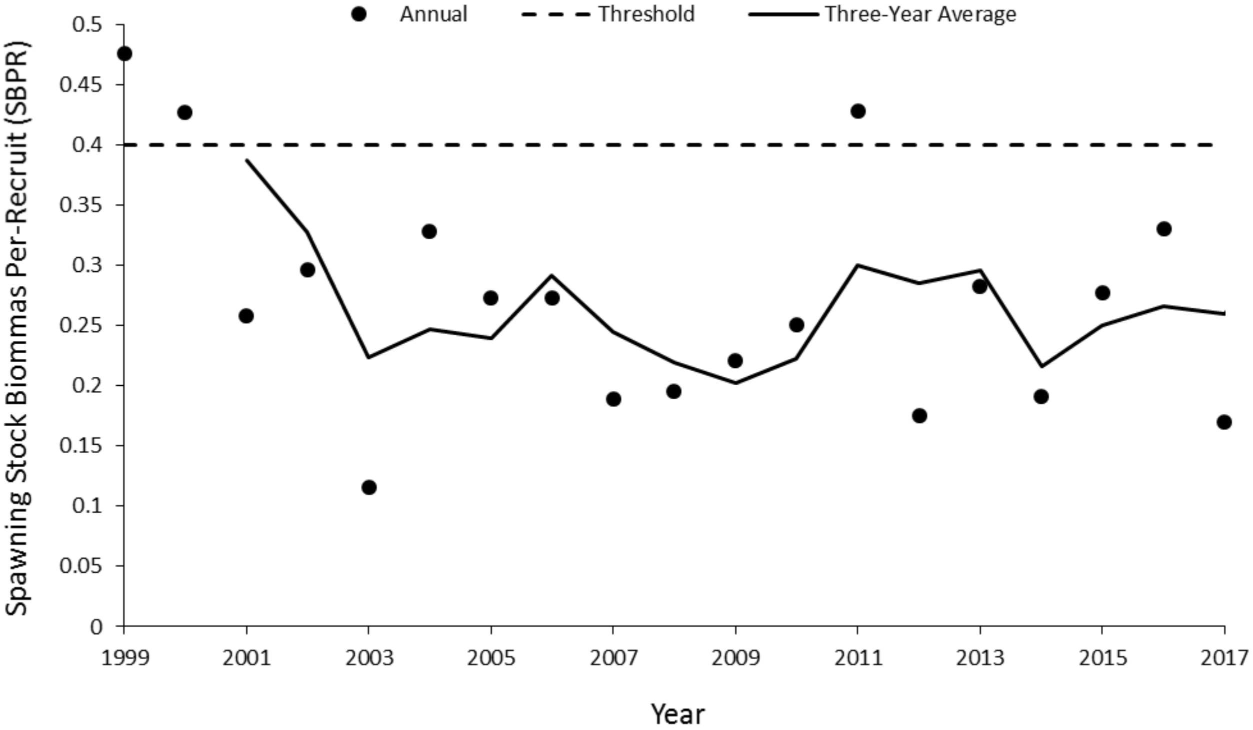


Figure 235. Potomac SCAA model annual (circles) and three-year running average (solid black line) SBPR estimates compared to the $SBPR_{40\%}$ reference point.

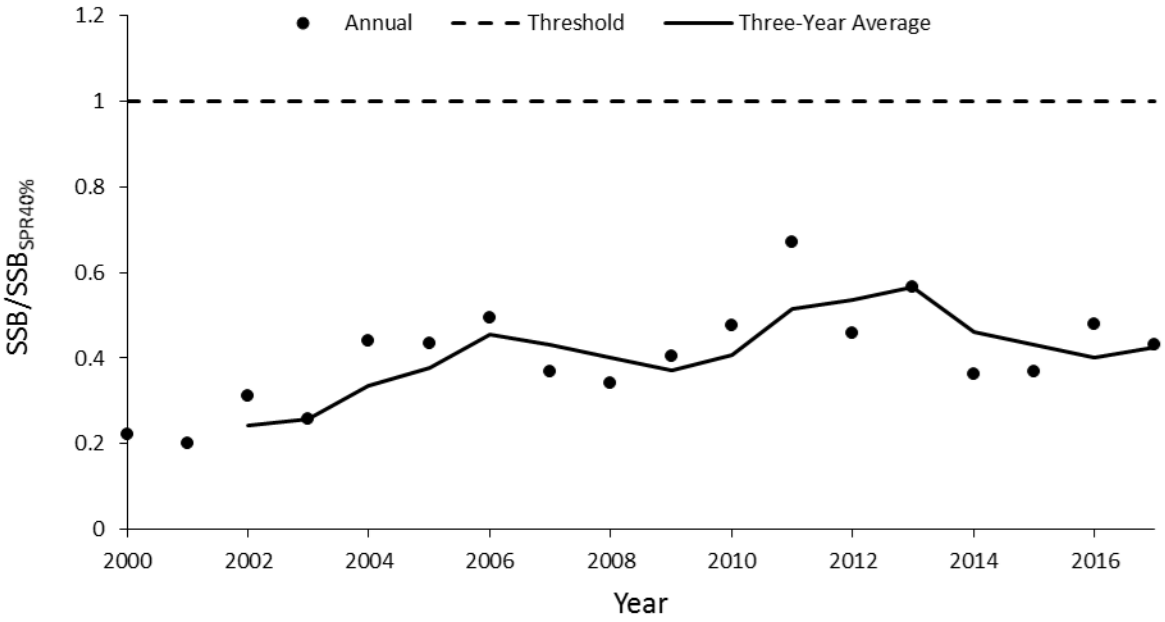


Figure 236. Potomac SCAA model annual (circles) and three-year running average (solid black line) relative spawning stock biomass compared to the reference point (1.0).

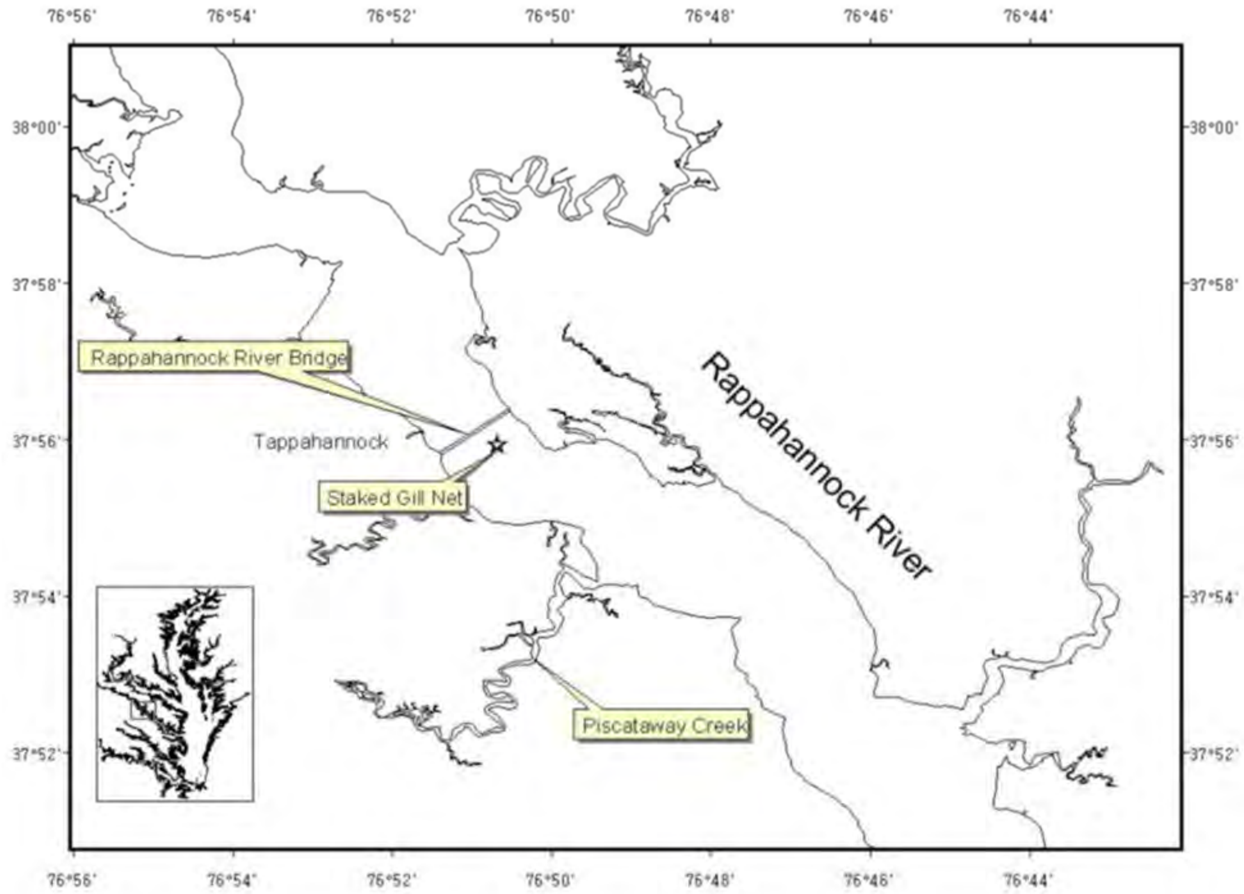


Figure 237. Location of the staked gill net fished by the VIMS Rappahannock River Adult Gill Net Survey.

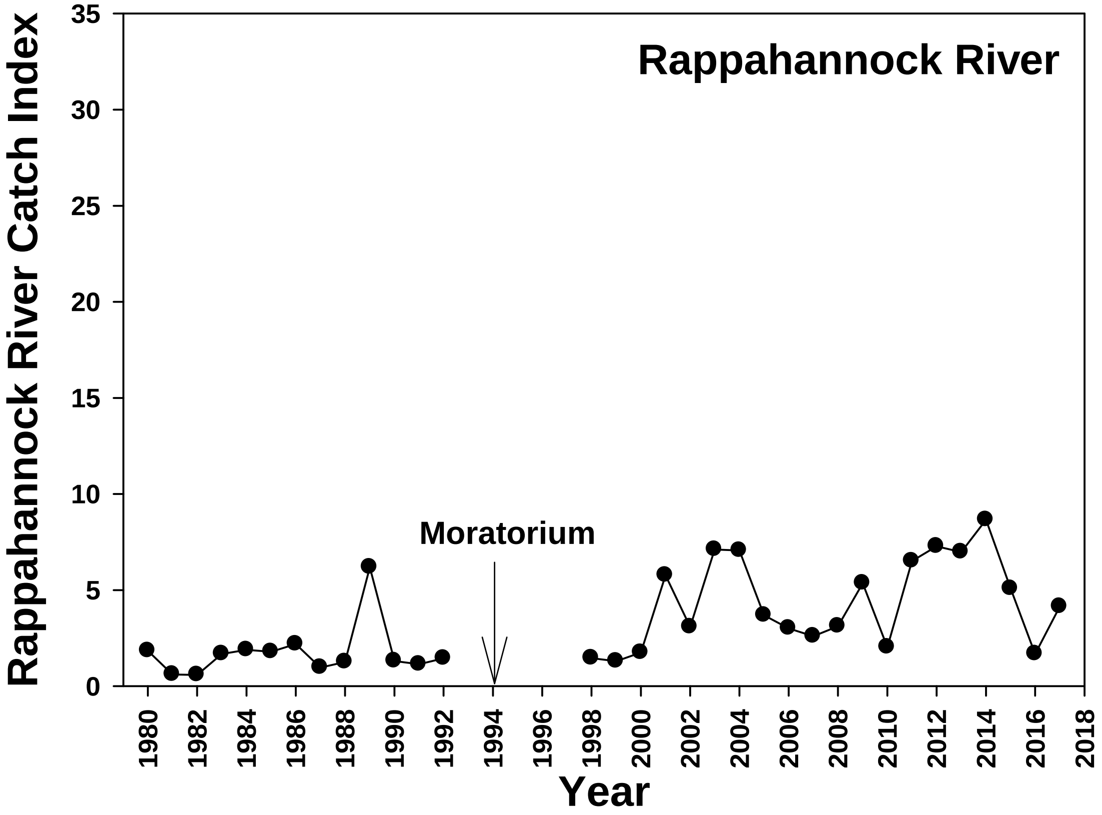


Figure 238. Recent (1998-2017) and historic values of the catch index (weight-based) of female American shad on the Rappahannock River.

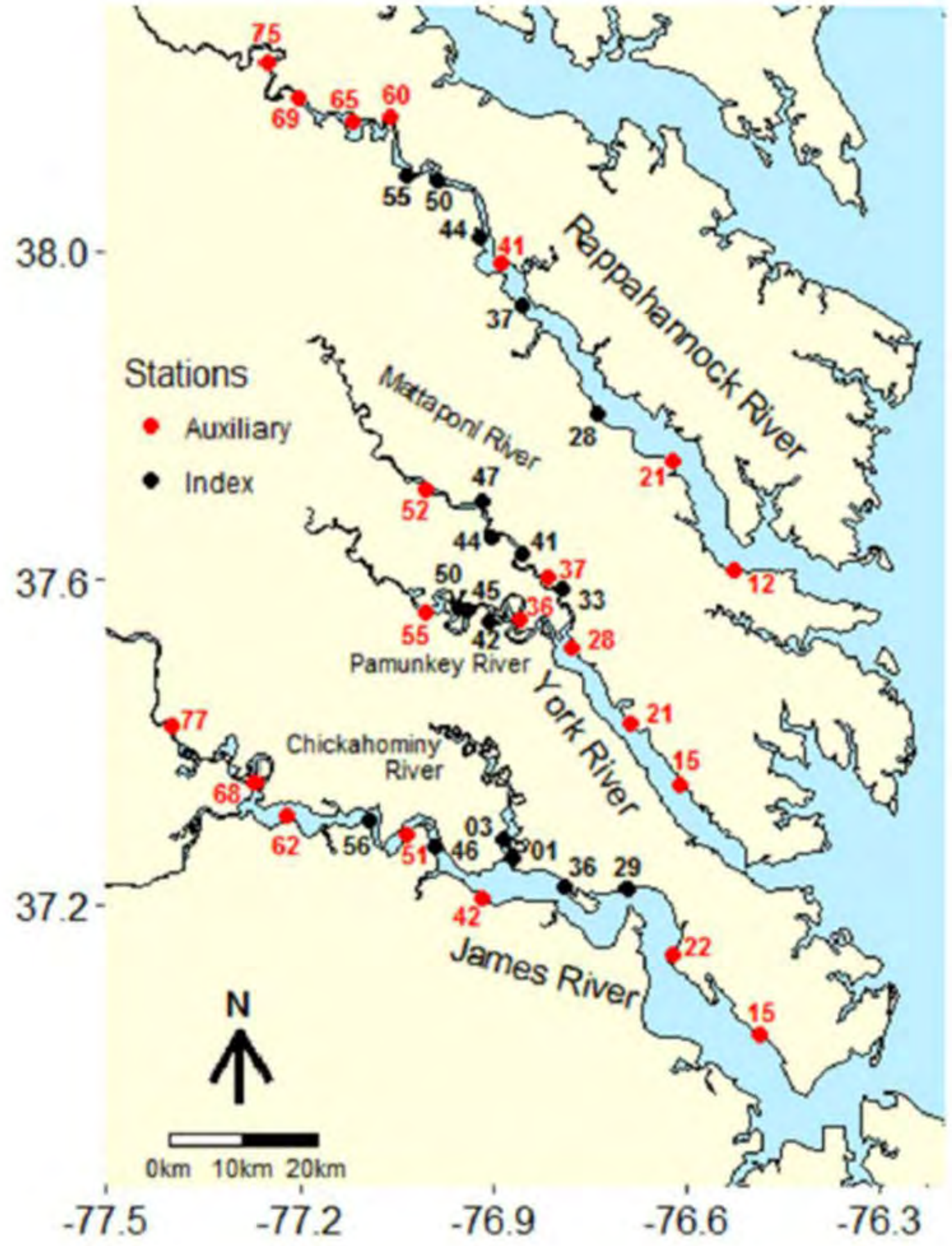


Figure 239. VIMS Juvenile Seine Survey stations. Station numbers denote the approximate river mile from the mouth.

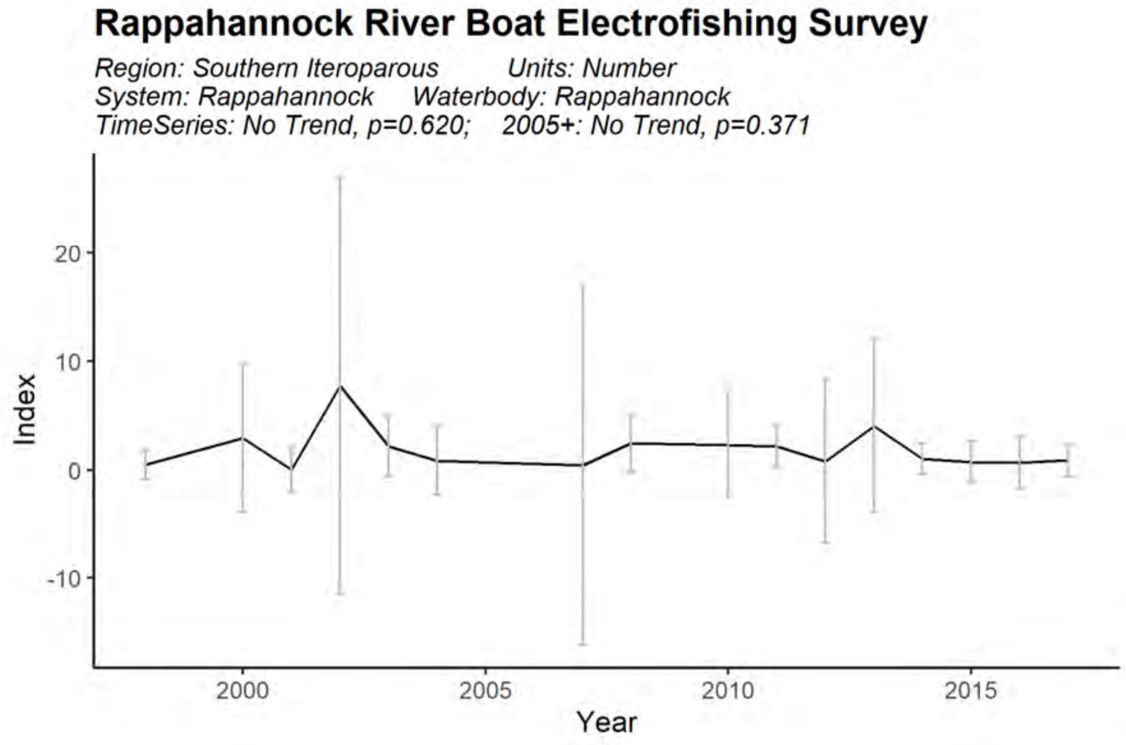


Figure 240. Rappahannock River Boat Electrofishing Survey index and Mann-Kendall results.

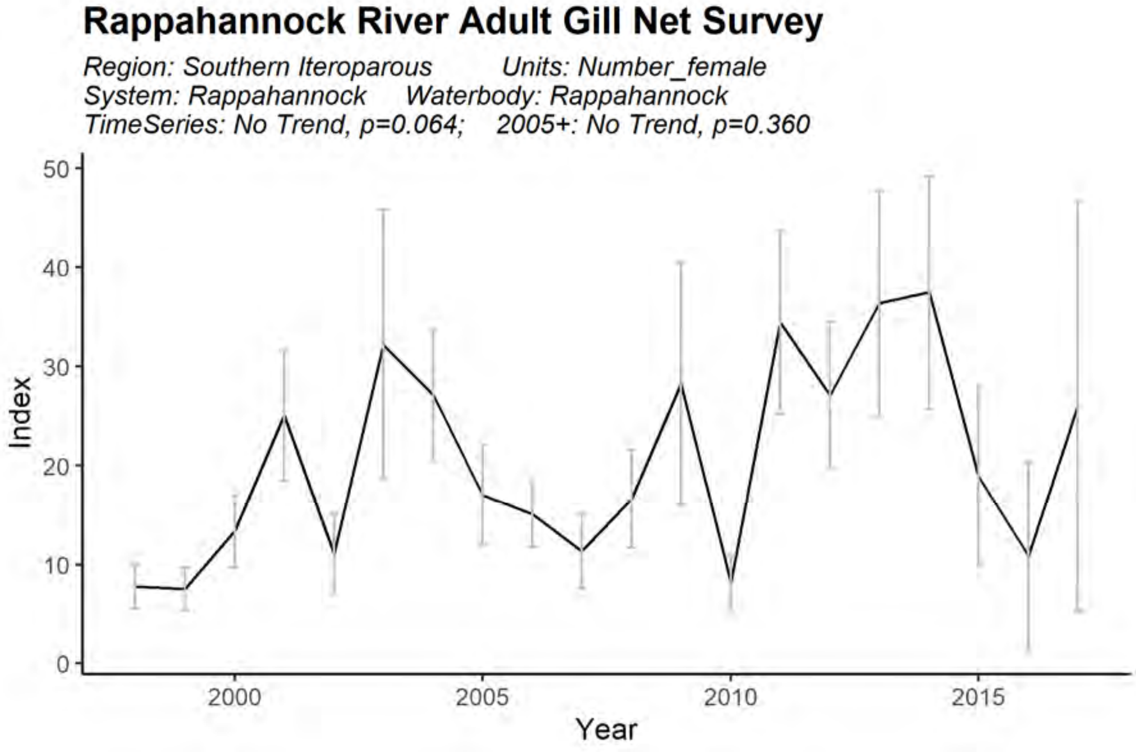


Figure 241. Rappahannock River Adult Gill Net Survey index and Mann-Kendal results.

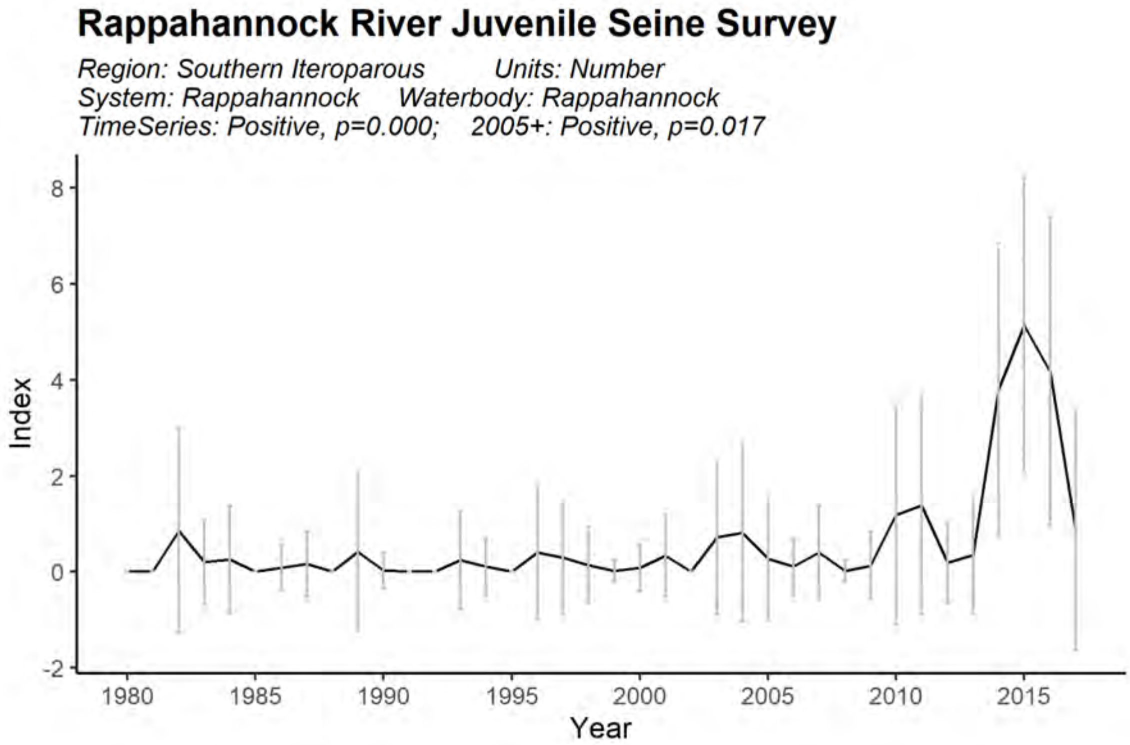


Figure 242. Rappahannock River Juvenile Seine Survey index and Mann-Kendall results.

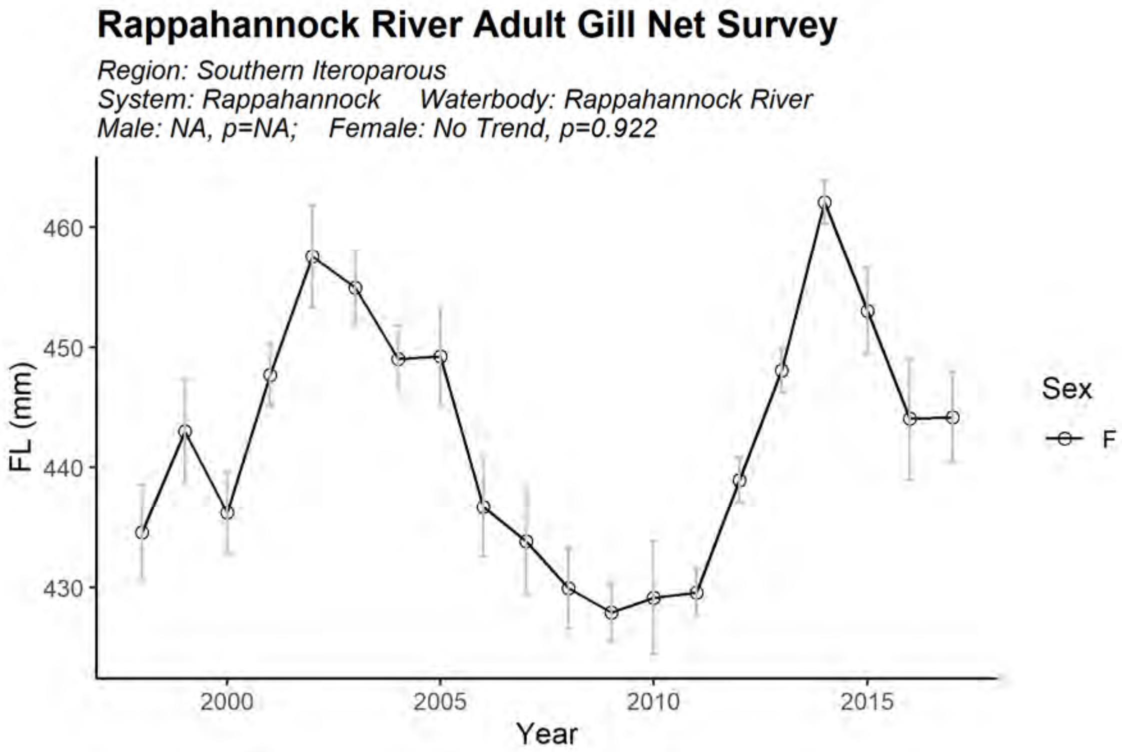


Figure 243. Annual mean length of female American shad from the Rappahannock River Adult Gill Net Survey and Mann-Kendall results.

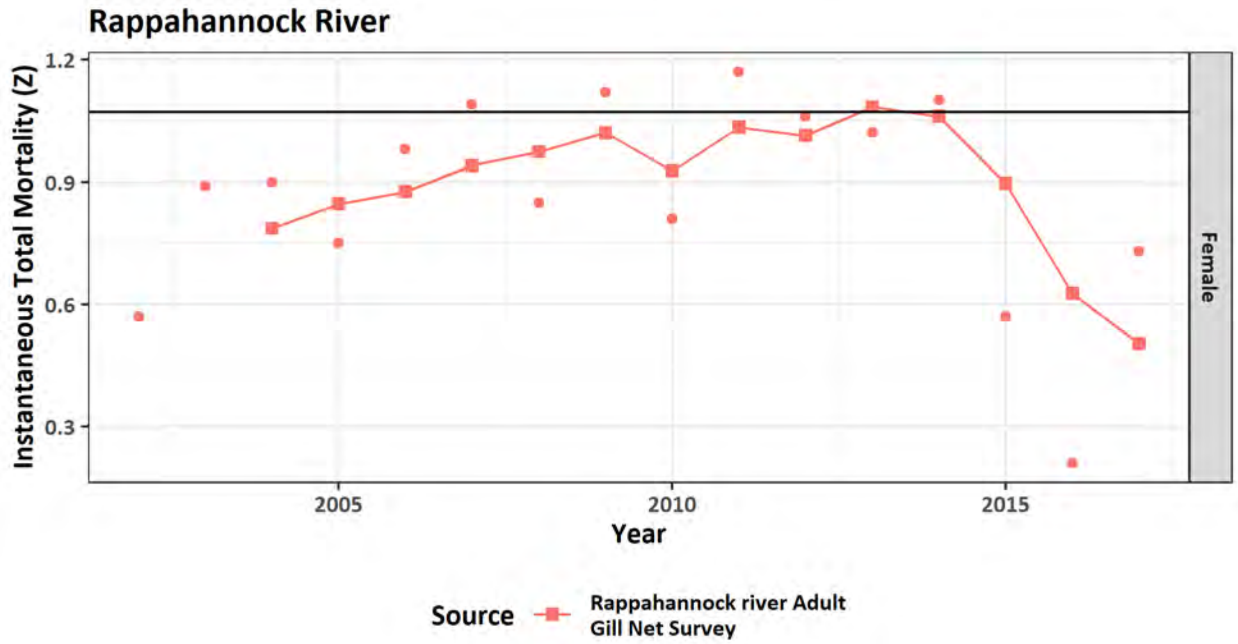


Figure 244. Three year average Z estimates via weighted linear regression by sex and monitoring program for the Rappahannock River System based on scale-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual Z estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).

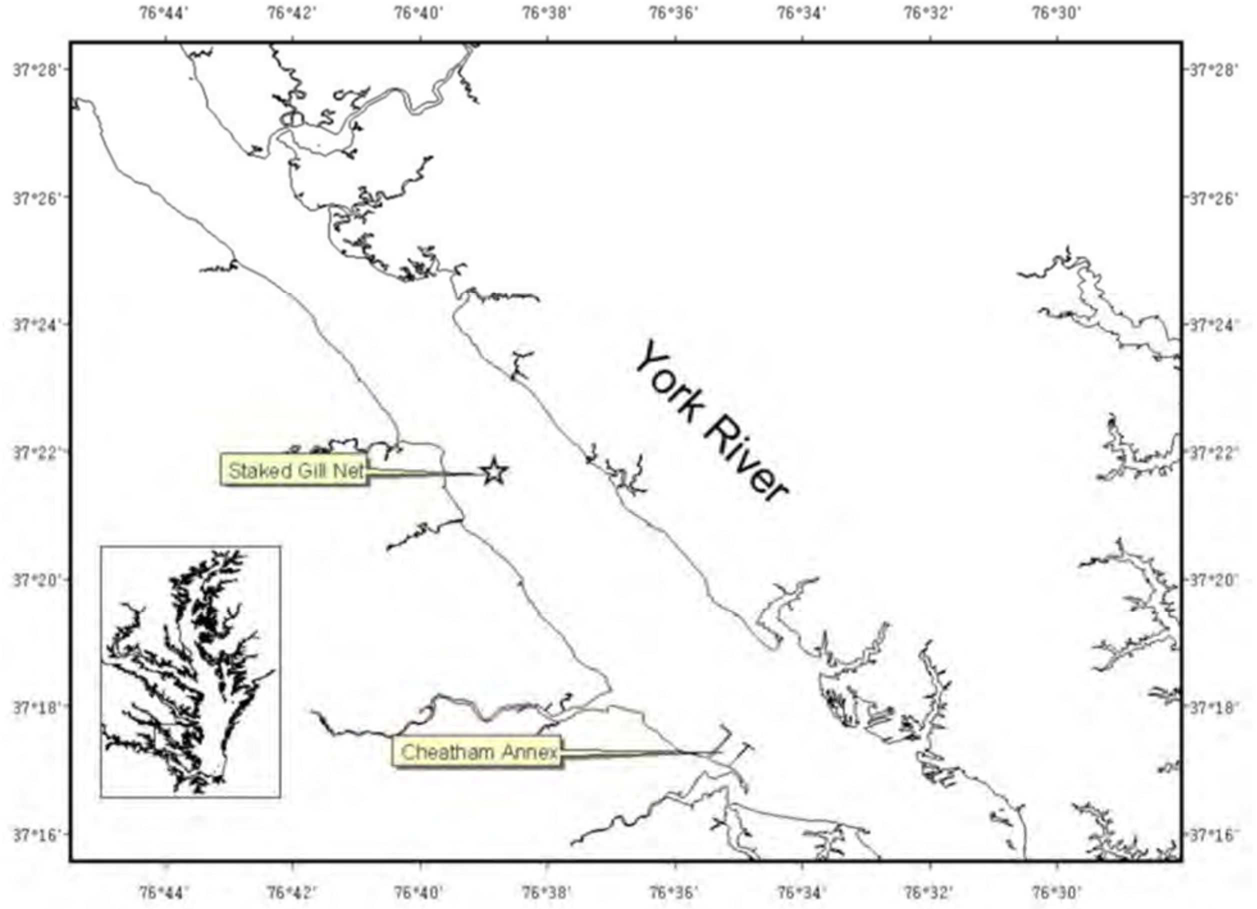


Figure 245. Location of the staked gill net fished by the VIMS York River Adult Gill Net Survey.

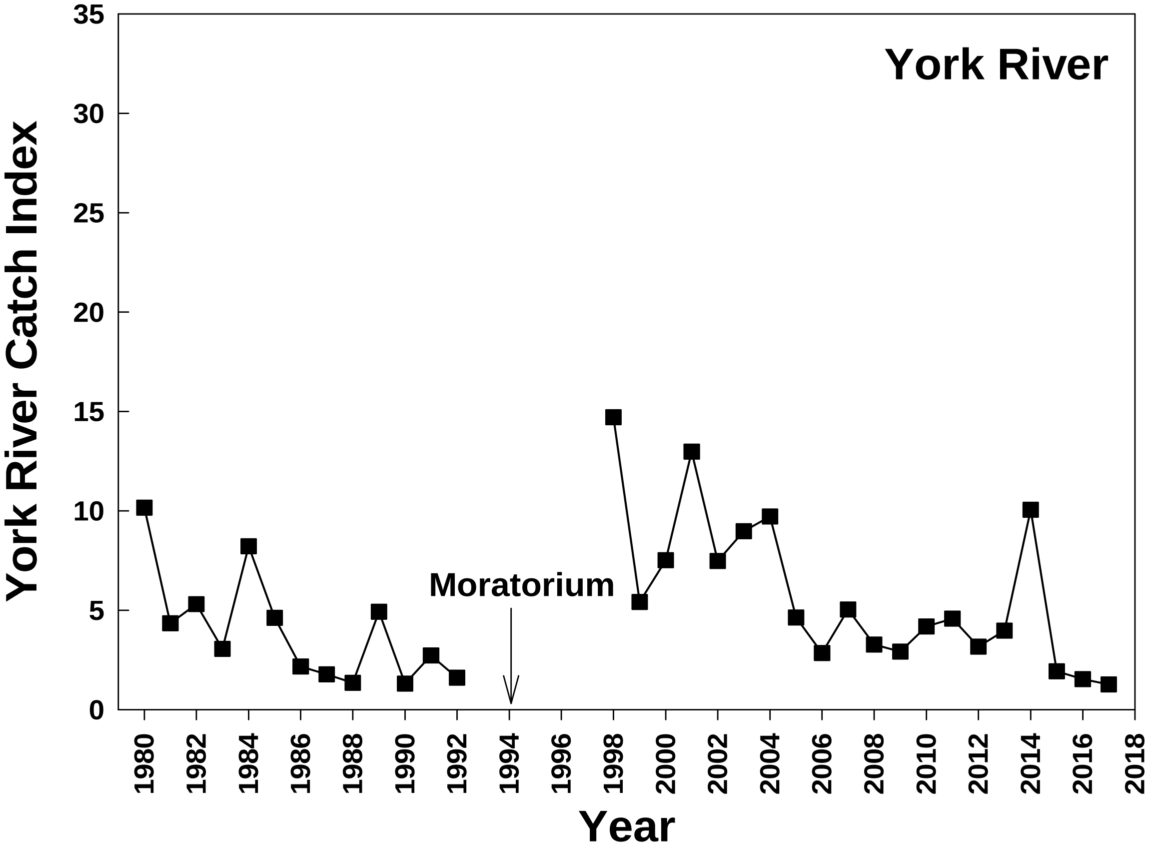


Figure 246. Recent (1998-2017) and historic values of the catch index (weight-based) of female American shad on the York River.

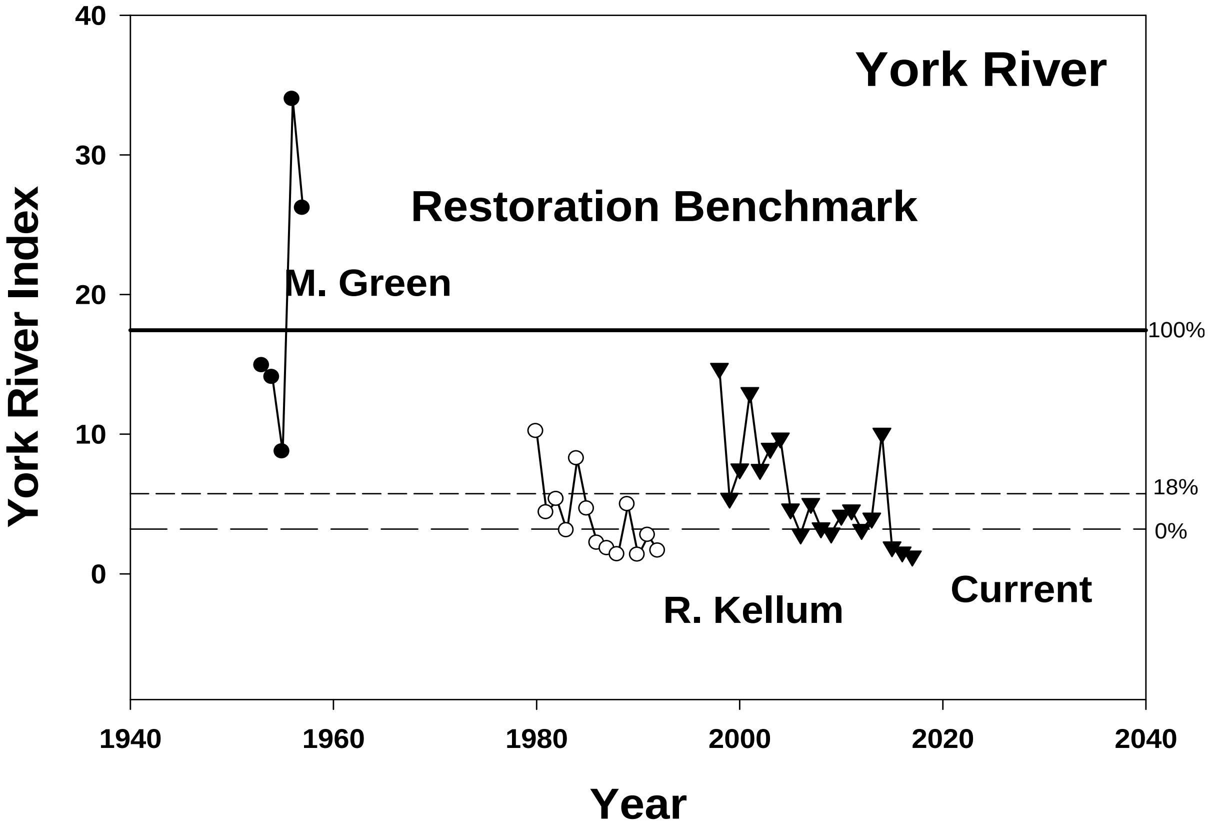


Figure 247. Catch indexes (weight-based) of historical logbook data from the 1950s (M. Greene), 1980s (R. Kellum), and current monitoring for the York River. The 1950s data have been adjusted by multiplying index values by 2.16 based on gear comparison trials. Horizontal lines are the geometric means of each data set (solid, 1950s; short dashes, current; long dashes, 1980s).

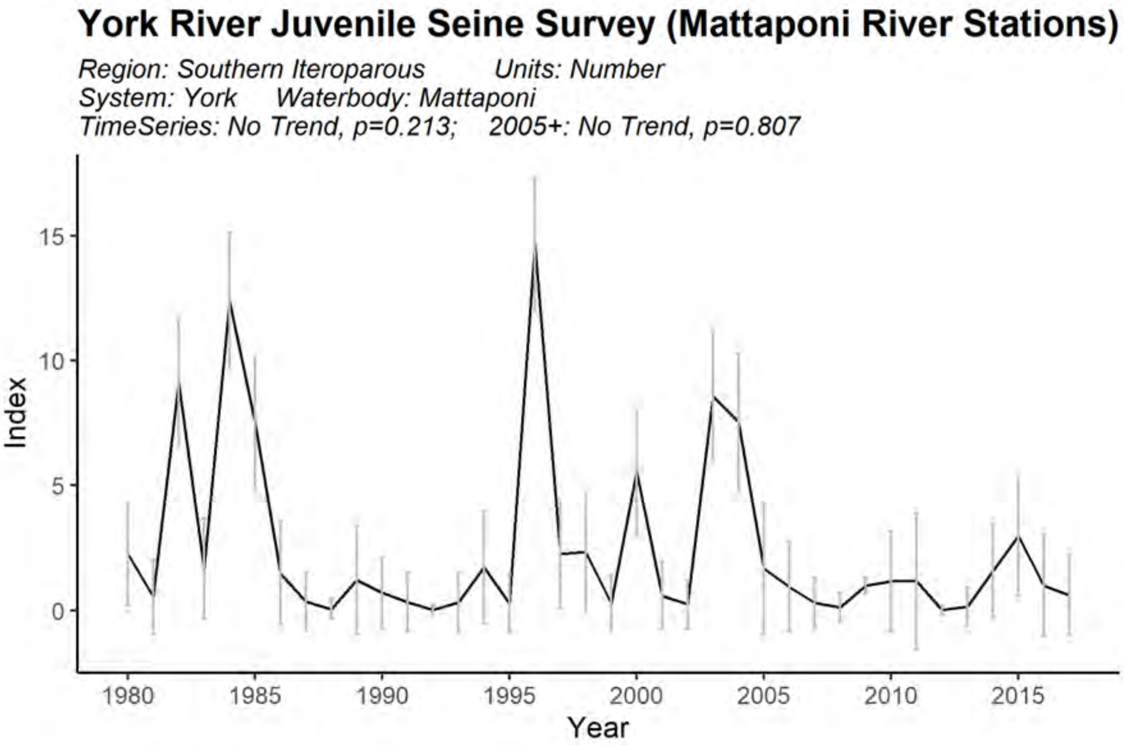


Figure 248. York River Juvenile Seine Survey (Mattaponi River Stations) index and Mann-Kendall results.

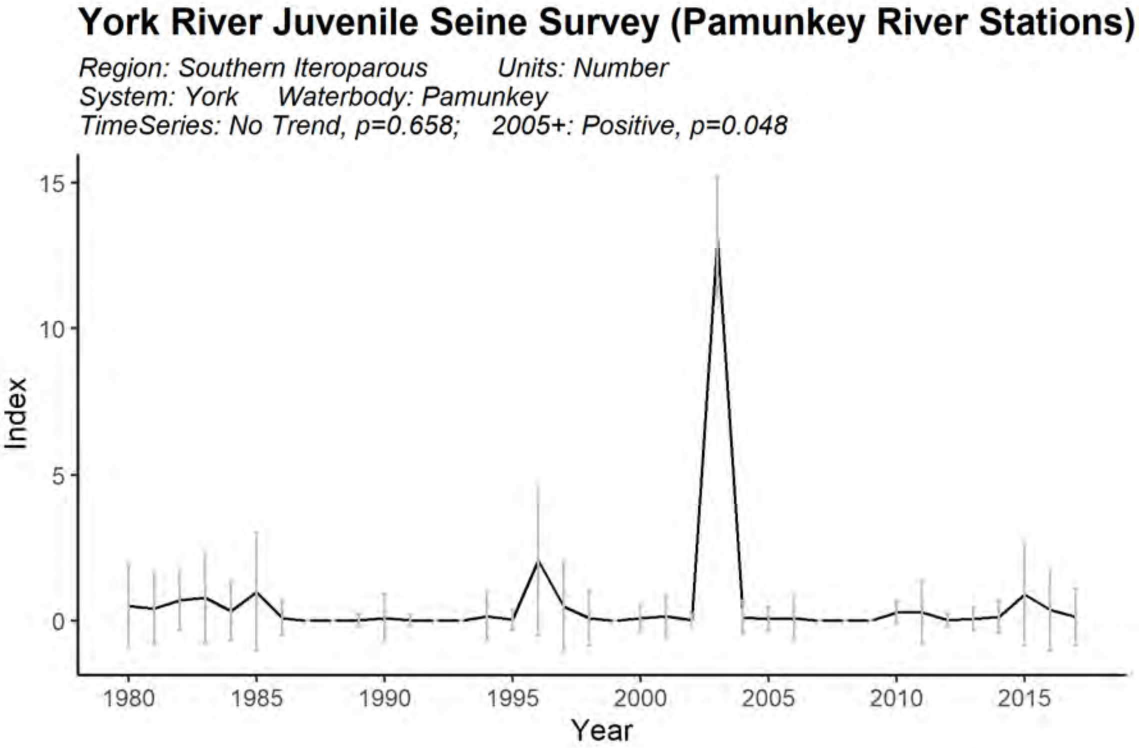


Figure 249. York River Juvenile Seine Survey (Pamunkey River Stations) index and Mann-Kendall results.

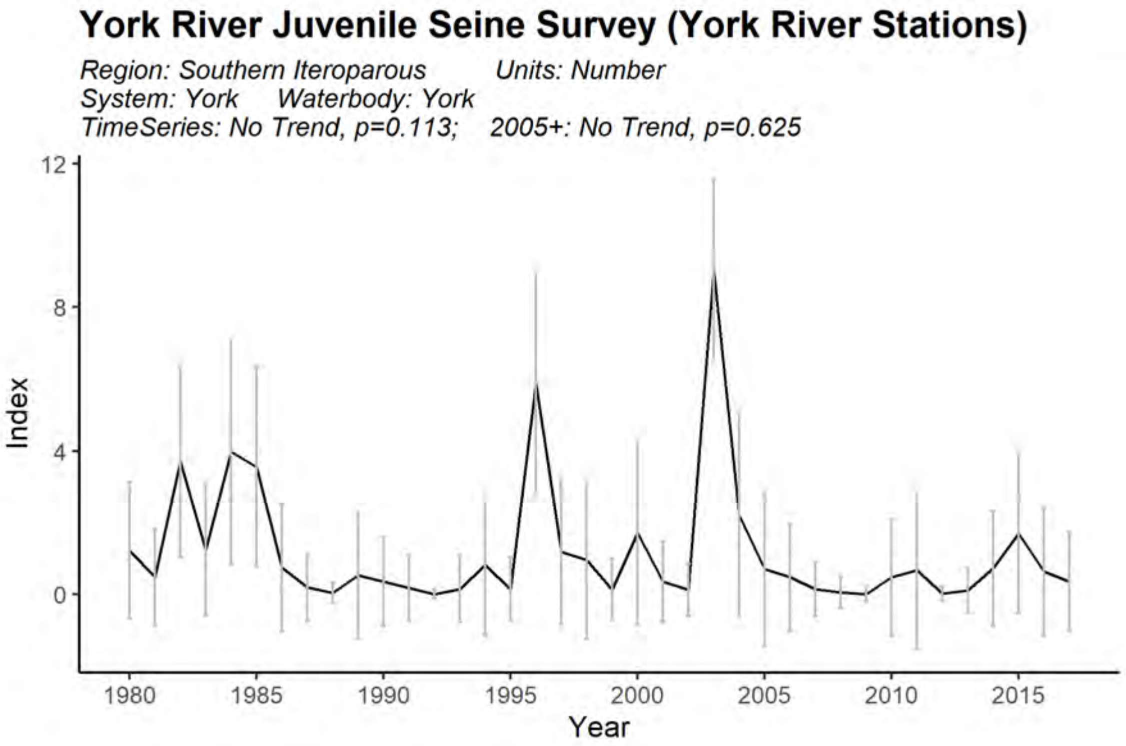


Figure 250. York River Juvenile Seine Survey (York River Stations) index and Mann-Kendall results.

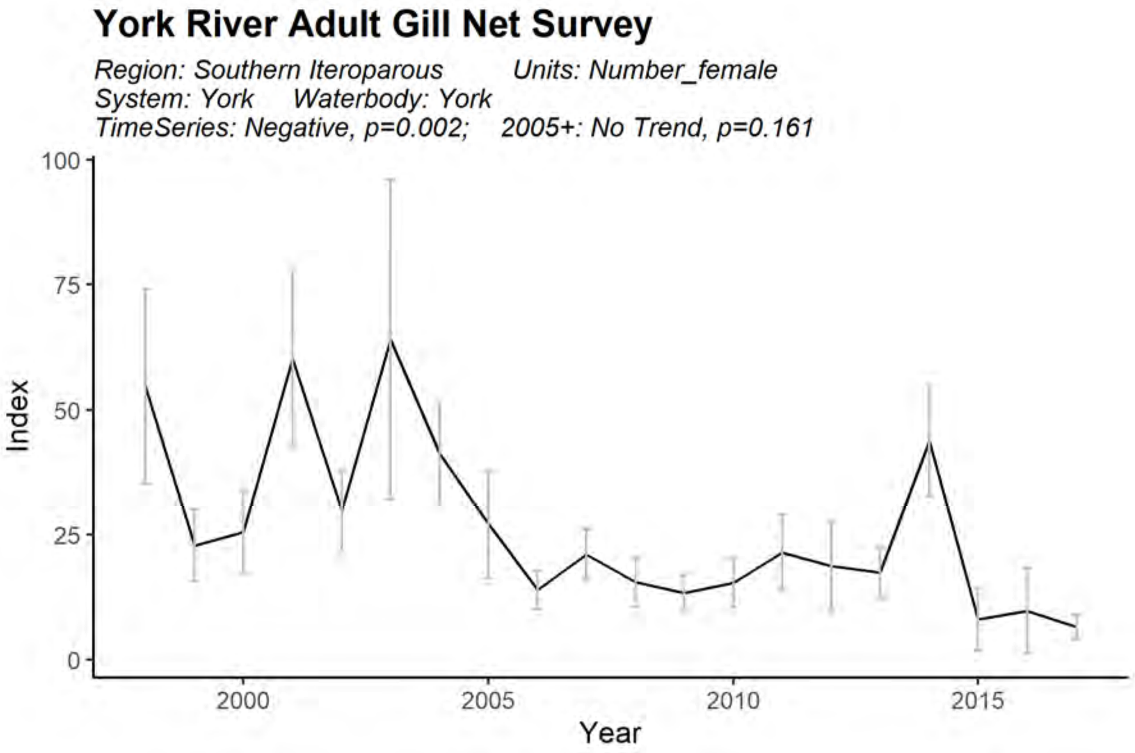


Figure 251. York River Adult Gill Net Survey index and Mann-Kendall results.

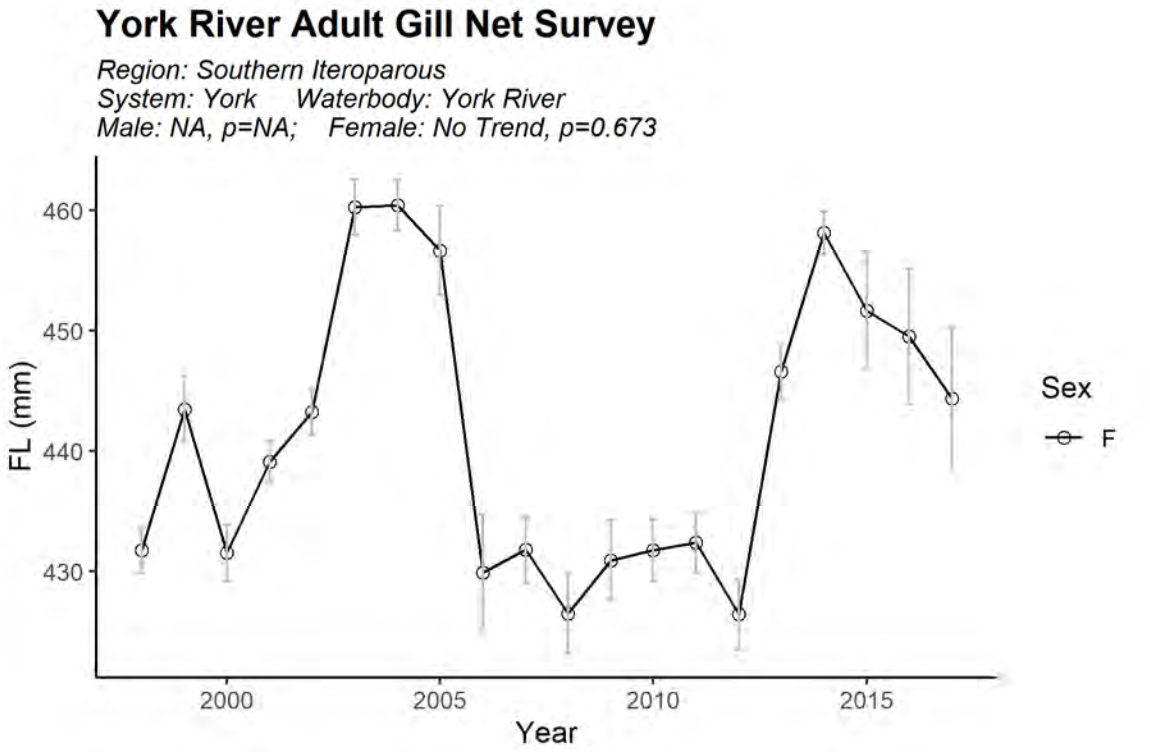


Figure 252. Annual mean length of female American shad from the York River Adult Gill Net Survey and Mann-Kendall results.

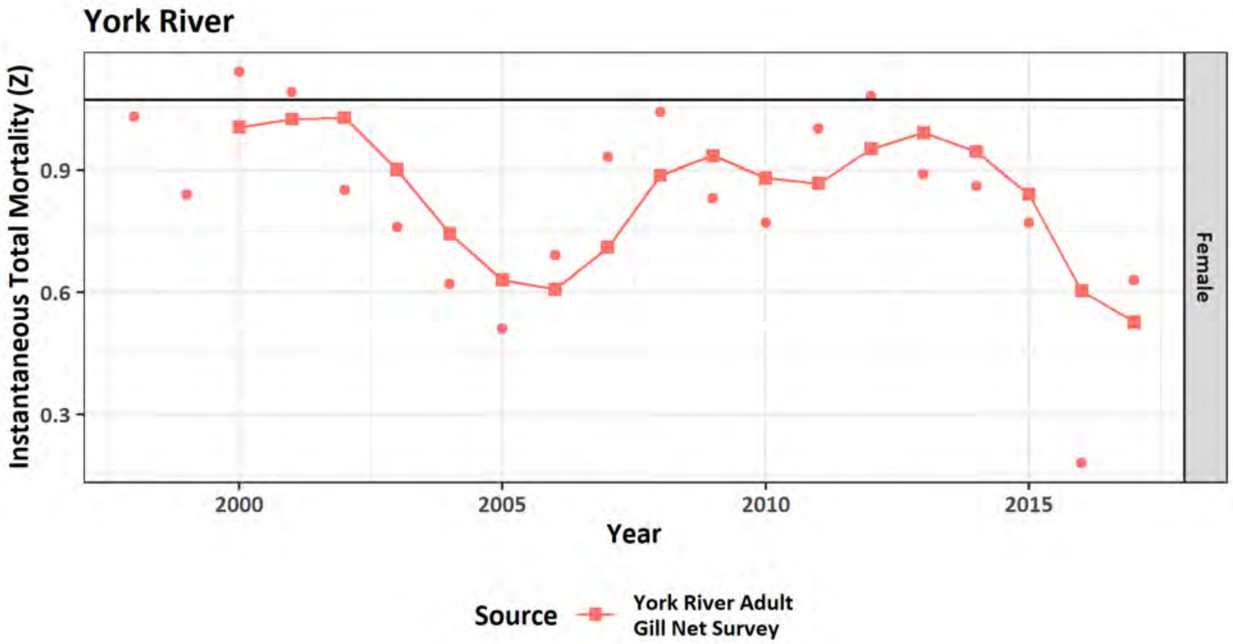


Figure 253. Three year average Z estimates via weighted linear regression by sex and monitoring program for the York River System based on scale-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual Z estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).

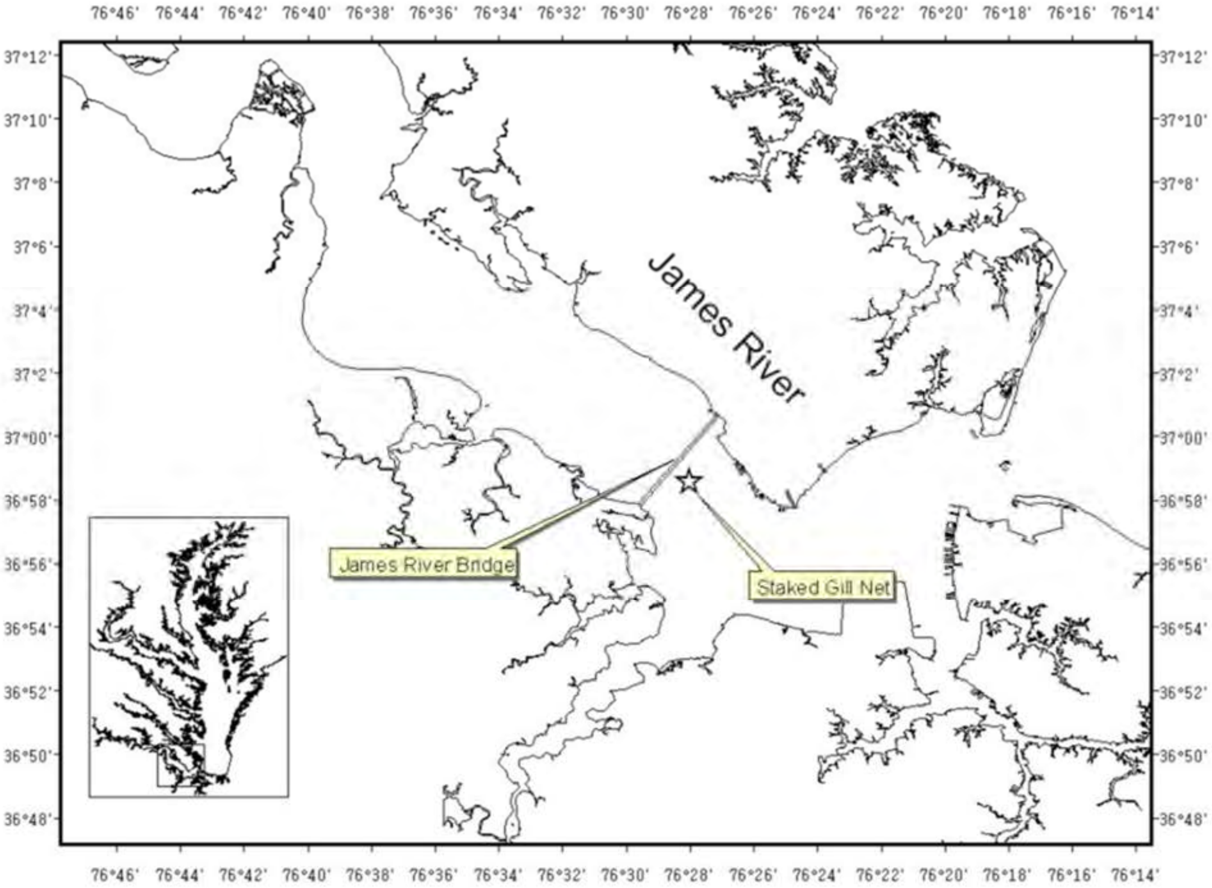


Figure 254. Location of the staked gill net fished by the VIMS James River Adult Gill Net Survey.

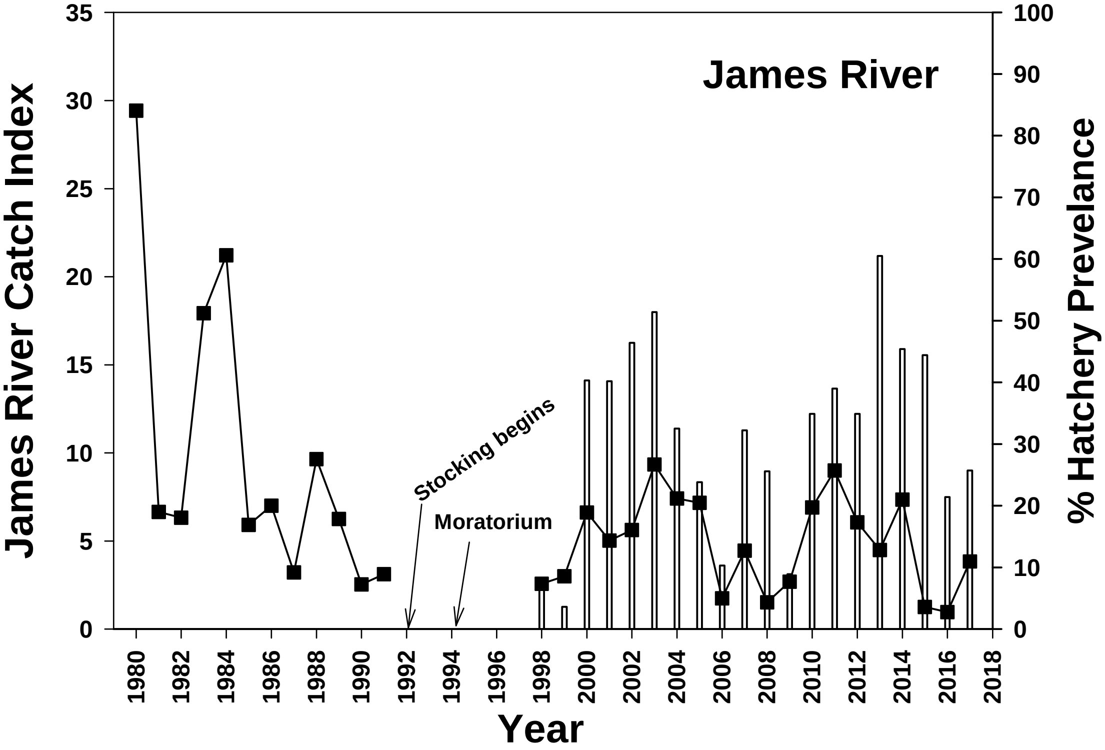


Figure 255. Recent (1998-2017) and historic values of the catch index (weight-based) of female American shad on the James River.

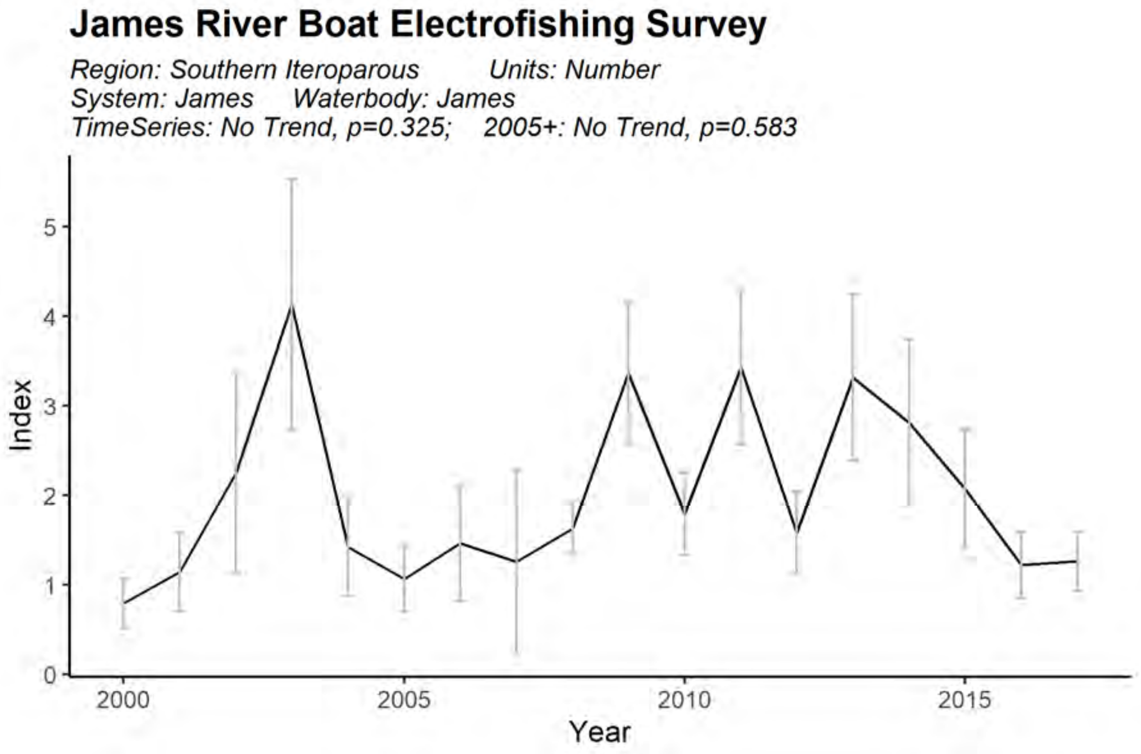


Figure 256. James River Boat Electrofishing Survey index and Mann-Kendall results.

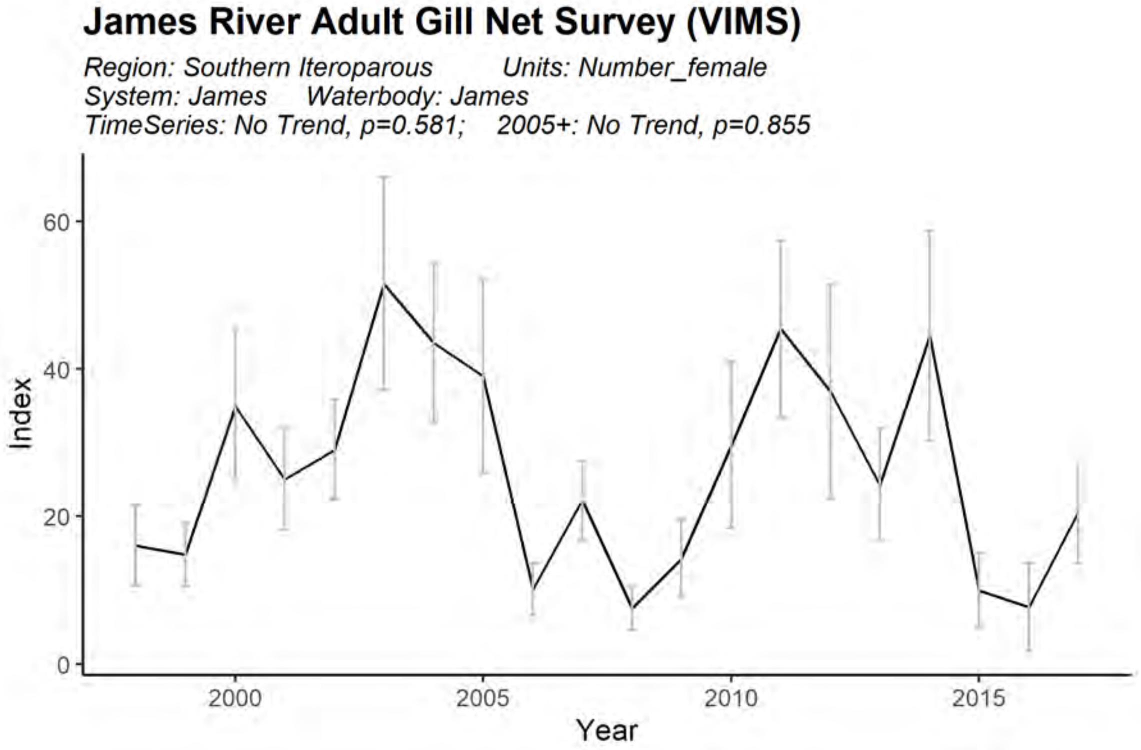


Figure 257. James River Adult Gill Net Survey index and Mann-Kendal results.

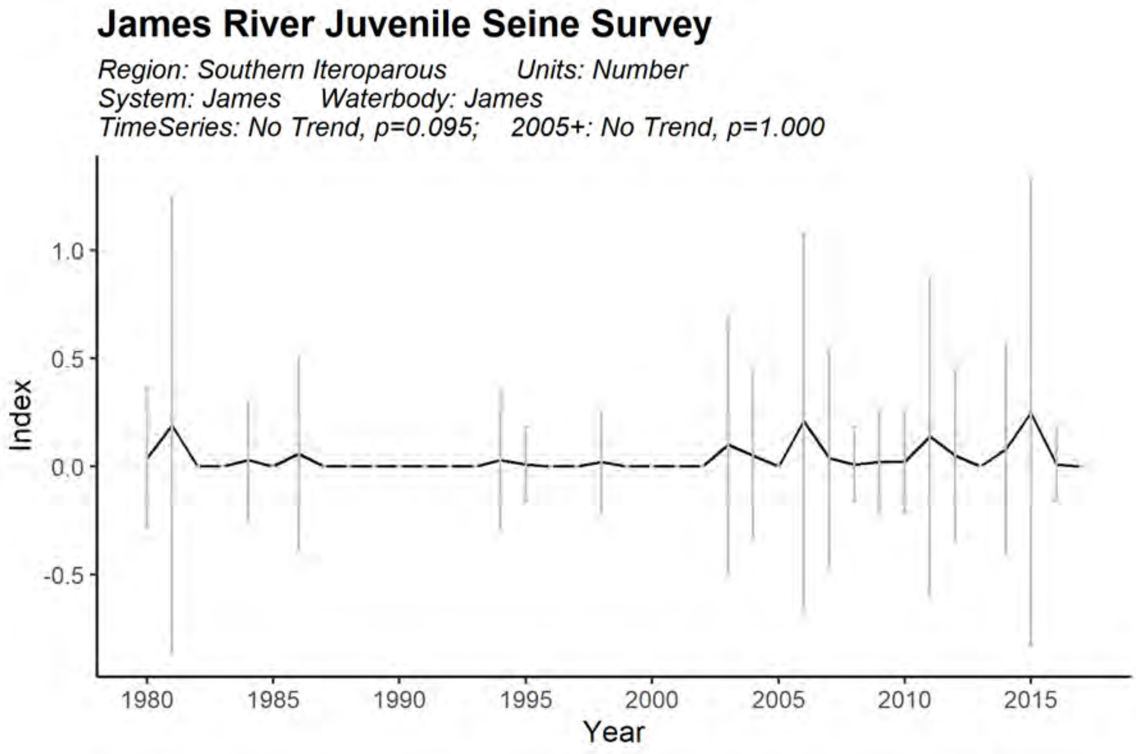


Figure 258. James River Juvenile Seine Survey index and Mann-Kendall results.

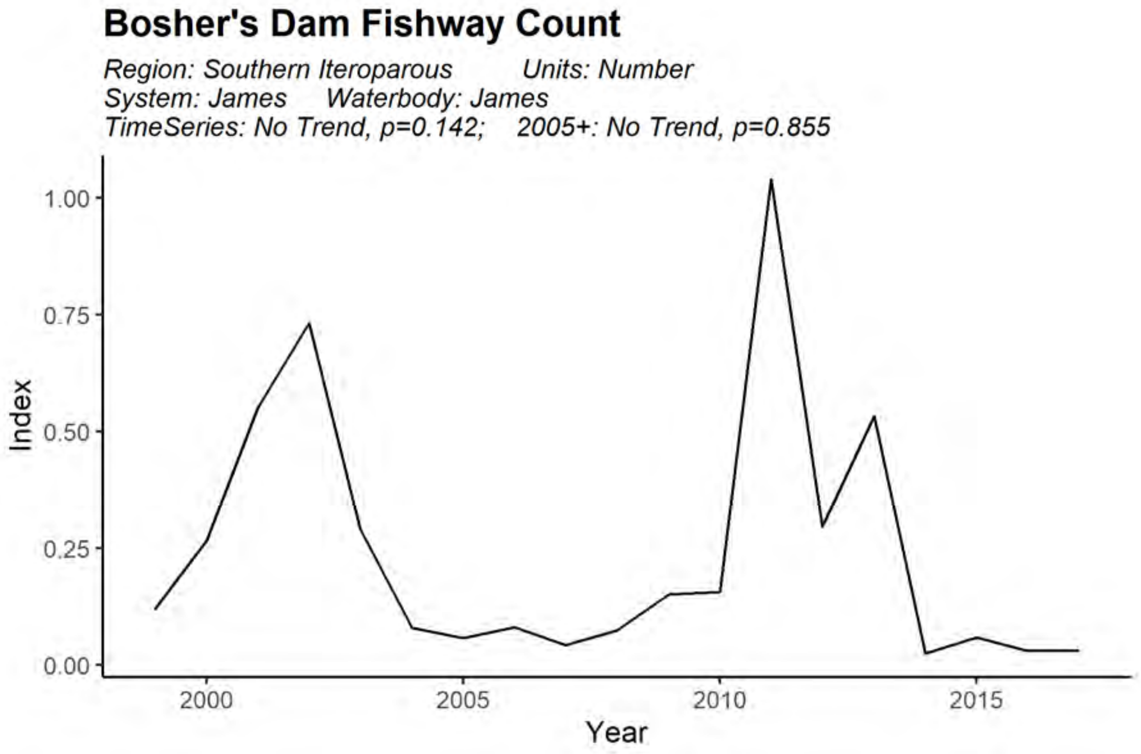


Figure 259. Bosher's Dam Fishway Count index and Mann-Kendall results.

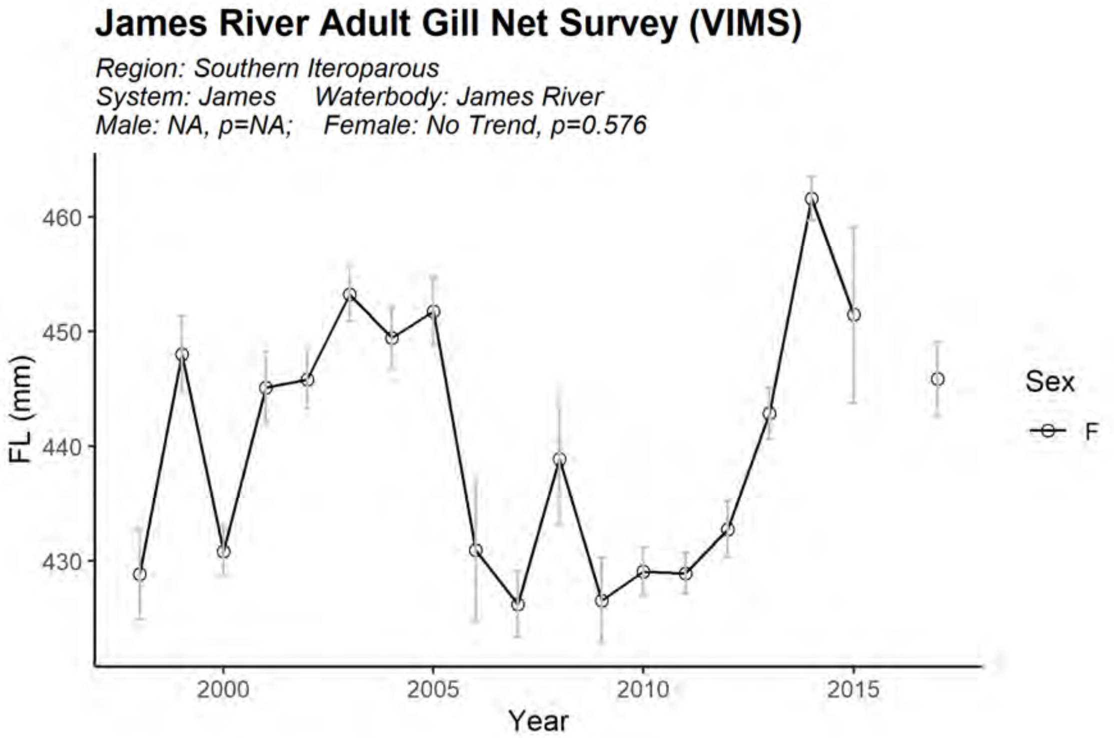


Figure 260. Annual mean length of female American shad from the James River Adult Gill Net Survey and Mann-Kendall results.

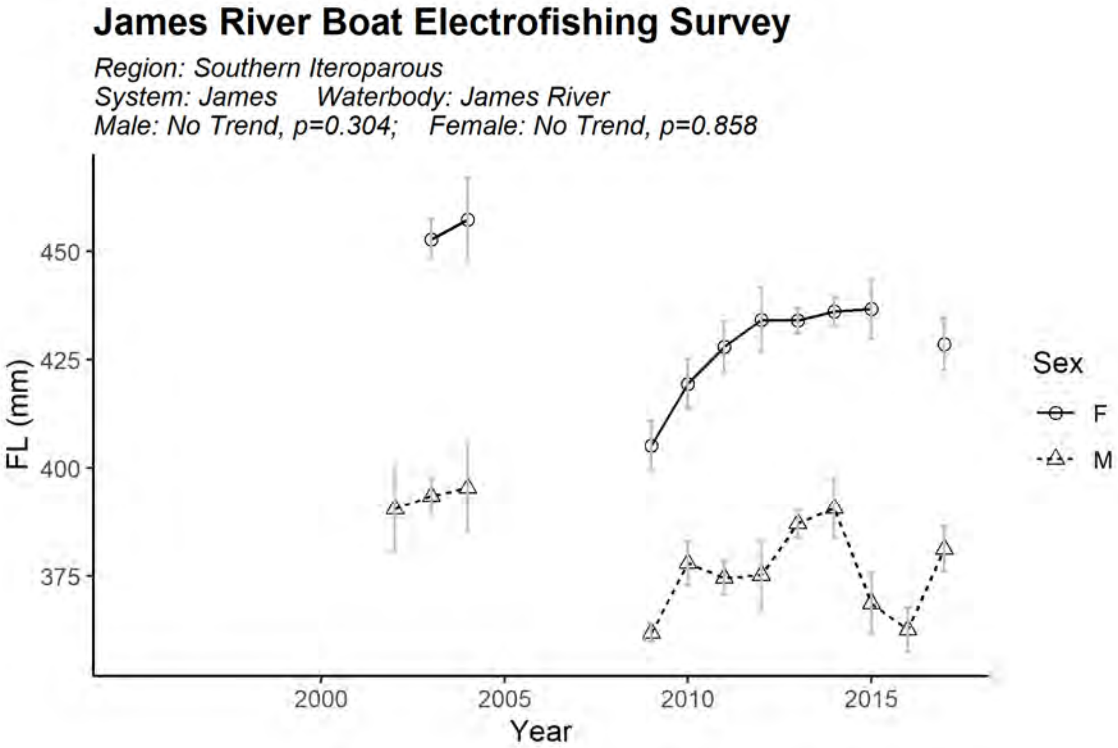


Figure 261. Annual mean length of male and female American shad from the James River Boat Electrofishing Survey and Mann-Kendall results.

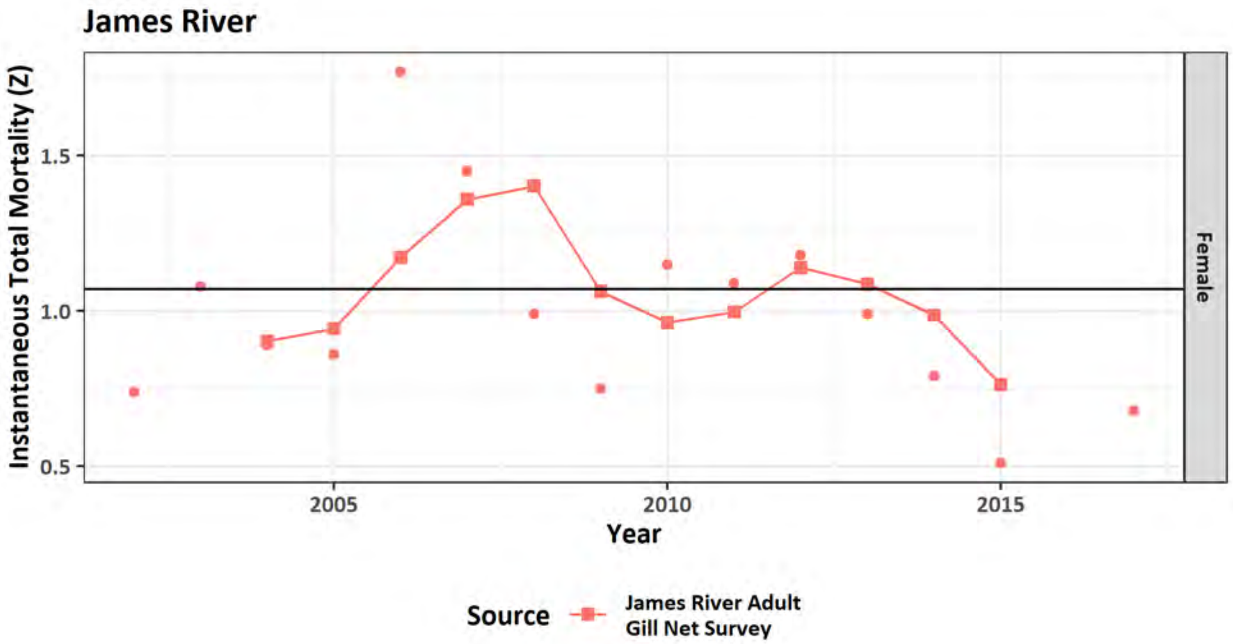


Figure 262. Three year average Z estimates via weighted linear regression by sex and monitoring program for the James River System based on scale-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual Z estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).

Figure 263. Map of North Carolina river systems including major dams and shad sustainability areas.

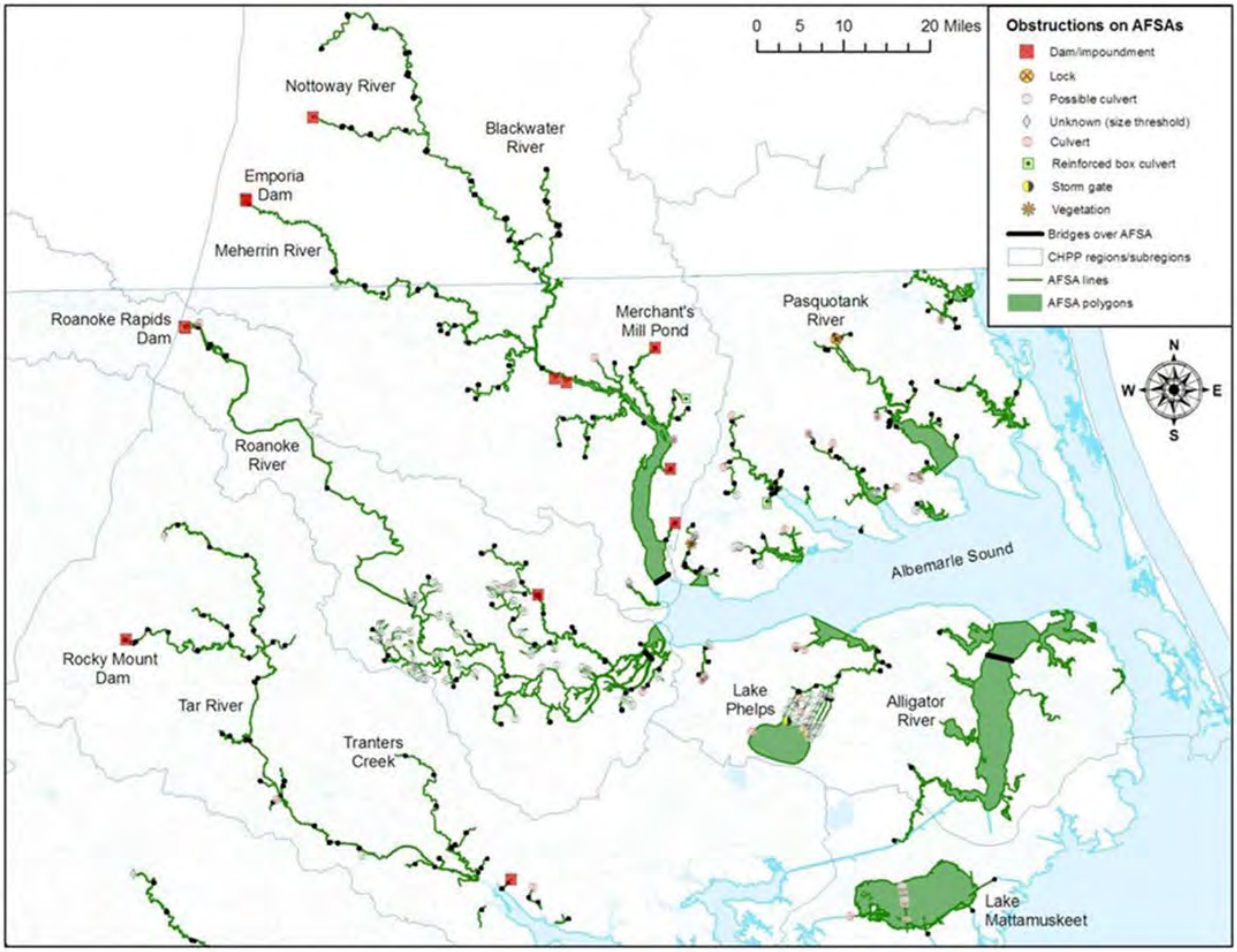


Figure 264. Anadromous fish spawning areas in the Albemarle Sound and Tar-Pamlico River areas (NCDMF and NCWRC 2014).

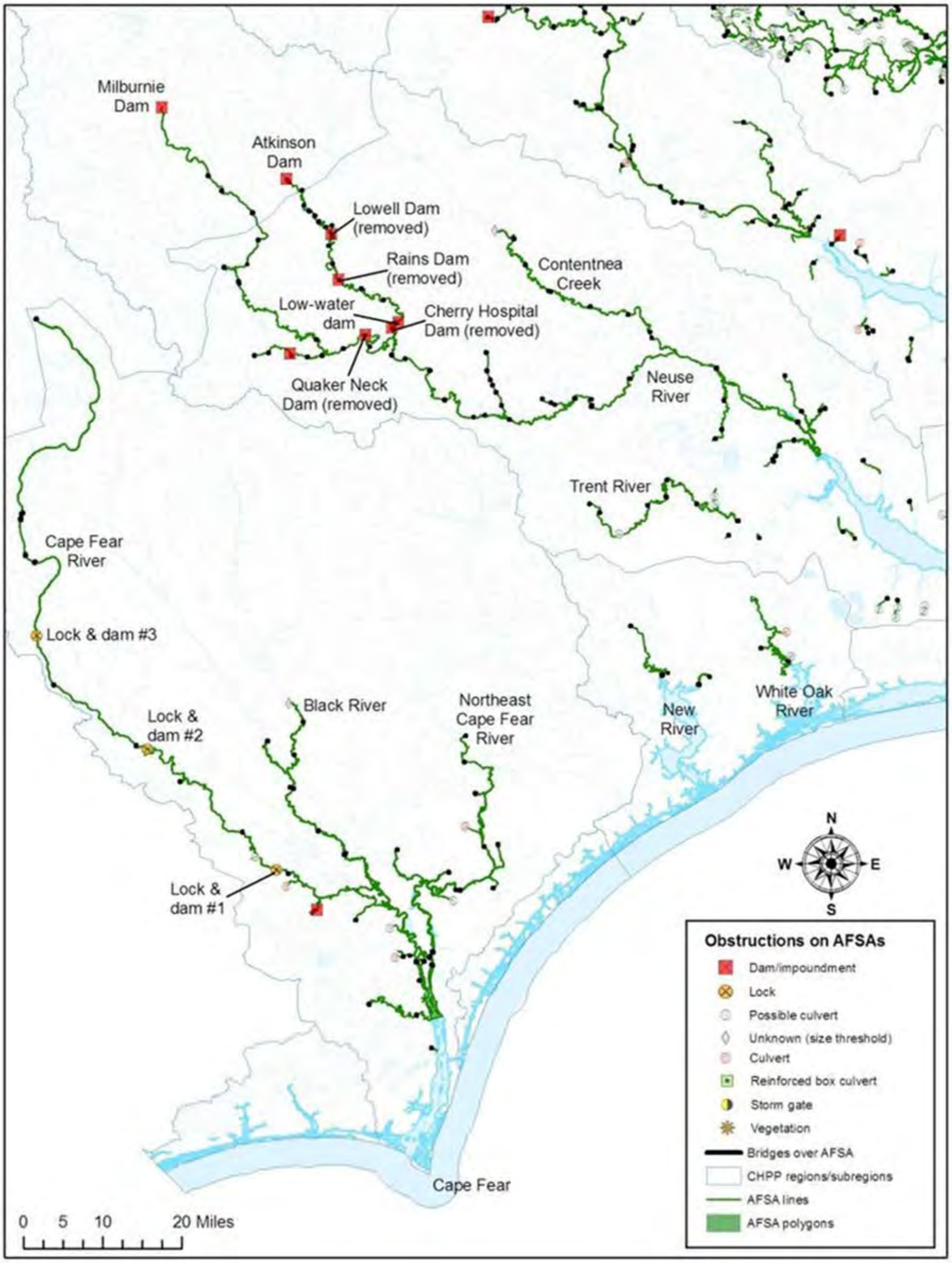


Figure 265. Anadromous fish spawning areas in the Neuse River and Cape Fear River areas (NCDMF and NCWRC 2014). Note: Milburnie Dam on the Neuse River was removed in 2017.

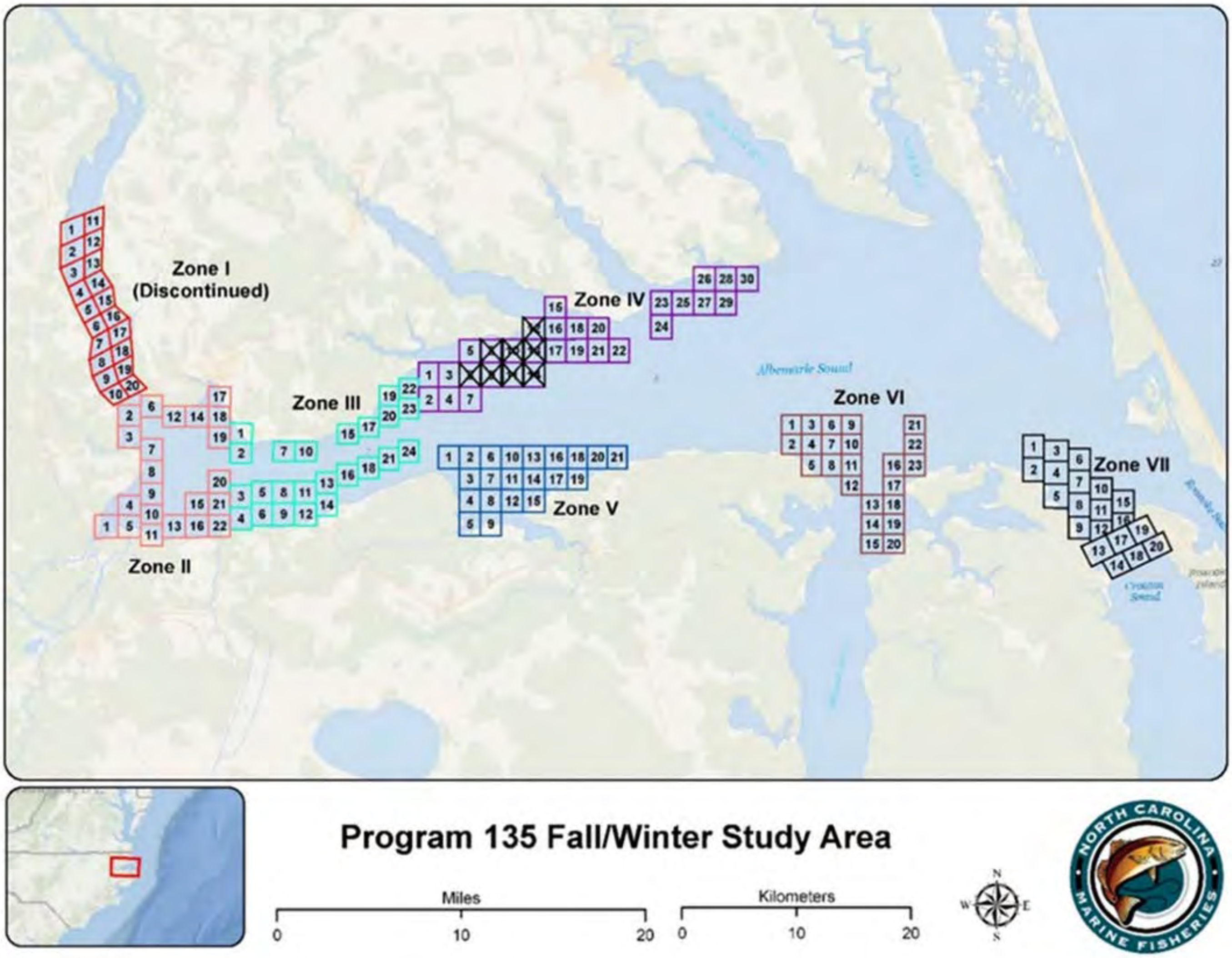


Figure 266. Sample zones for the NCDMF Albemarle Sound Fall/Winter Independent Gill Net Survey, Albemarle and Croatan sounds, NC. Zone I sampling discontinued at the end of the 1993 season, at which time sampling in Zone VII commenced.

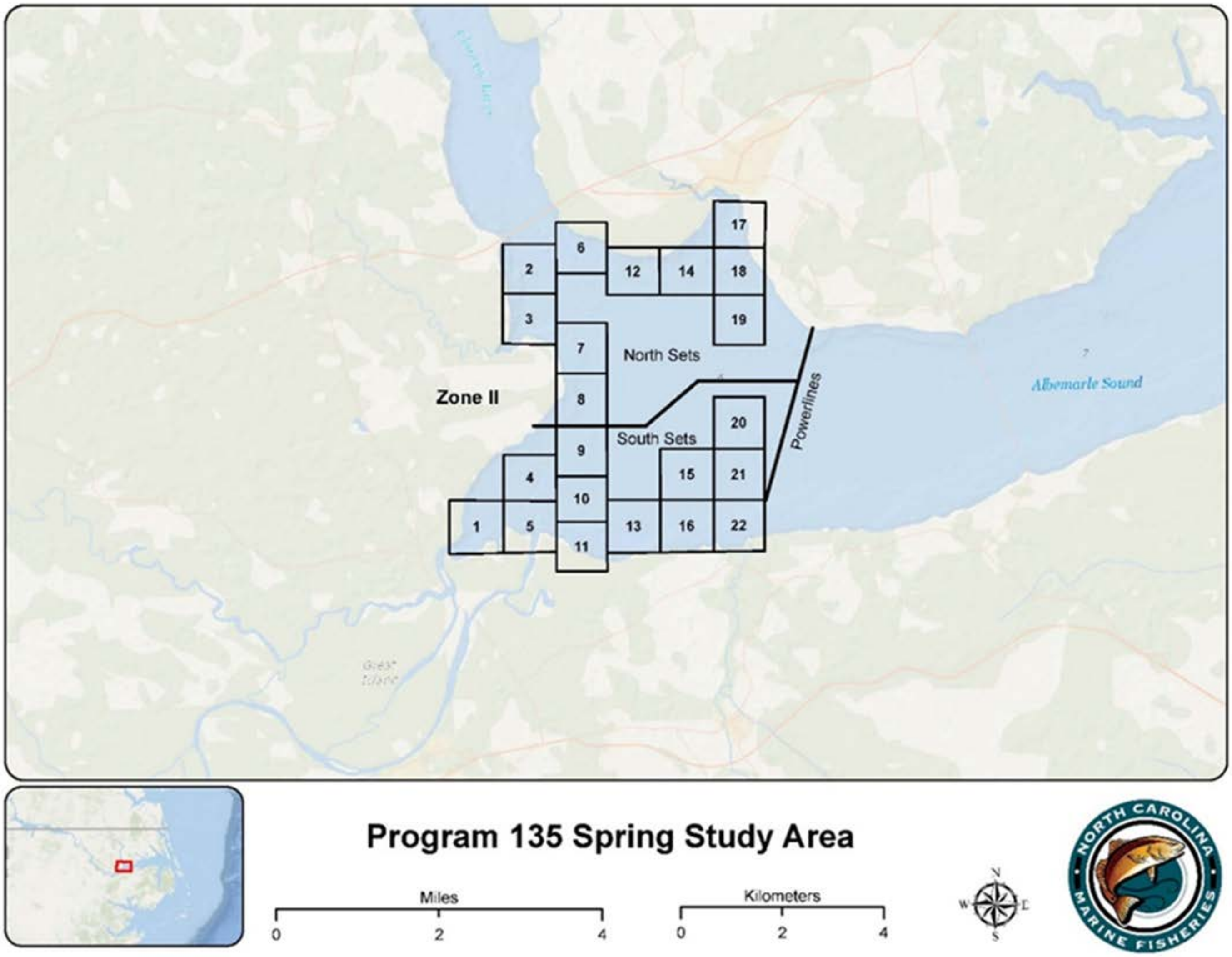


Figure 267. Sample zones for the NCDMF Albemarle Sound Independent Gill Net Survey, grid and area locations in Zone II.

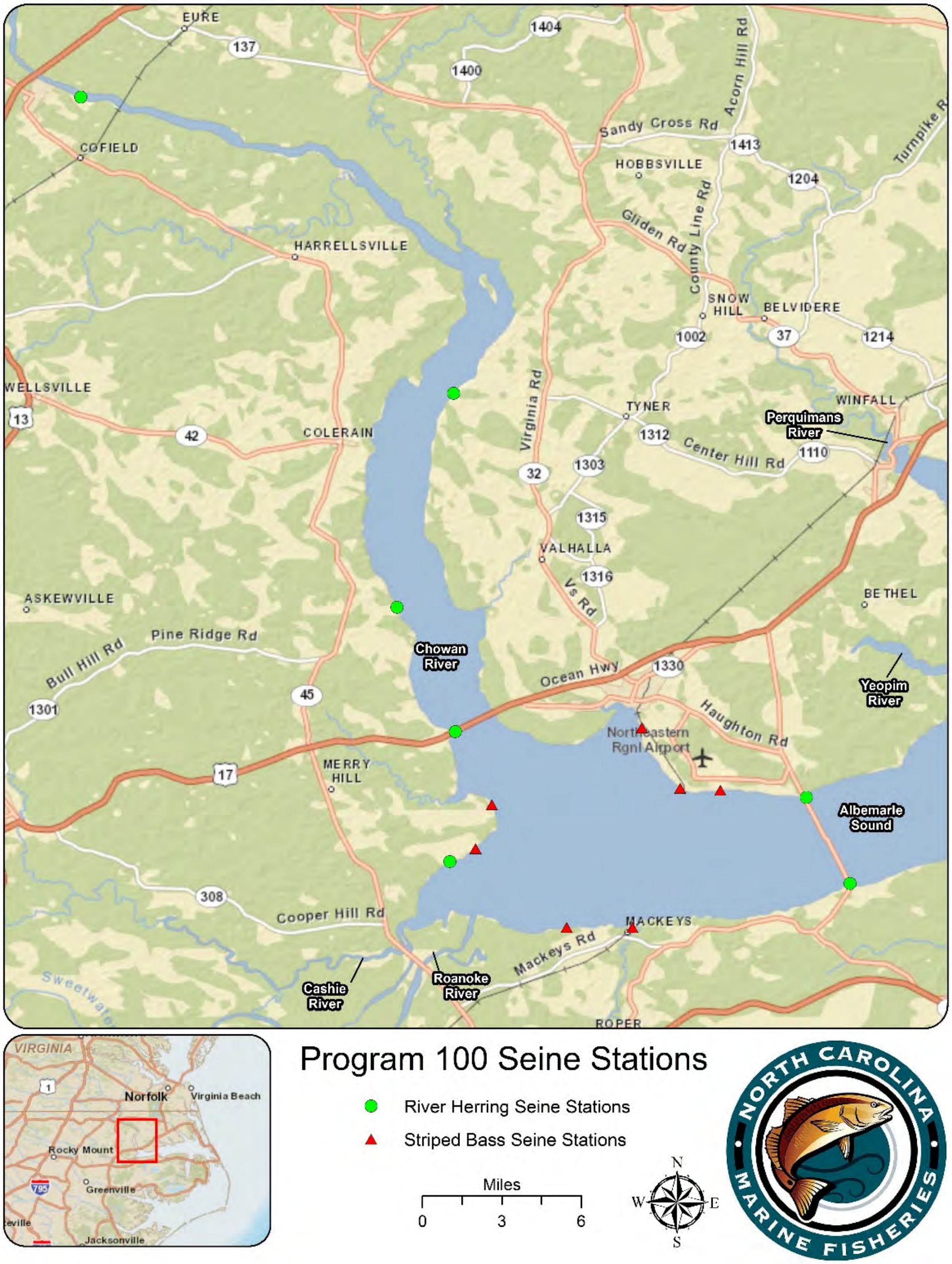


Figure 268. NCDMF Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey stations.

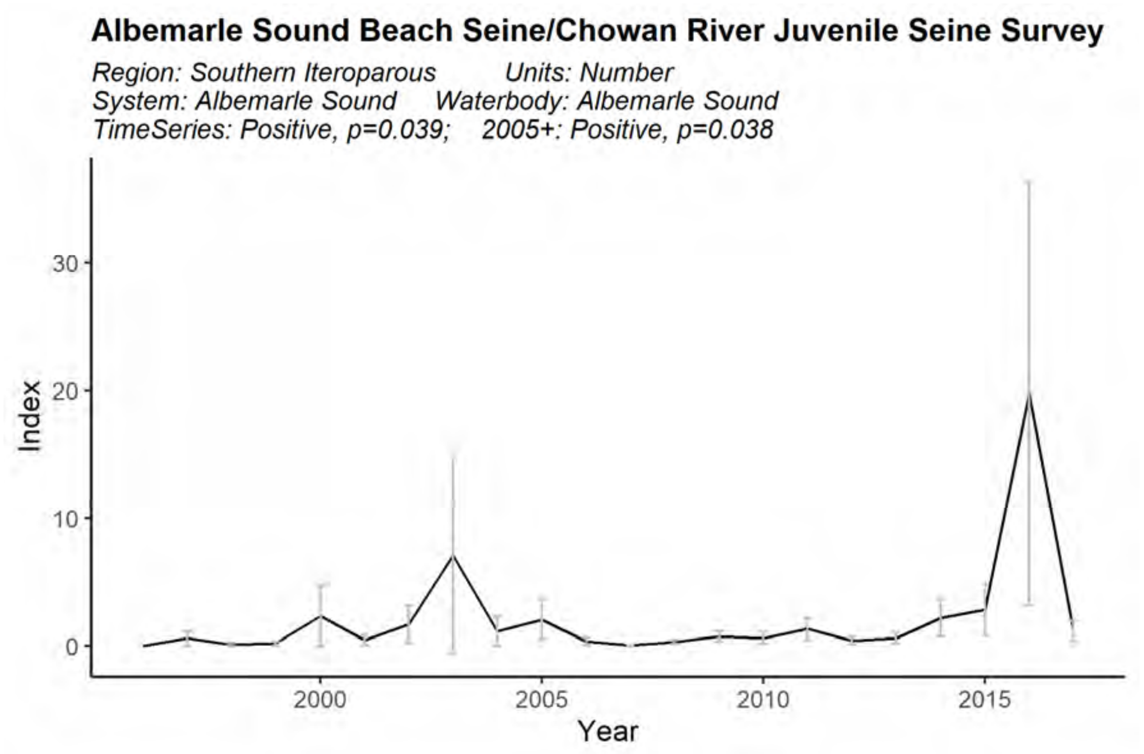


Figure 269. Abundance index developed from the Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey and Mann-Kendall results.

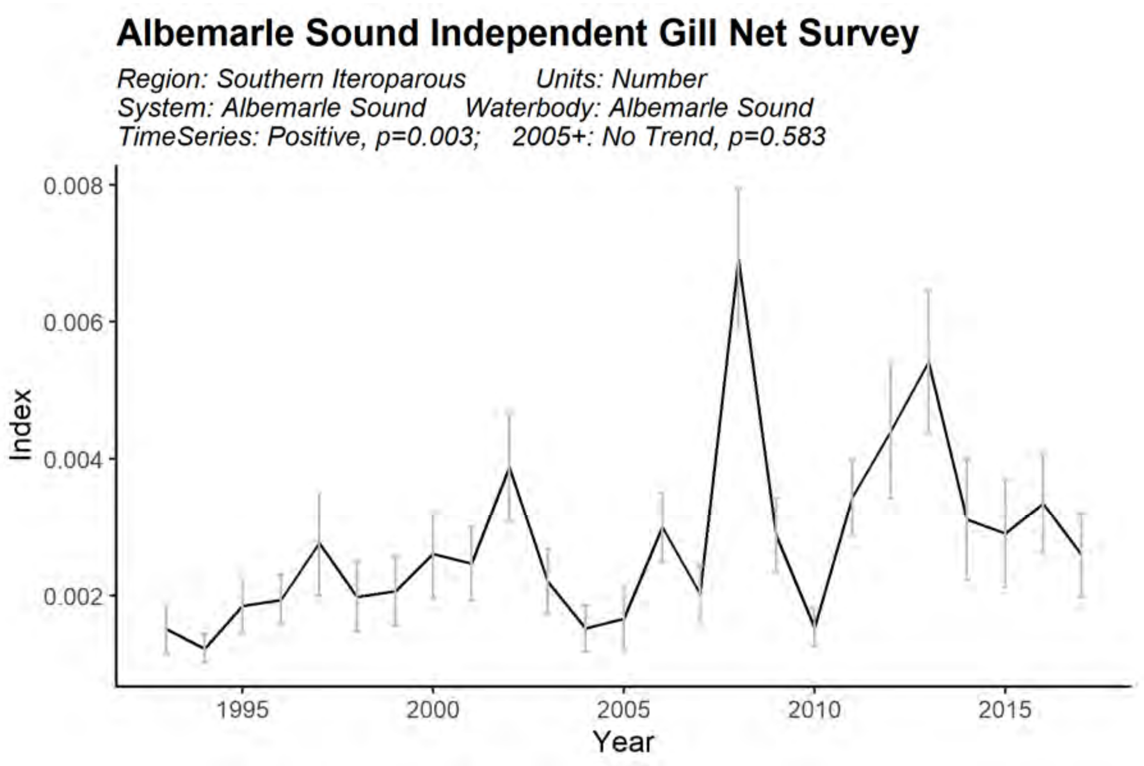


Figure 270. Abundance index developed from the Albemarle Sound Independent Gill Net Survey and Mann-Kendall results.

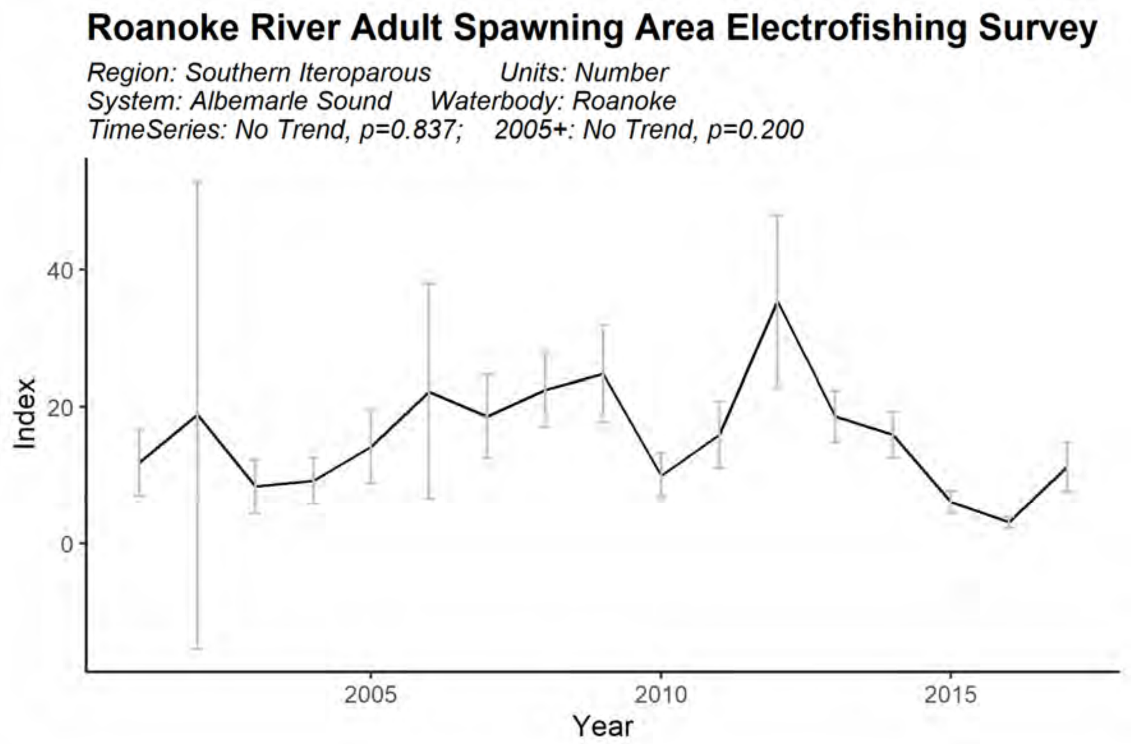


Figure 271. **Abundance index developed from the Roanoke River Adult Spawning Area Electrofishing Survey and Mann-Kendall results.**

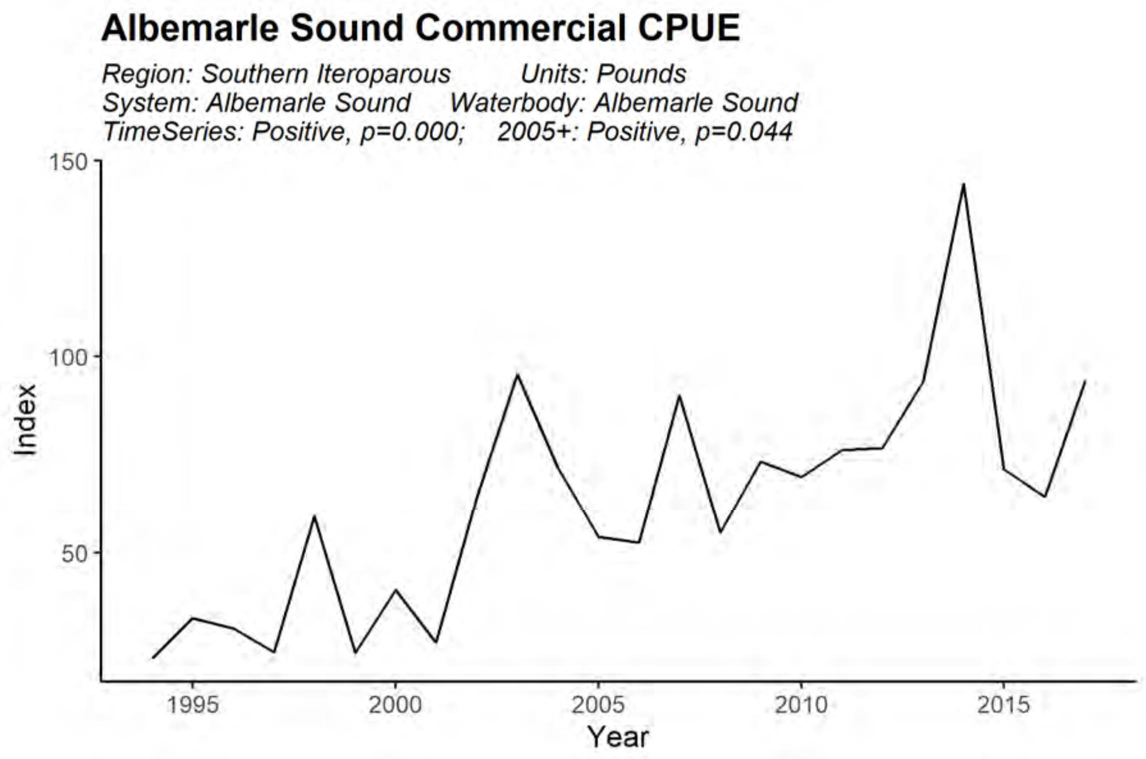


Figure 272. **Abundance index developed from the Albemarle Sound Commercial CPUE and Mann-Kendall results.**

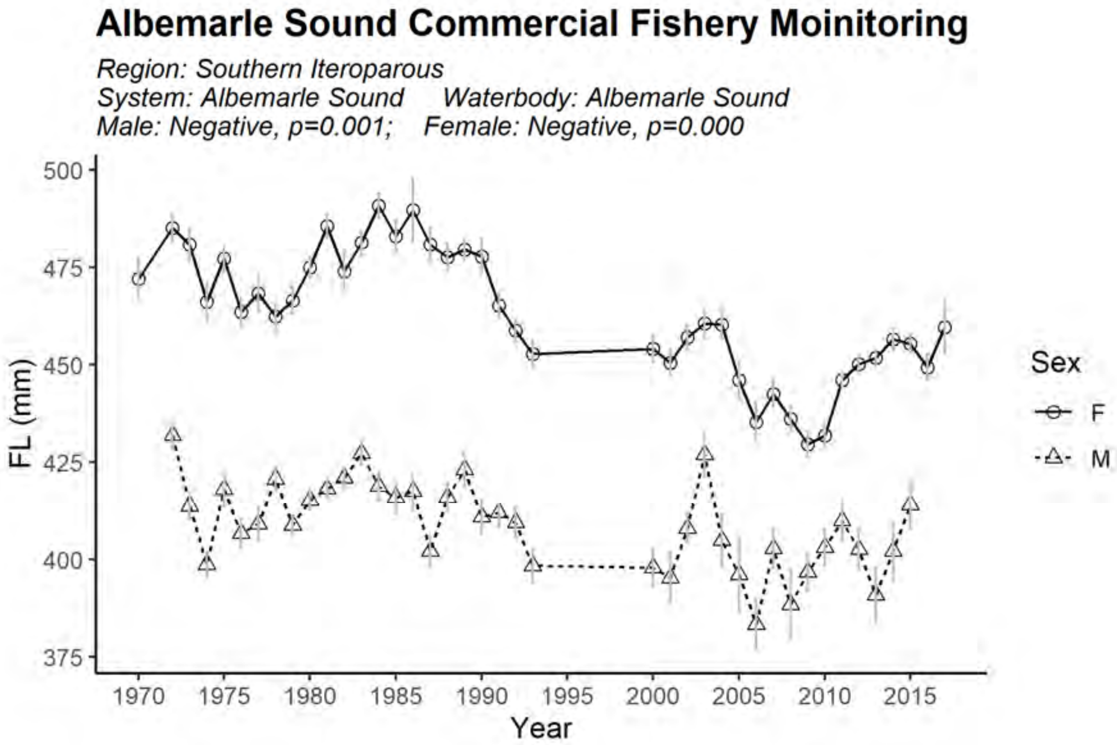


Figure 273. Mean fork length over time for the Albemarle Sound Commercial Monitoring and Mann-Kendall results.

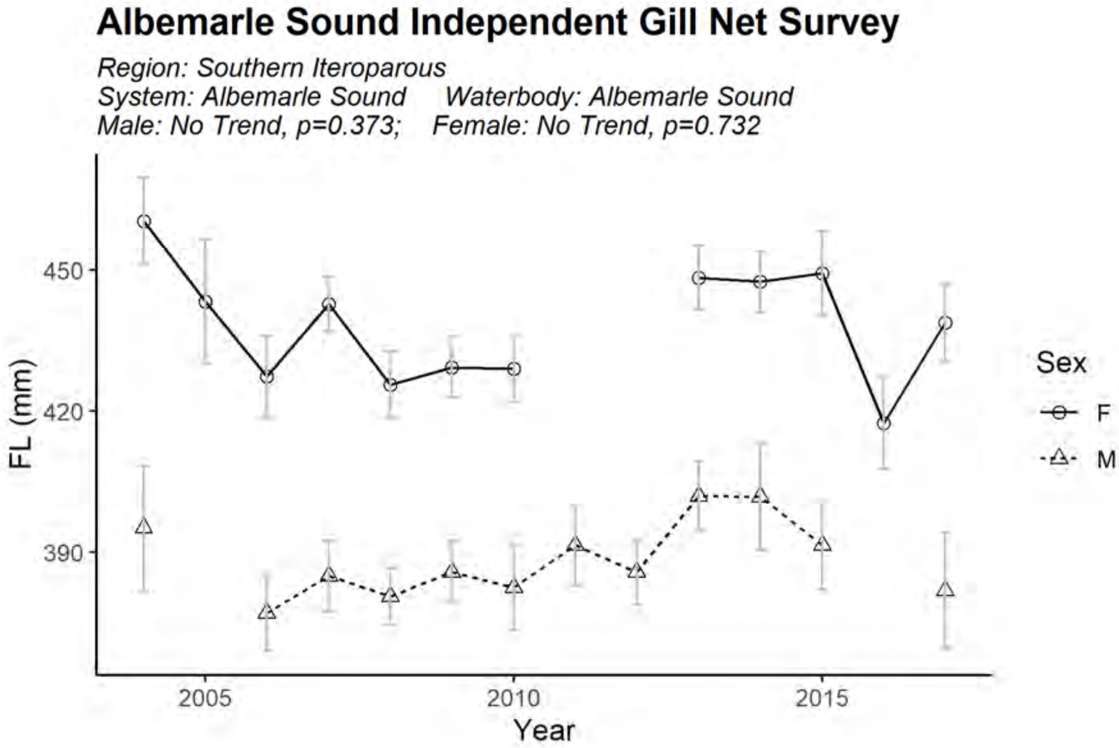


Figure 274. Mean fork length over time for the Albemarle Sound Independent Gill Net Survey and Mann-Kendall results.

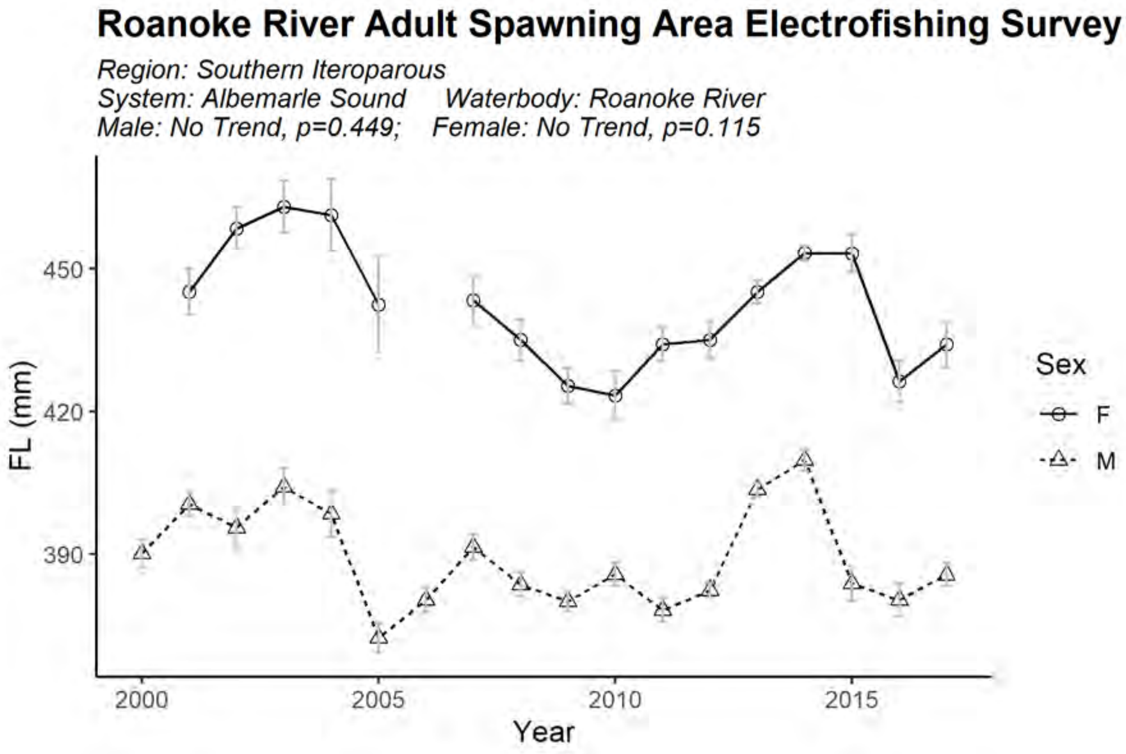


Figure 275. Mean fork length over time for the Roanoke River Adult Spawning Area Electrofishing Survey and Mann-Kendall results.

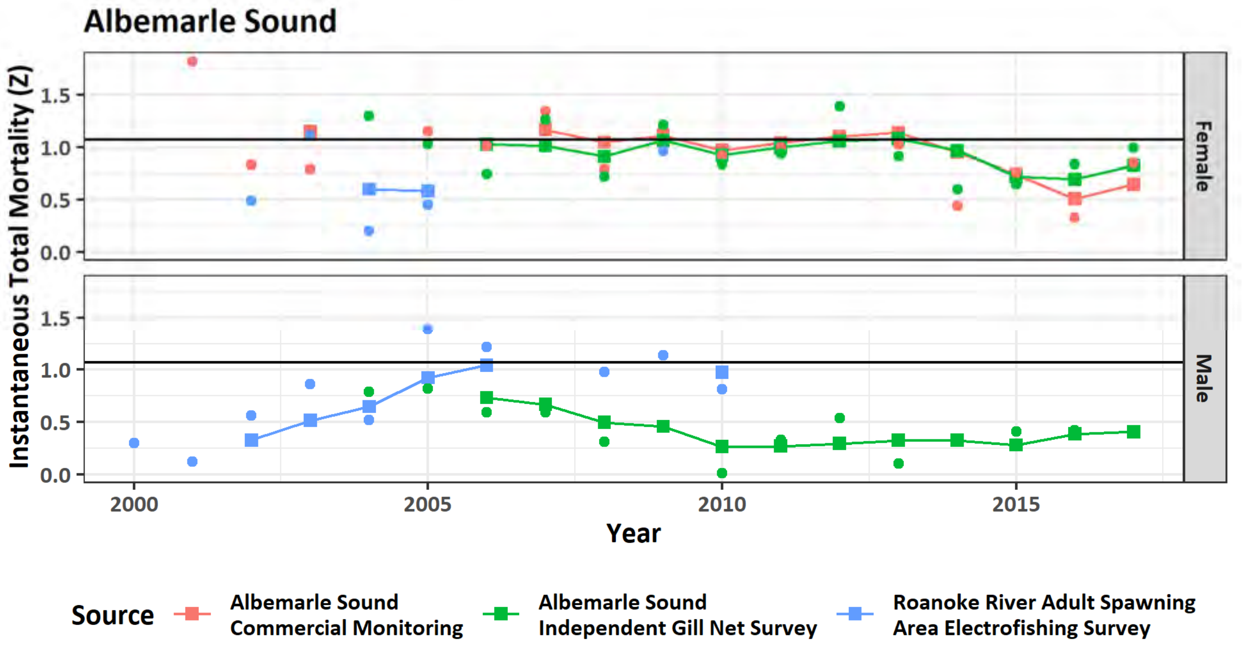


Figure 276. Three year average Z estimates via weighted linear regression by sex and monitoring program for the Albemarle Sound System based on scale-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual Z estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific Z40% reference points (solid, horizontal, black line).

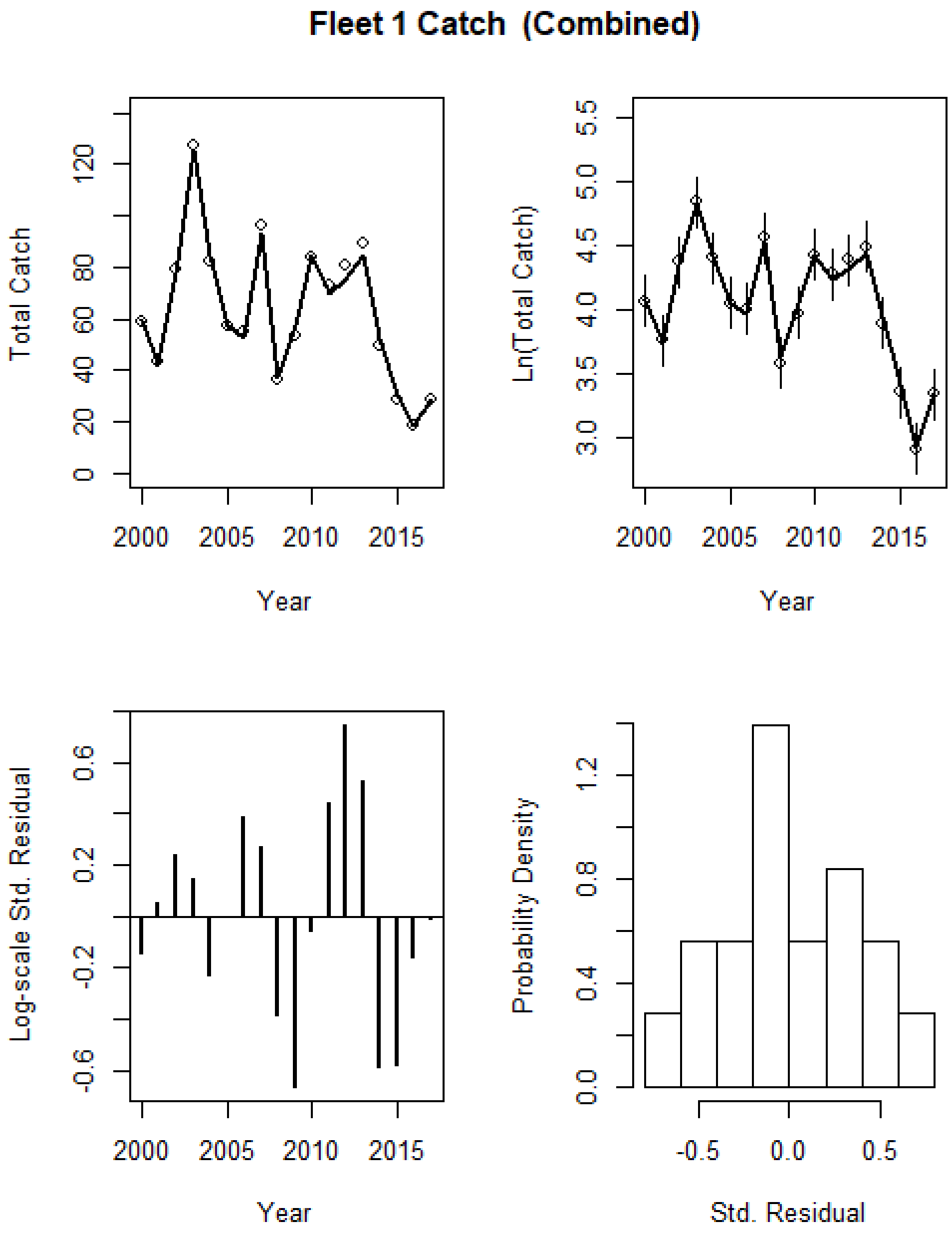


Figure 277. Fit diagnostics for total fishery catch (modeled as one fleet) in the final Albemarle Sound ASAP model.

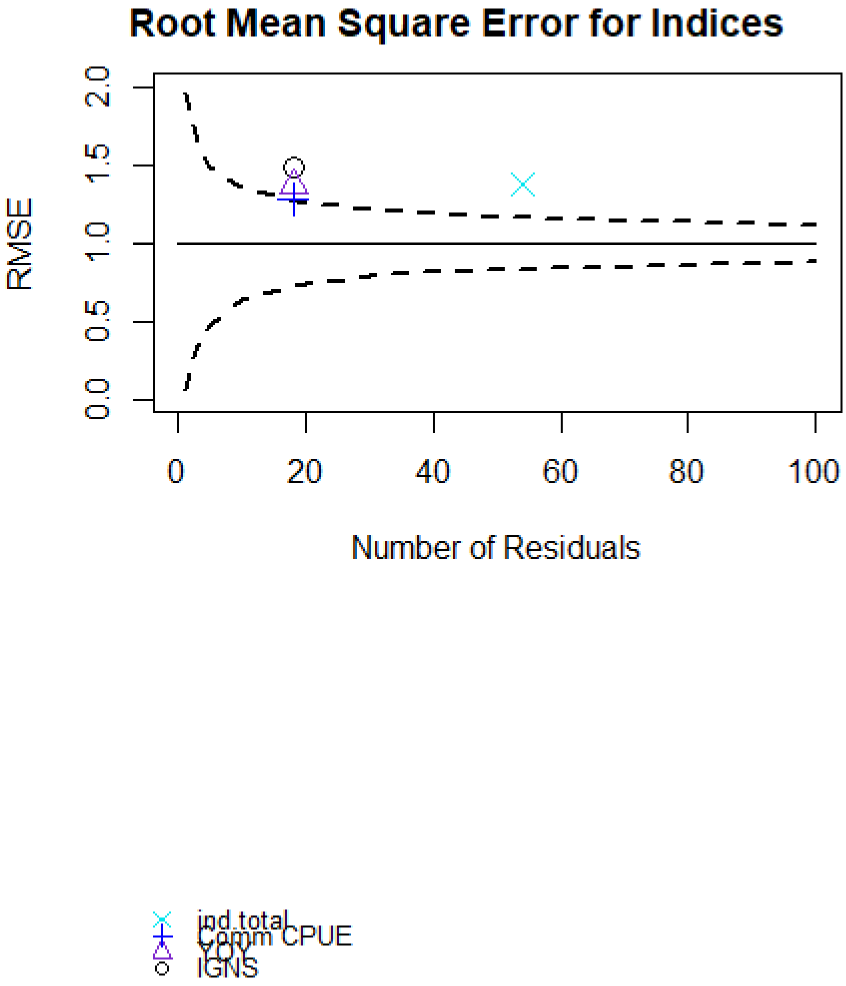


Figure 278. Root mean square errors (RMSE) for each index included in the final Albemarle Sound ASAP model. Comm CPUE is the Albemarle Sound Commercial CPUE, YOY is the Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey index, and IGNS is the Albemarle Sound Independent Gill Net Survey index.

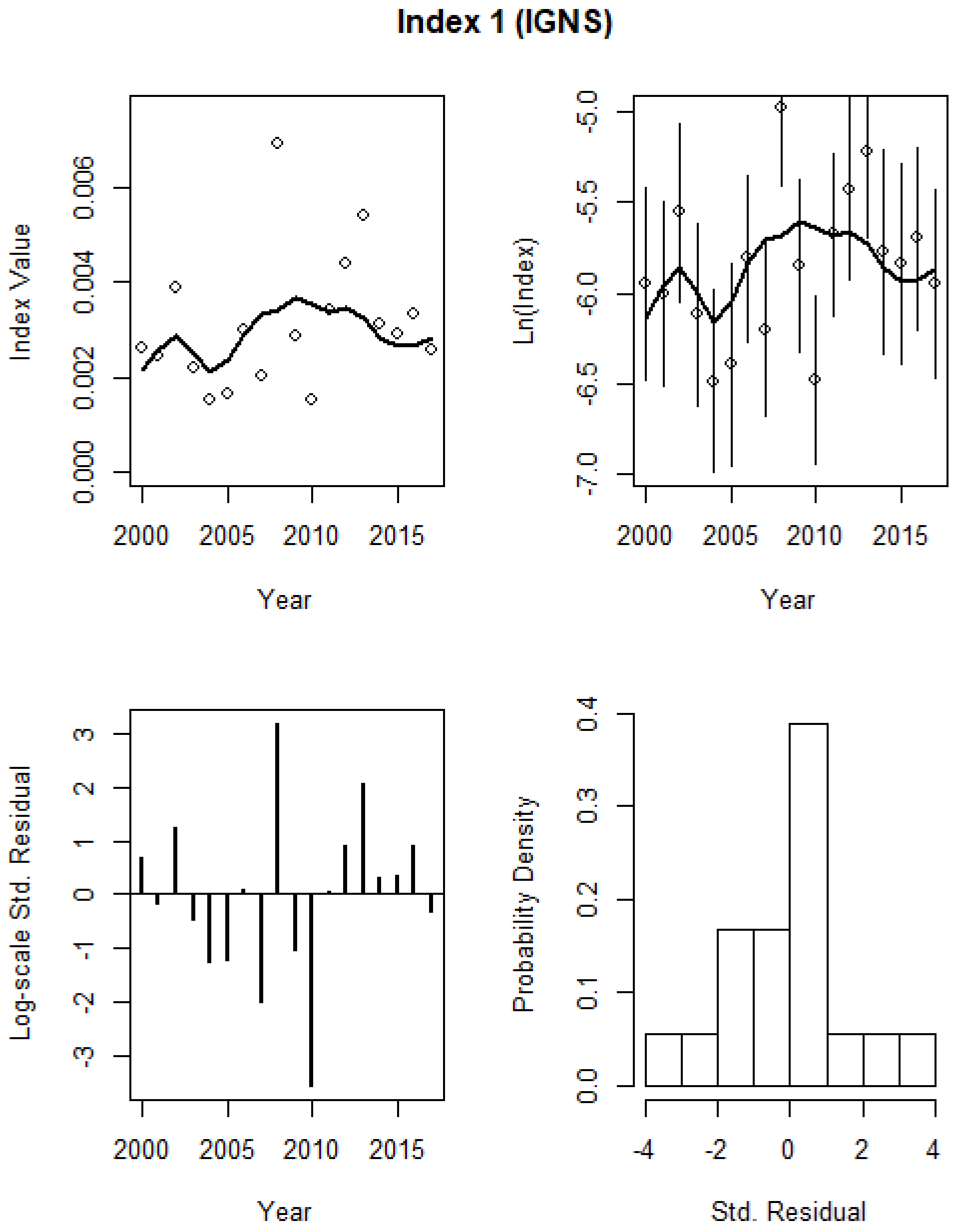


Figure 279. Fit diagnostics for the Albemarle Sound Independent Gill Net Survey index in the final Albemarle Sound ASAP model.

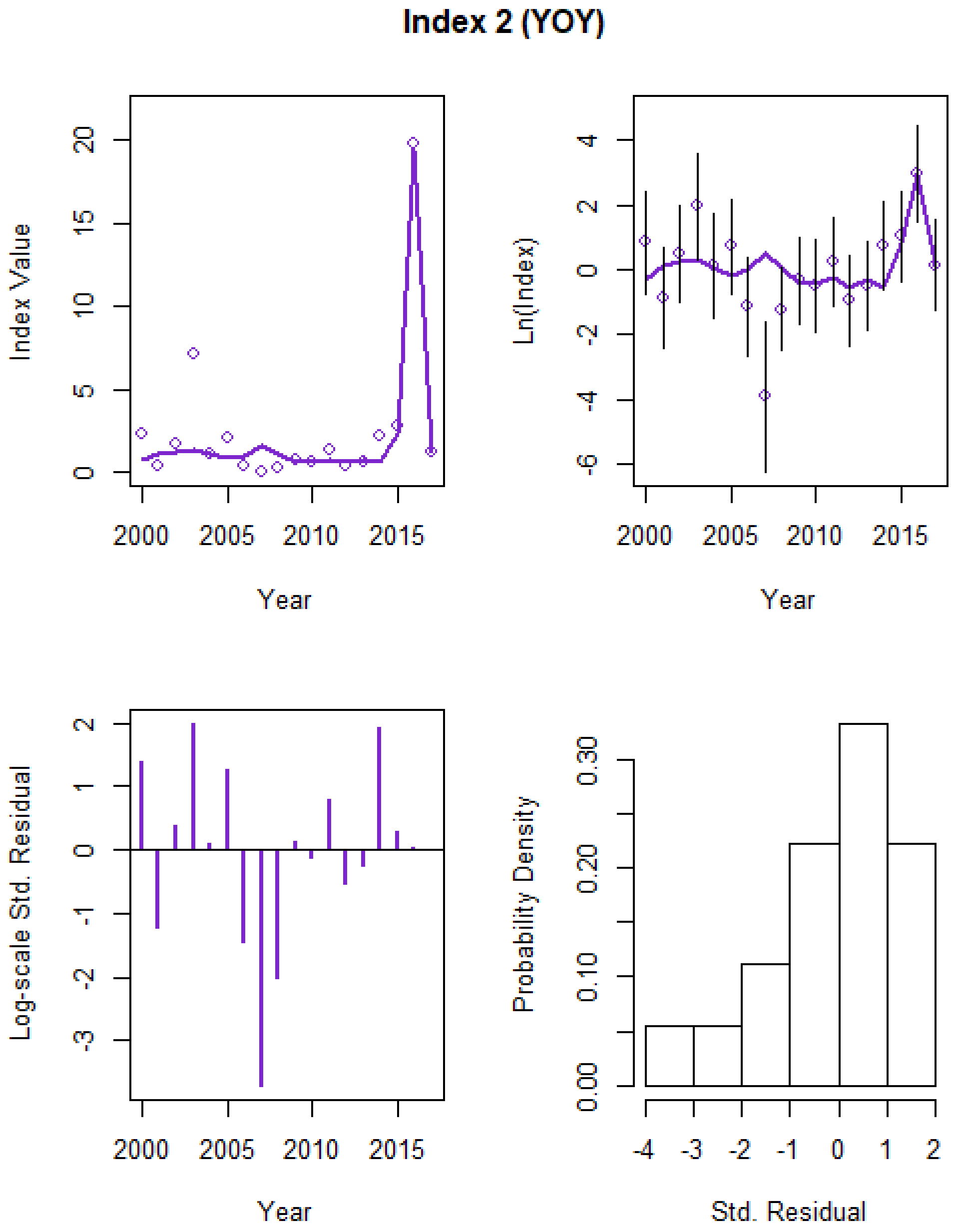


Figure 280. Fit diagnostics for the Albemarle Sound Beach Seine/Chowan River Juvenile Seine Survey index in the final Albemarle Sound ASAP model.

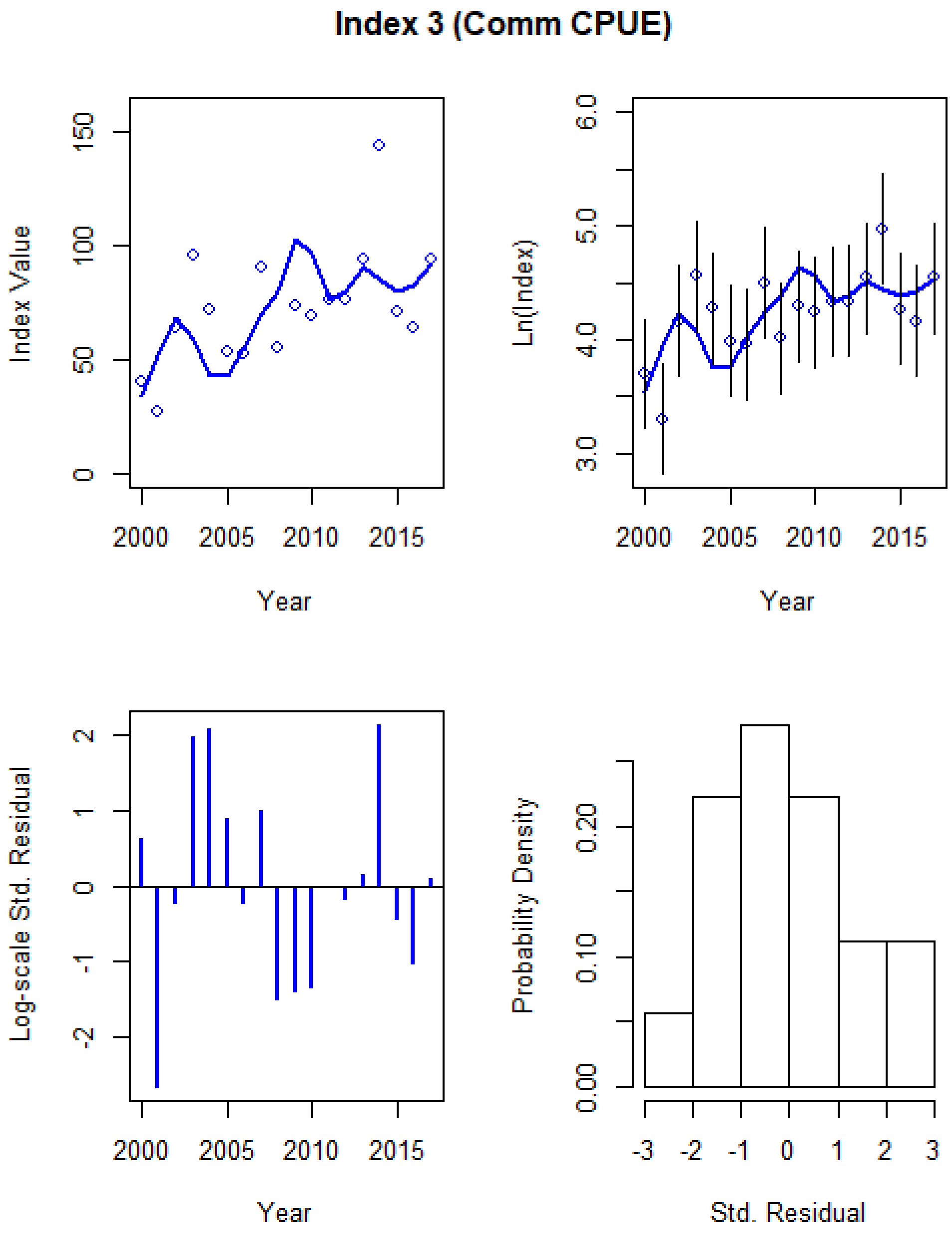


Figure 281. Fit diagnostics for the Albemarle Sound Commercial CPUE index in the final Albemarle Sound ASAP model.

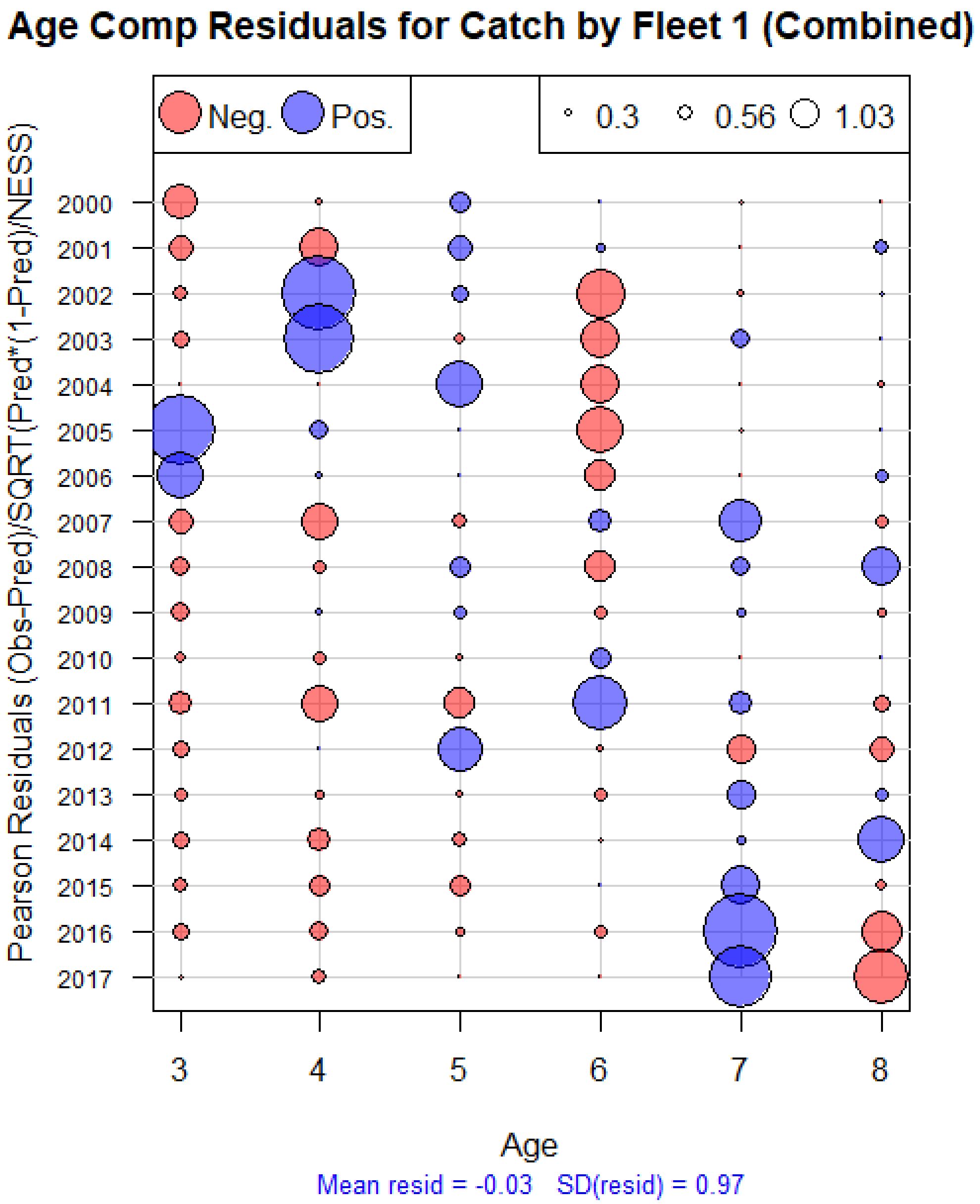


Figure 282. Pearson residuals for fishery age composition data from the final Albemarle Sound ASAP model.

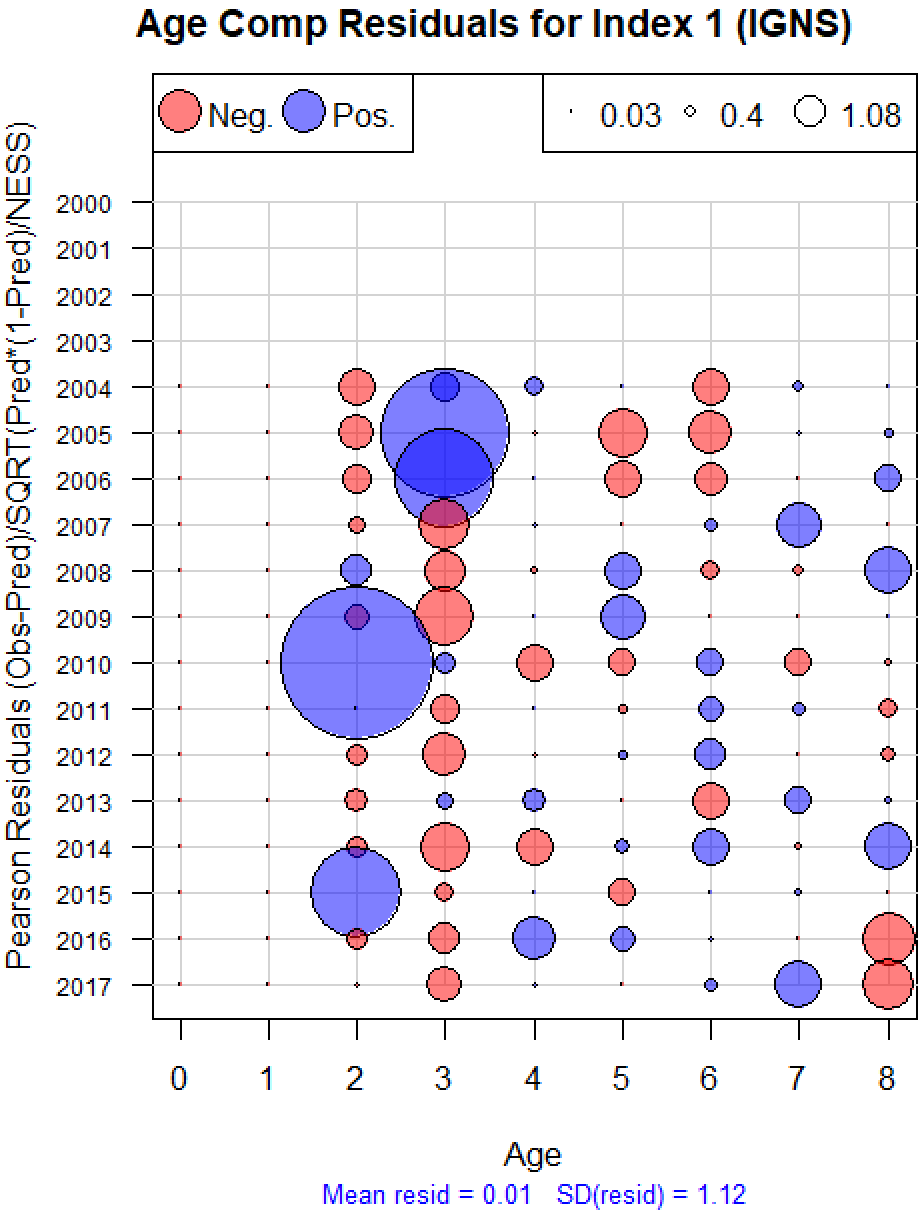


Figure 283. Pearson residuals for Albemarle Sound Independent Gill Net Survey age composition data from the final Albemarle Sound ASAP model.

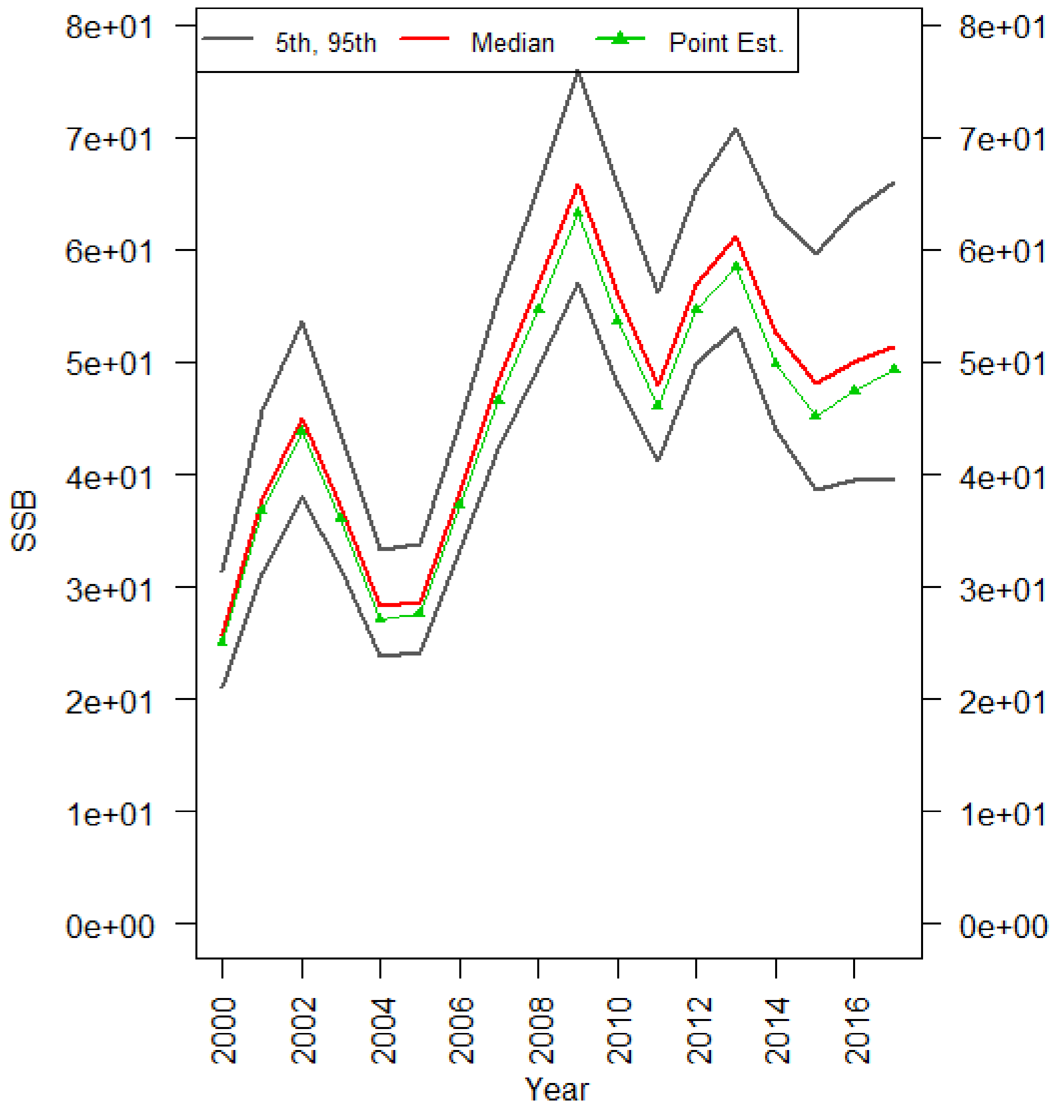


Figure 284. Estimated American shad spawning stock biomass (metric tons) and associated 90% probability interval from the final Albemarle Sound ASAP model. The dark grey lines represent the 5th and 95th percentiles and the green triangles represent the model point estimates.

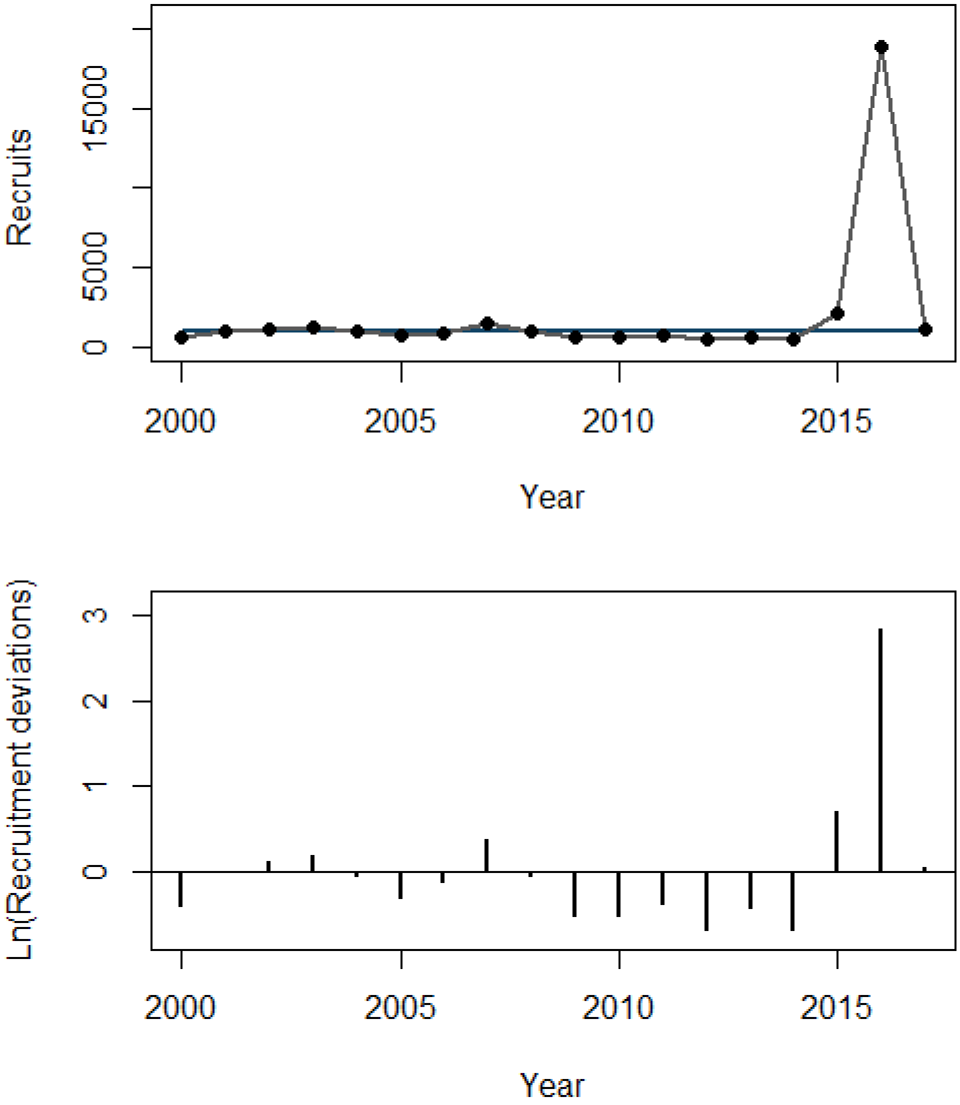


Figure 285. American shad estimated recruitment and recruitment residuals from the geometric mean for the final Albemarle Sound ASAP model.

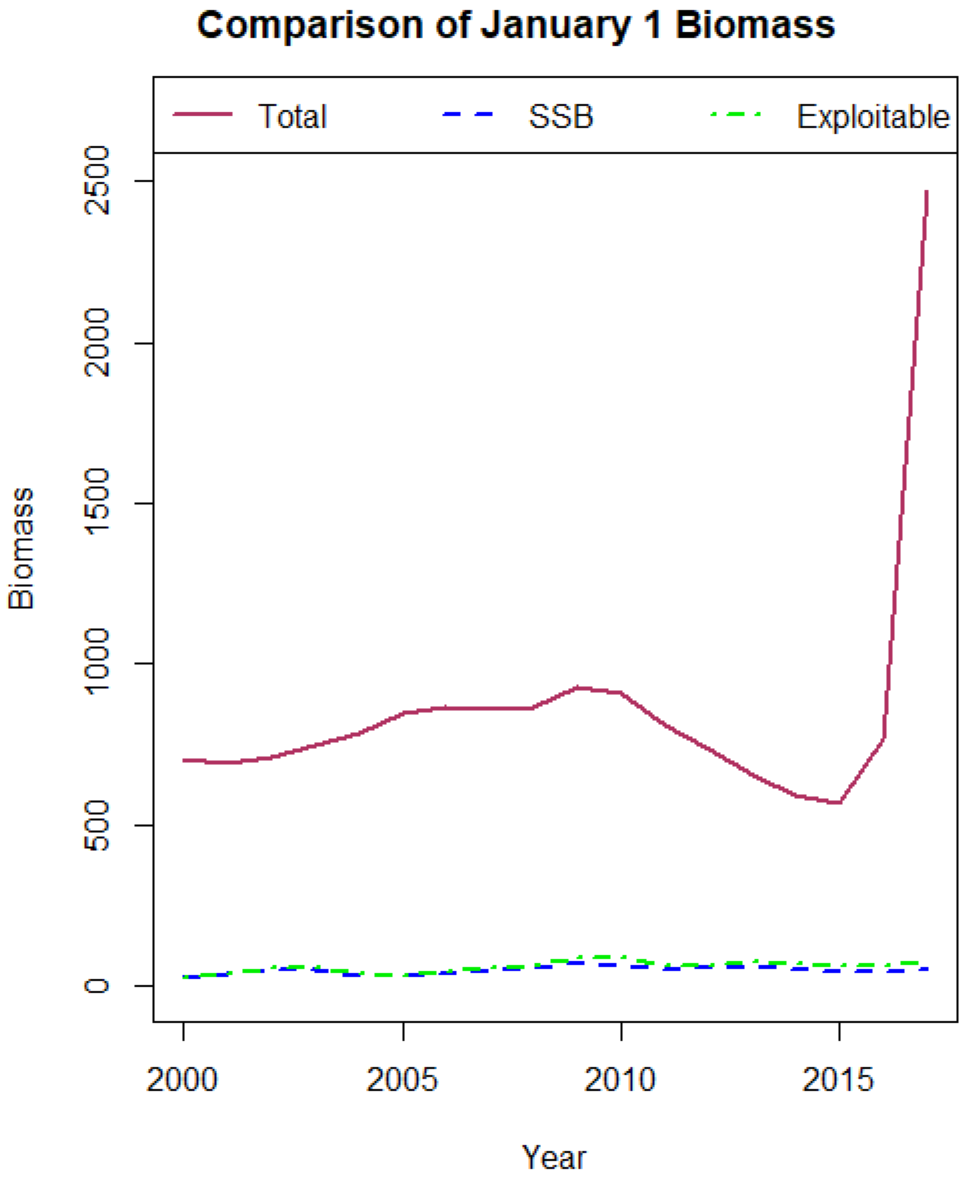


Figure 286. American shad estimated total, spawning stock and exploitable biomass from the final Albemarle Sound ASAP model.

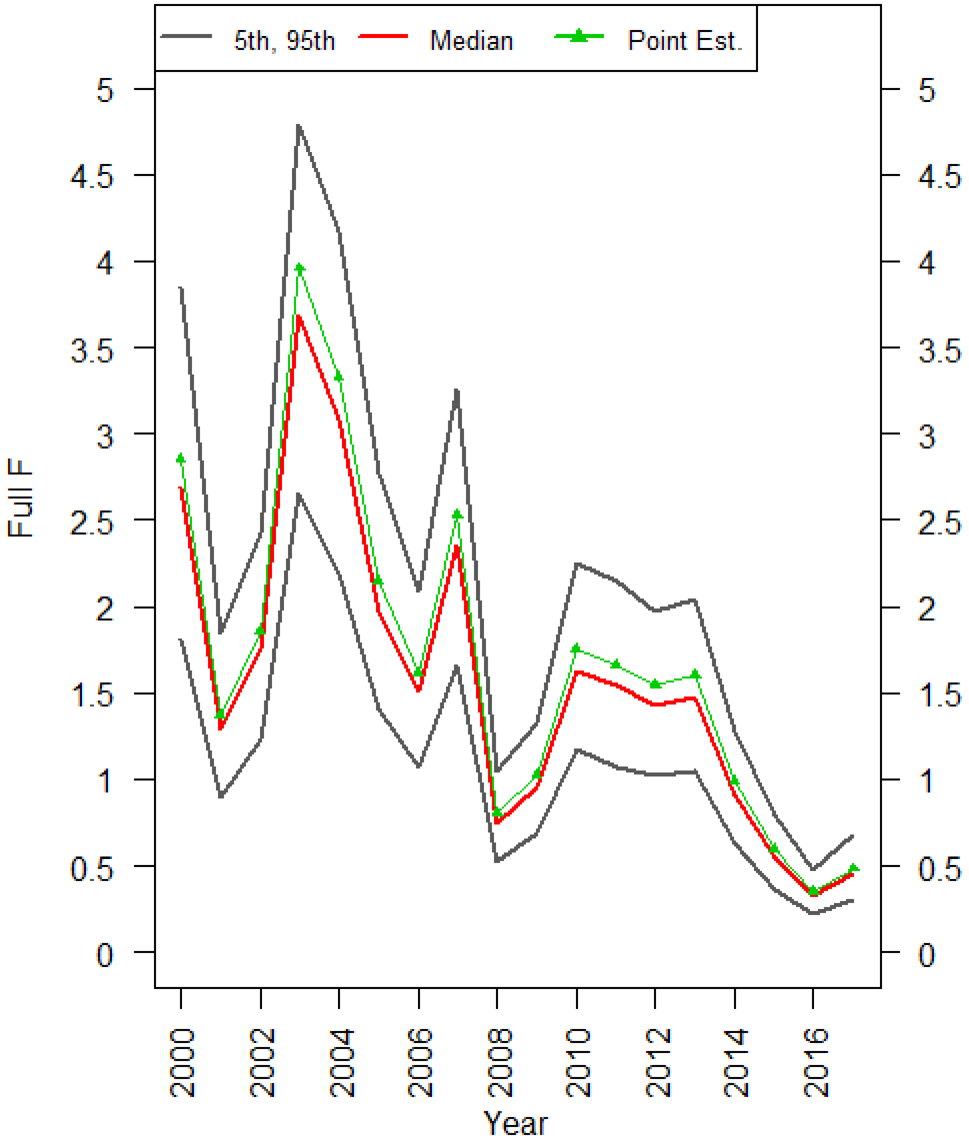


Figure 287. Estimated American shad fully-recruited fishing mortality and associated 90% probability interval from the final Albemarle Sound ASAP model. The dark grey lines represent the 5th and 95th percentiles and the green triangles represent the model point estimates.

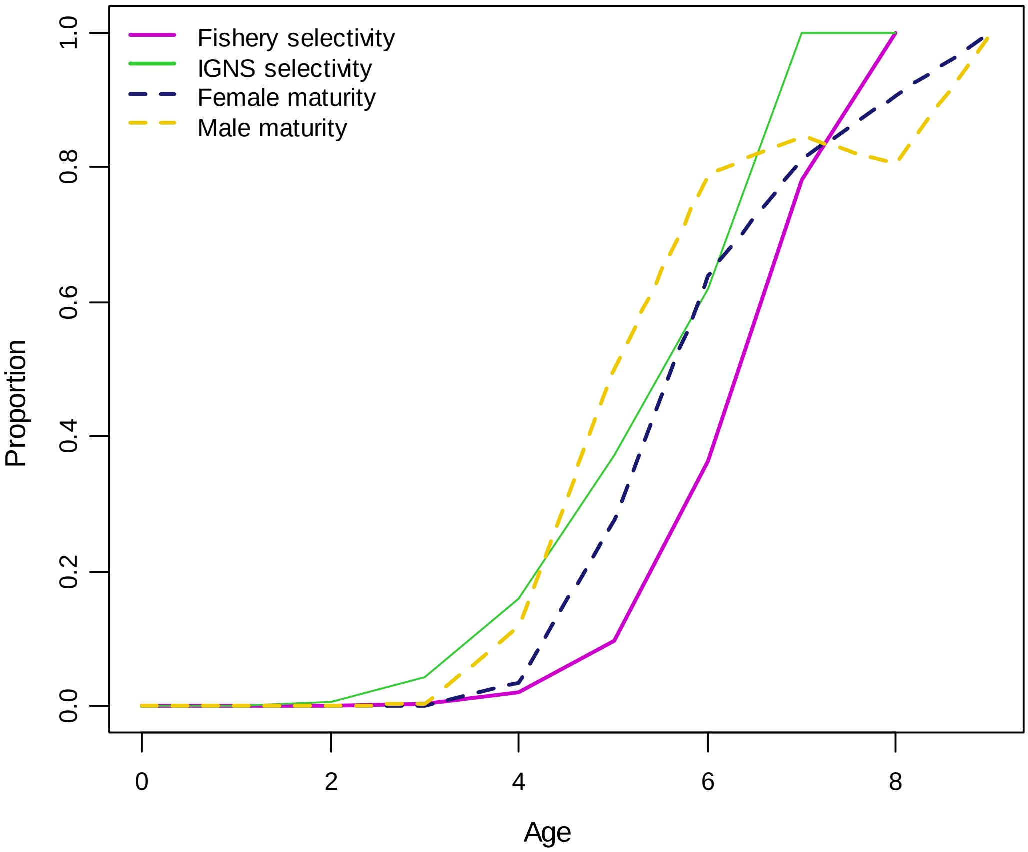


Figure 288. Comparison of age-specific fishery selectivity (estimated), independent gill net selectivity (estimated) and maturity (inputted) from the final Albemarle Sound ASAP model.

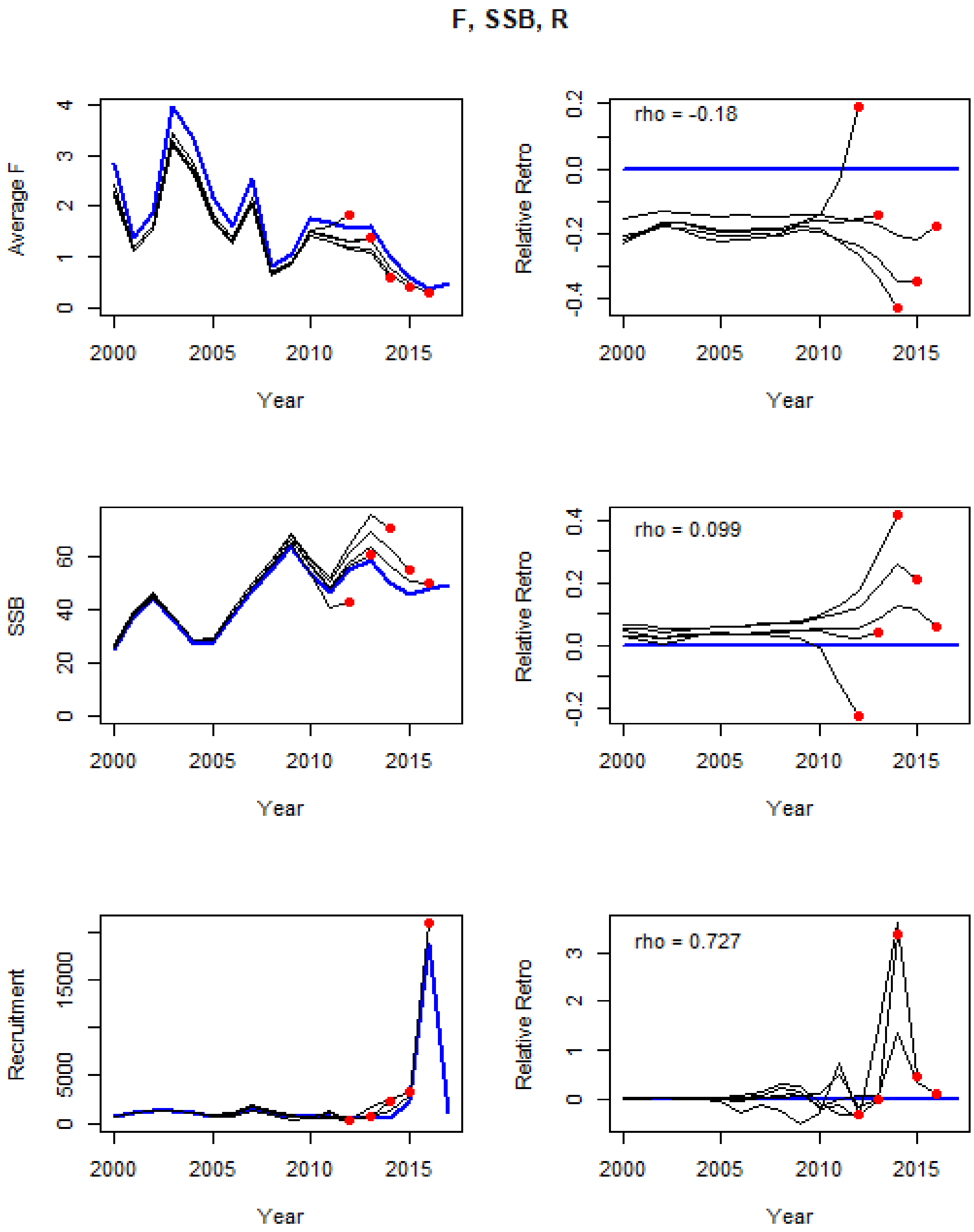


Figure 289. Retrospective analysis for American shad spawning stock biomass, fishing mortality and recruitment. Mohn's rho estimates are based on a five-year retrospective peel.

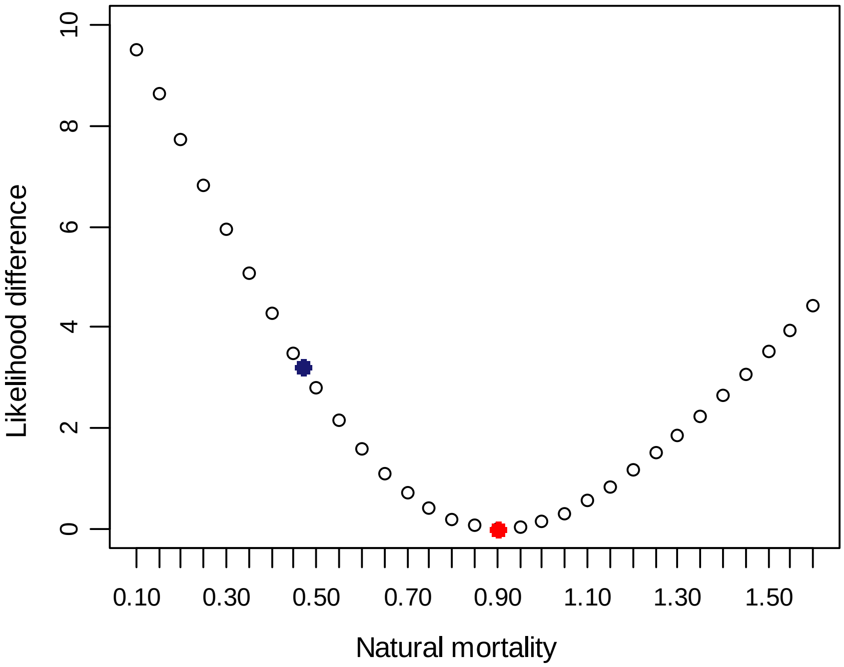


Figure 290. Likelihood profile of natural mortality for the final Albemarle Sound ASAP model. A constant natural mortality of 0.47 (blue circle) was used in the model and the minimum value from the profile corresponded to a natural mortality of 0.90 (orange circle).

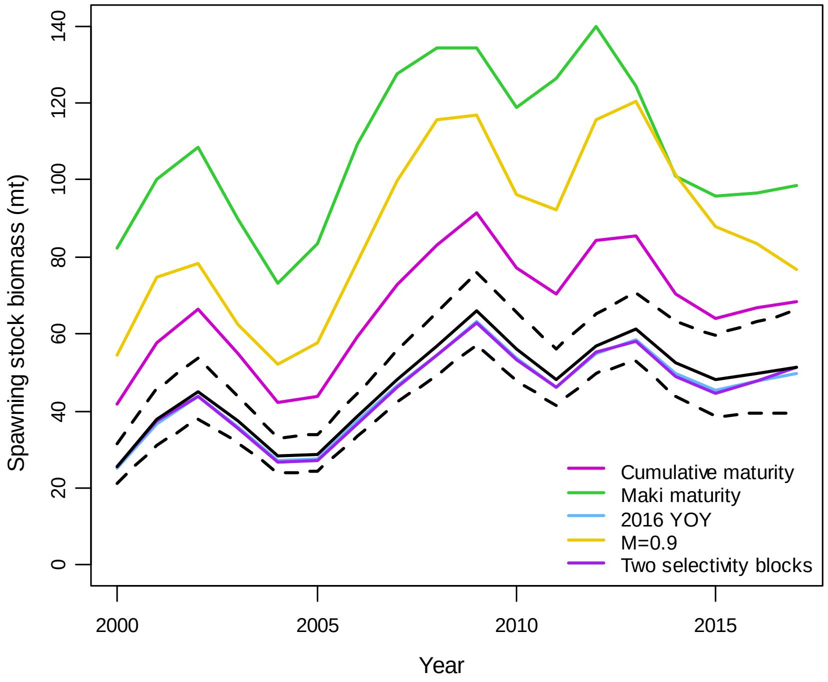


Figure 291. Comparison of American shad spawning stock biomass estimates across ASAP sensitivity runs. The solid black line represents the median of the 90th probability interval from the final ASAP model and the black dashed lines represent the 5th and 95th percentiles.

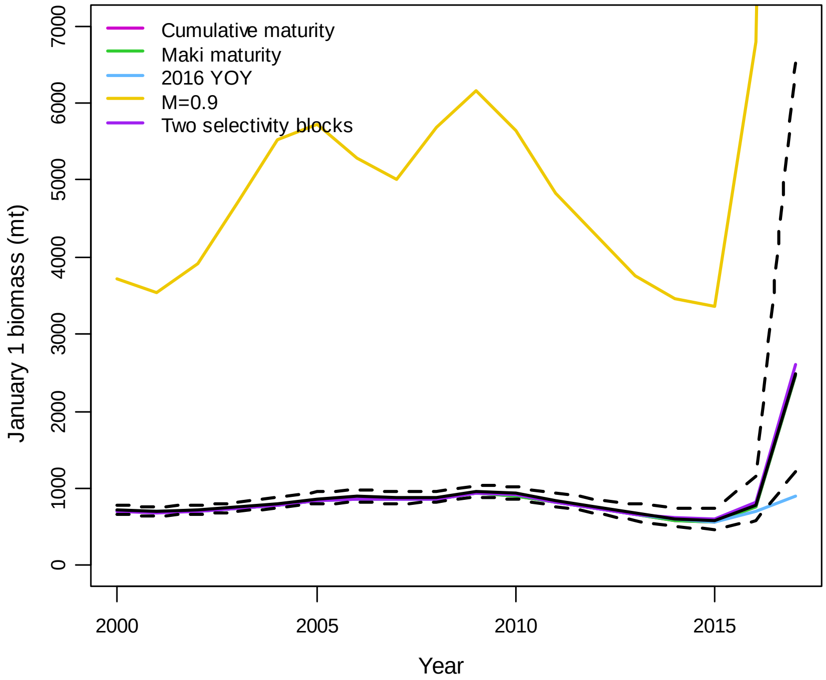


Figure 292. Comparison of American shad January-1 biomass estimates across ASAP sensitivity runs. The solid black line represents the median of the 90th probability interval from the final ASAP model and the black dashed lines represent the 5th and 95th percentiles.

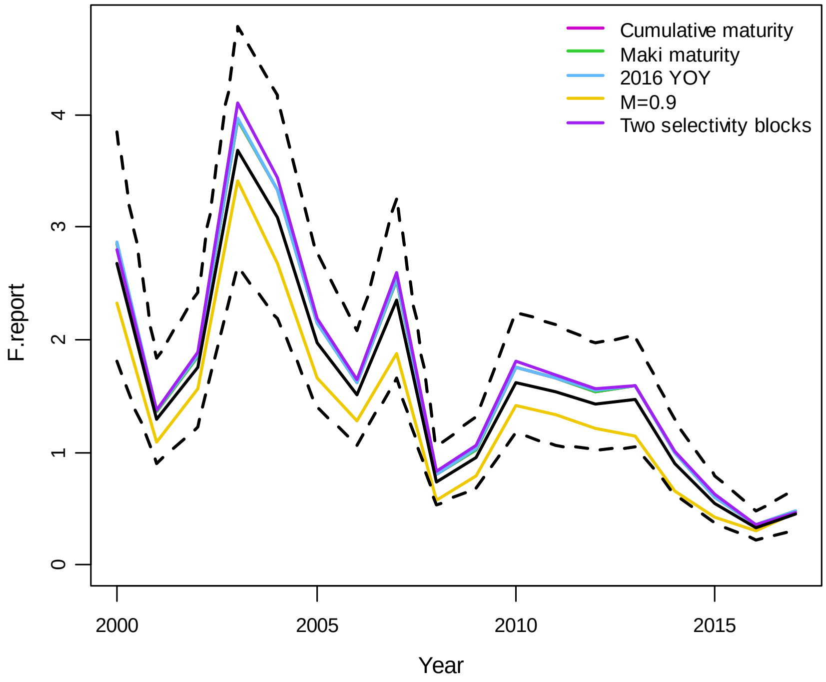
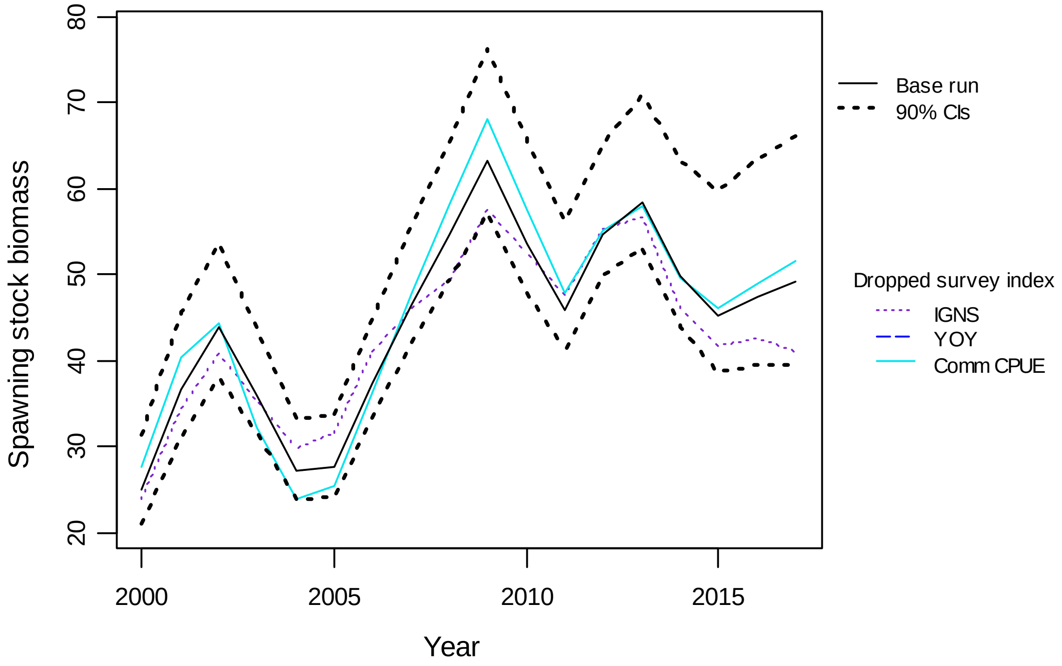


Figure 293. Comparison of American shad average age 6-9 fishing mortality estimates across ASAP sensitivity runs. The solid black line represents the median of the 90th probability interval from the final ASAP model and the black dashed lines represent the 5th and 95th percentiles.



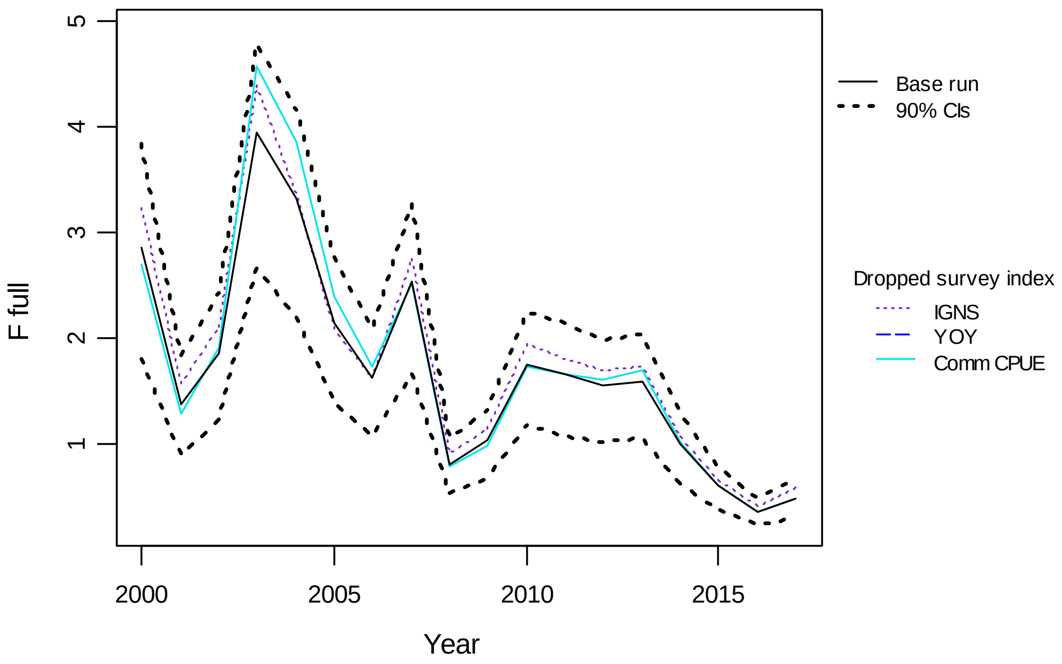


Figure 294. Estimated spawning stock biomass, fully-recruited fishing mortality and associated 90% probability interval from the final Albemarle Sound ASAP model and sensitivity runs where individual indices were dropped from the model. The sensitivity run where the YOY index was dropped did not converge.

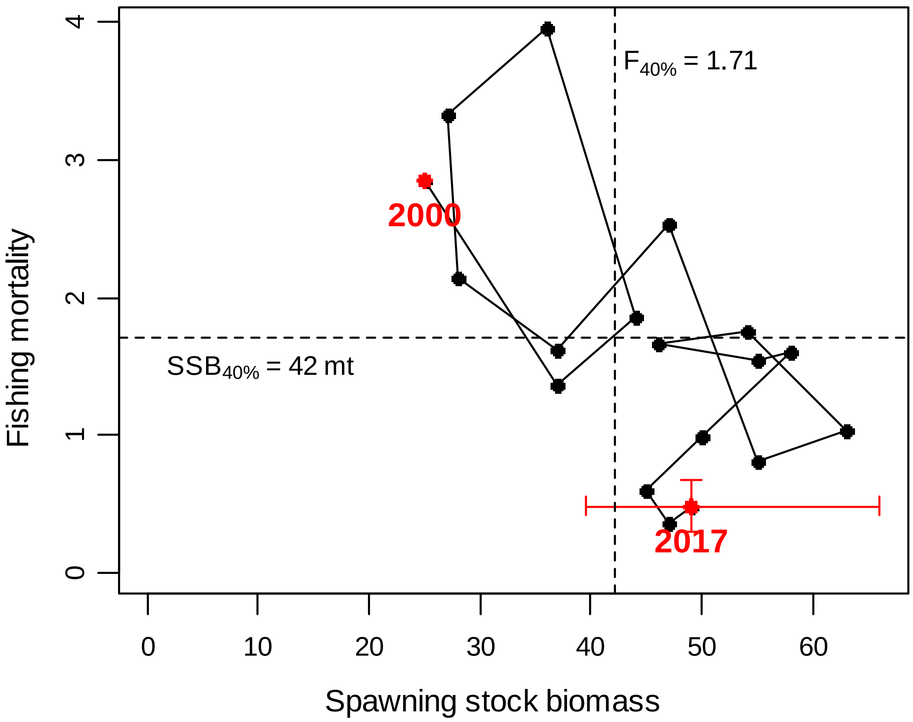


Figure 295. Time series trajectory of American shad fully selected fishing mortality and spawning stock biomass estimates from 1968 to 2016 relative to the corresponding biological reference points.

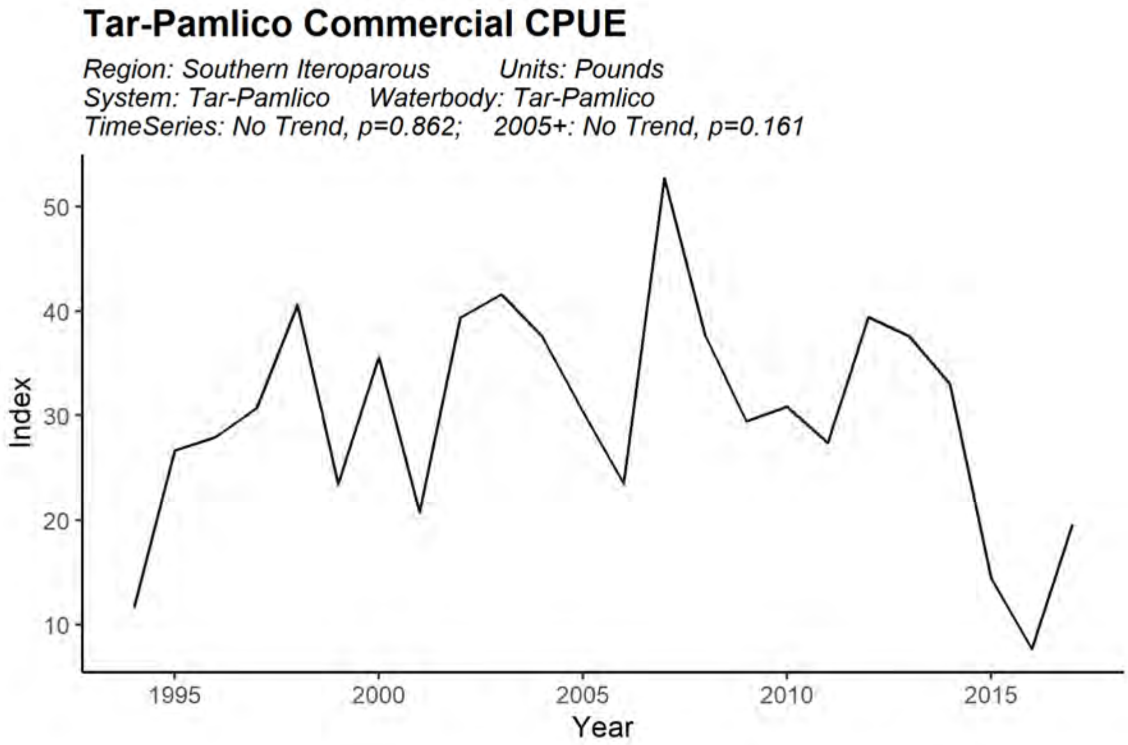


Figure 296. Abundance index developed from the Tar-Pamlico Commercial CPUE and Mann-Kendall results.

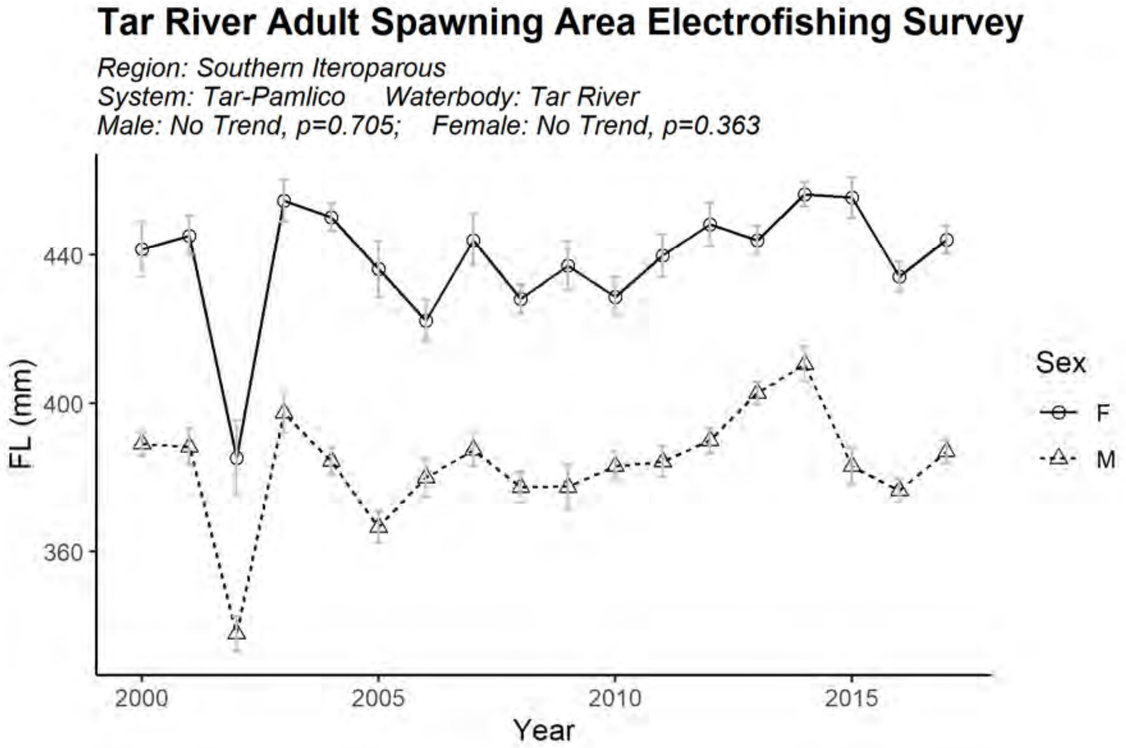


Figure 297. Mean fork length over time for the Tar River Adult Spawning Area Electrofishing Survey and Mann-Kendall results.

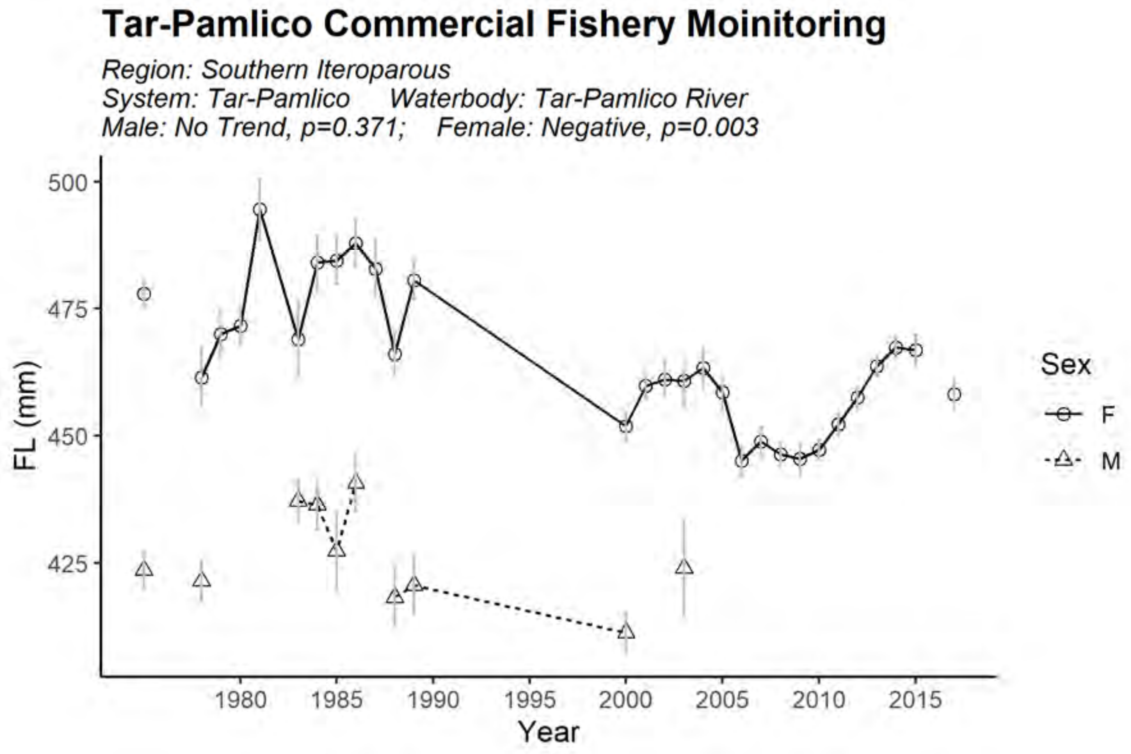


Figure 298. Mean fork length over time for the Tar-Pamlico Commercial Monitoring and Mann-Kendall results.

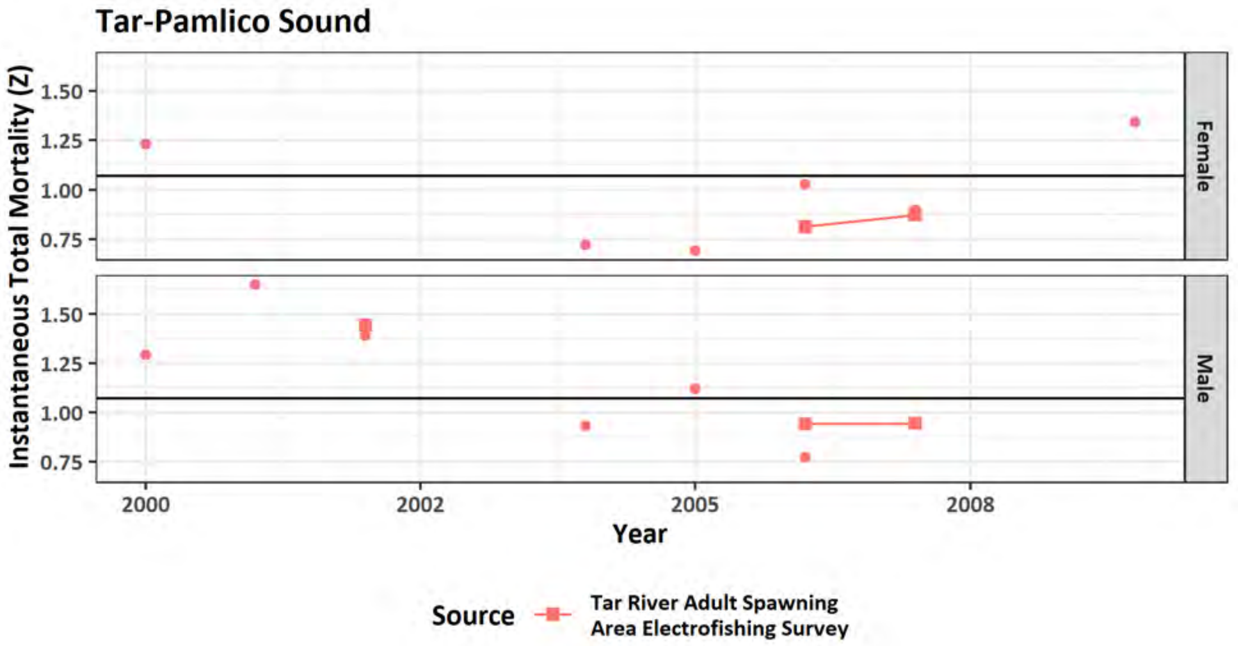


Figure 299. Three year average Z estimates via weighted linear regression by sex and monitoring program for the Tar-Pamlico Sound System based on scale-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual Z estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).

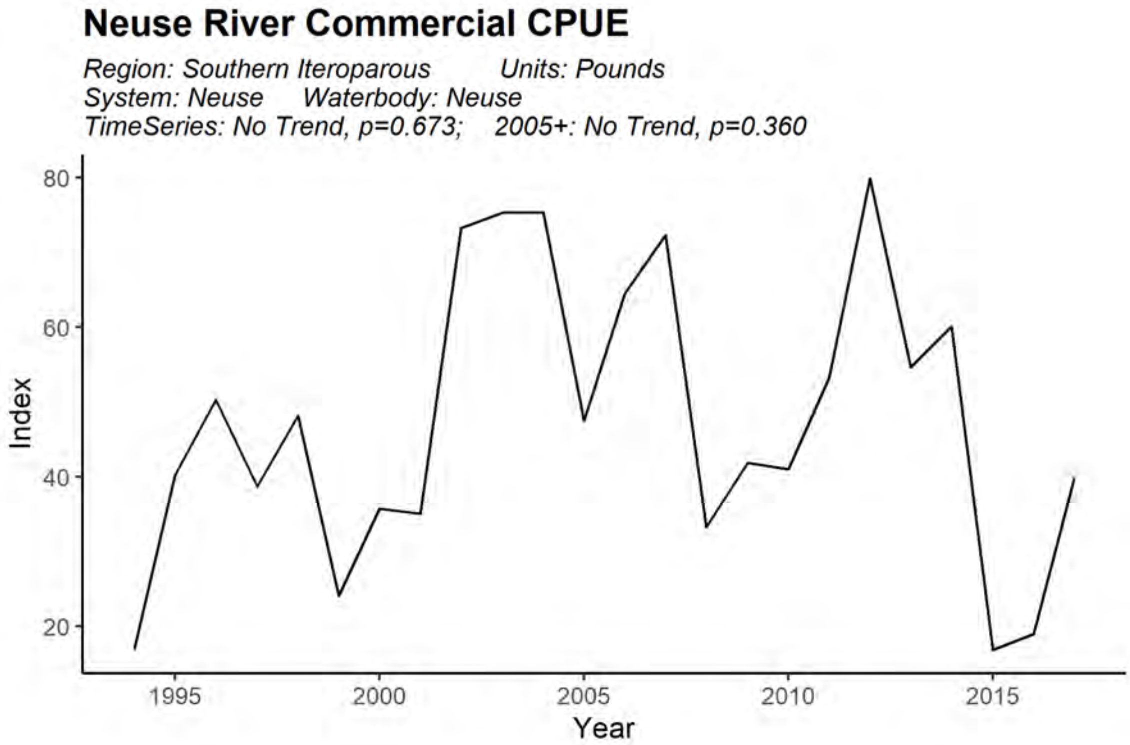


Figure 300. Abundance index developed from the Neuse River Commercial CPUE and Mann-Kendall results.

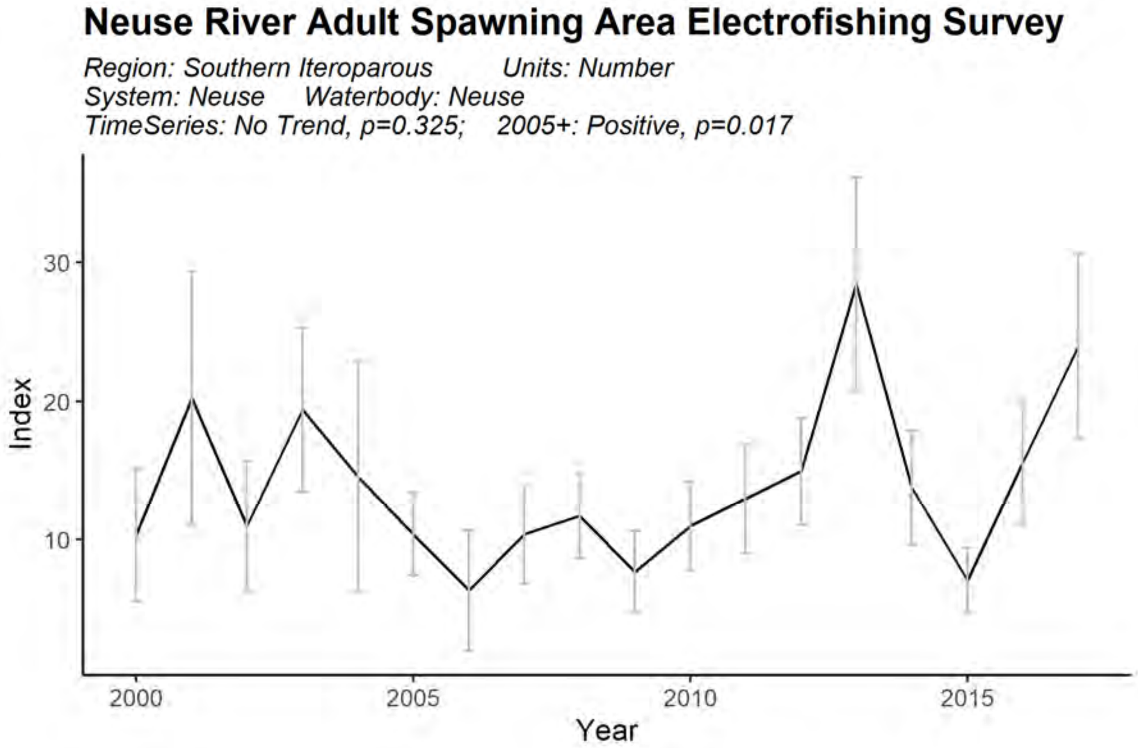


Figure 301. Abundance index developed from the Neuse River Adult Spawning Area Electrofishing Survey and Mann-Kendall results.

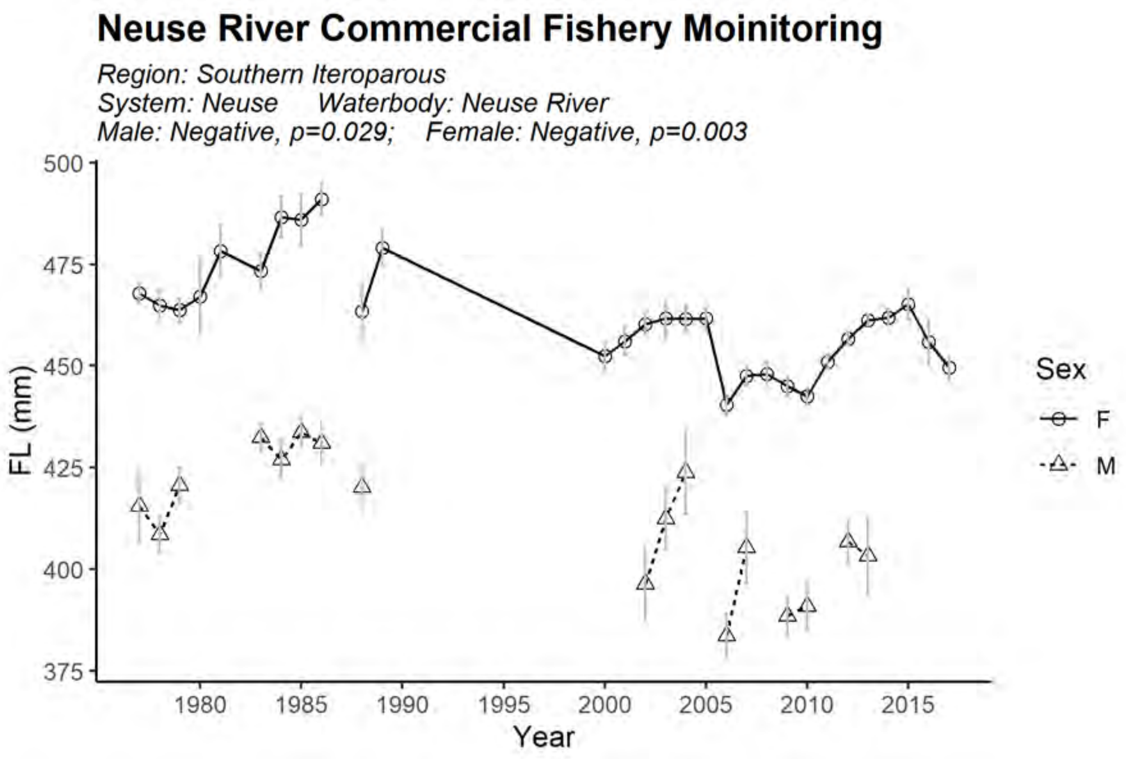


Figure 302. Mean fork length over time for the Neuse River Commercial Monitoring and Mann-Kendall results.

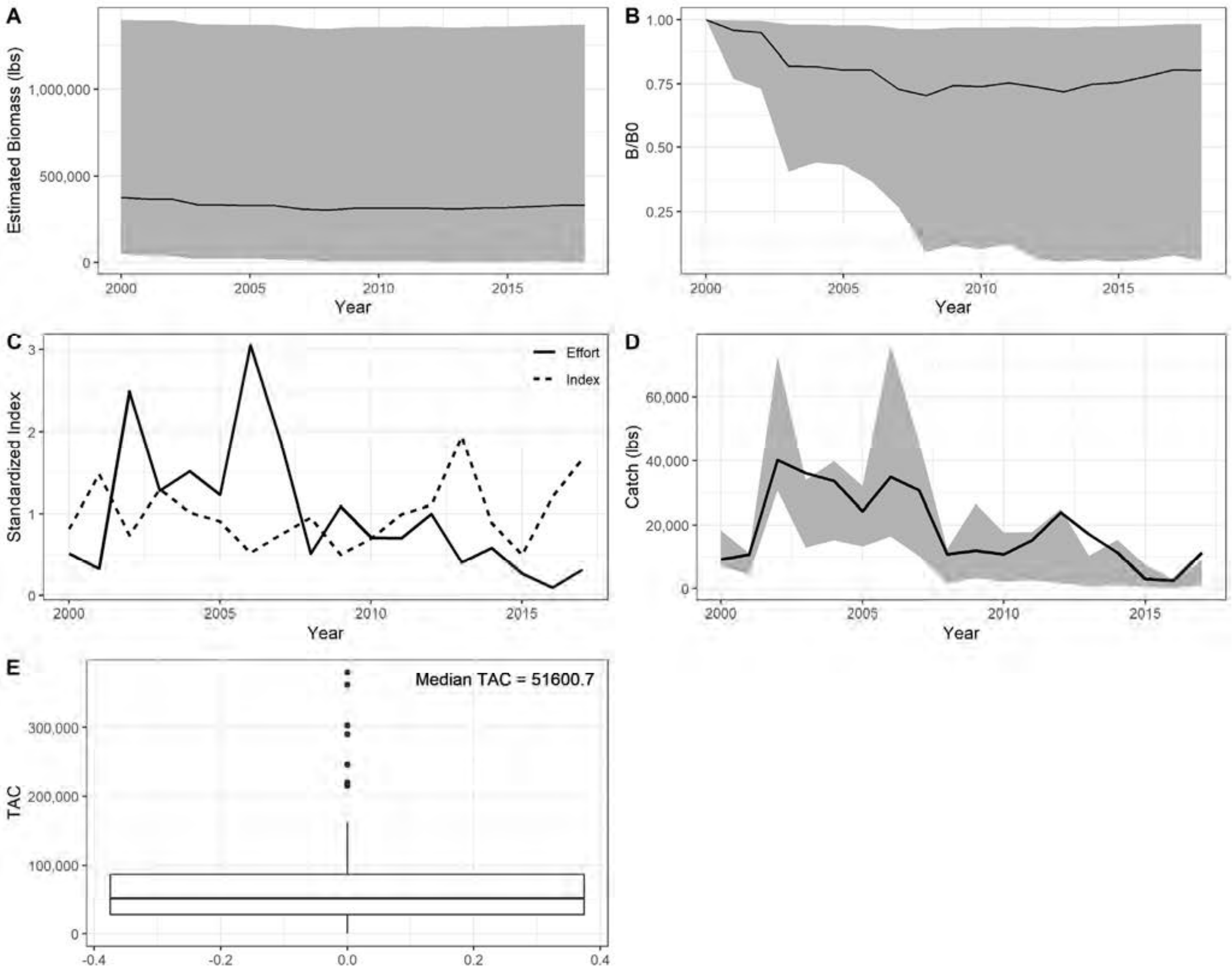


Figure 303. Output of delay-difference model for the Neuse American shad stock using the Neuse River Adult Spawning Area Electrofishing Survey index. (A) Estimated biomass of the population over time. The black line represents the median biomass over 100 simulations. (B) Ratio of estimated biomass to initial biomass. The black line represents the median biomass ratio over 100 simulations. (C) Standardized index and fishery effort over time. (D) Total catch over time. The black line represents the observed catch and the gray area represents estimates over 100 simulations. (E) Boxplot of Total Allowable Catch (TAC) estimates over 100 simulations.

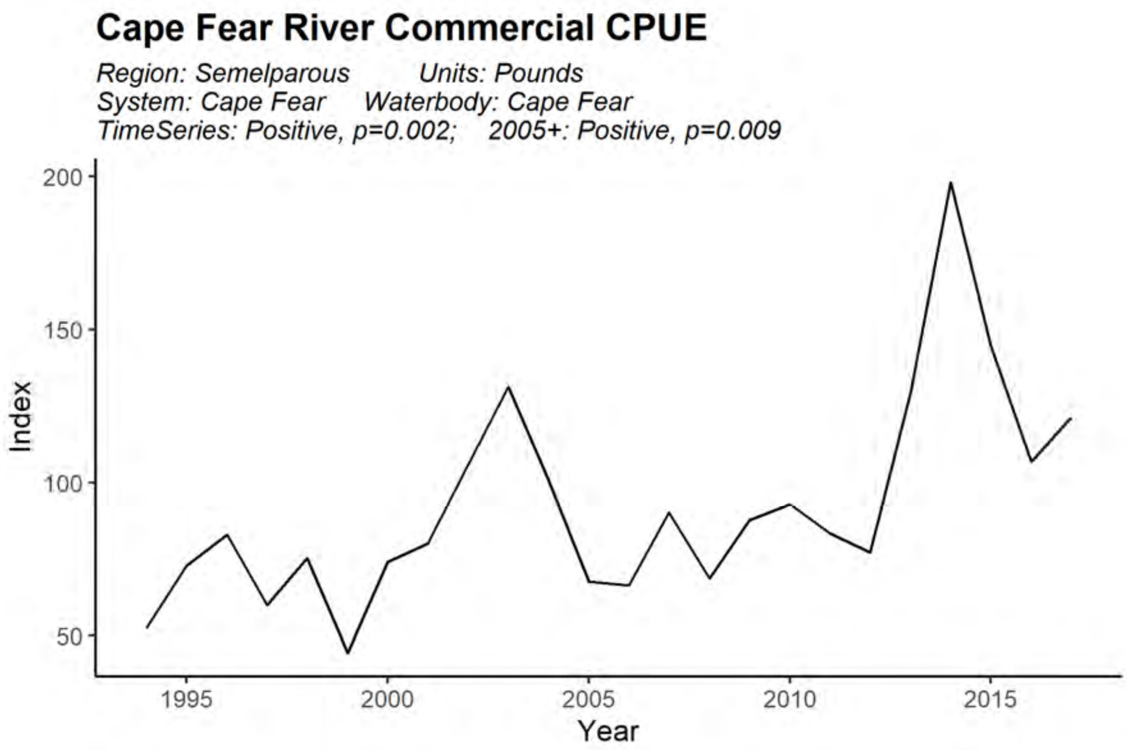


Figure 304. Abundance index developed from the Cape Fear River Commercial CPUE and Mann-Kendall results.

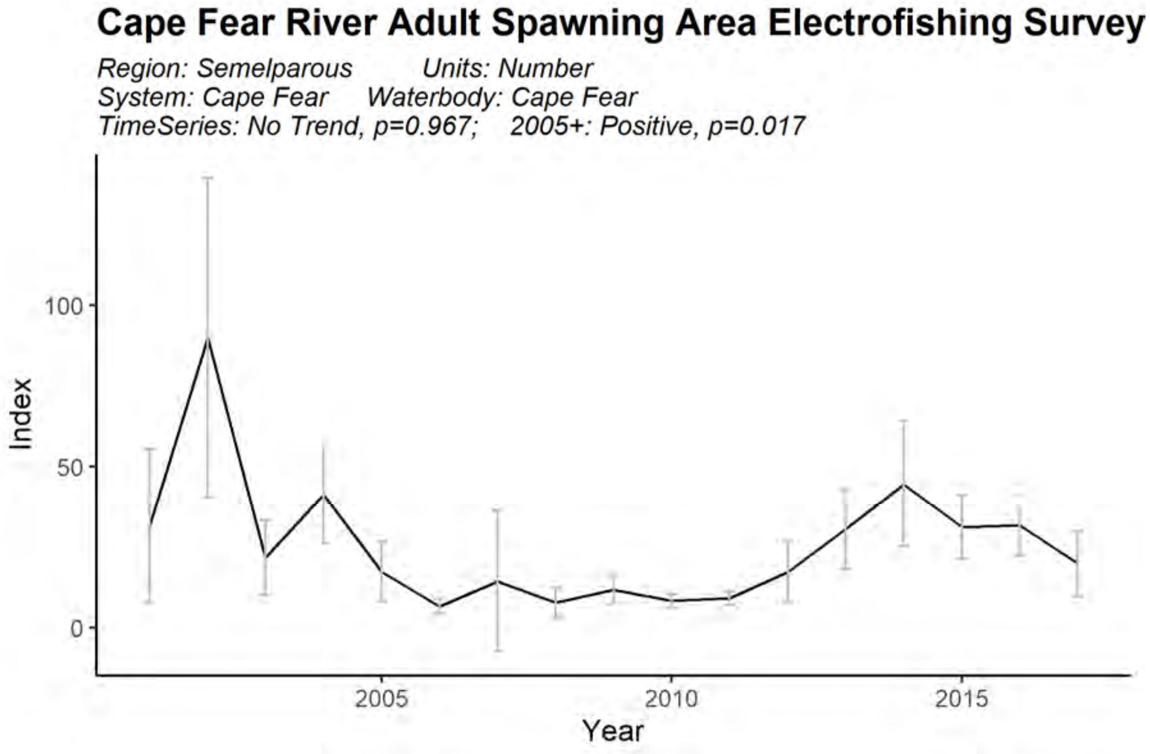


Figure 305. Abundance index developed from the Cape Fear River Adult Spawning Area Electrofishing Survey and Mann-Kendall results.

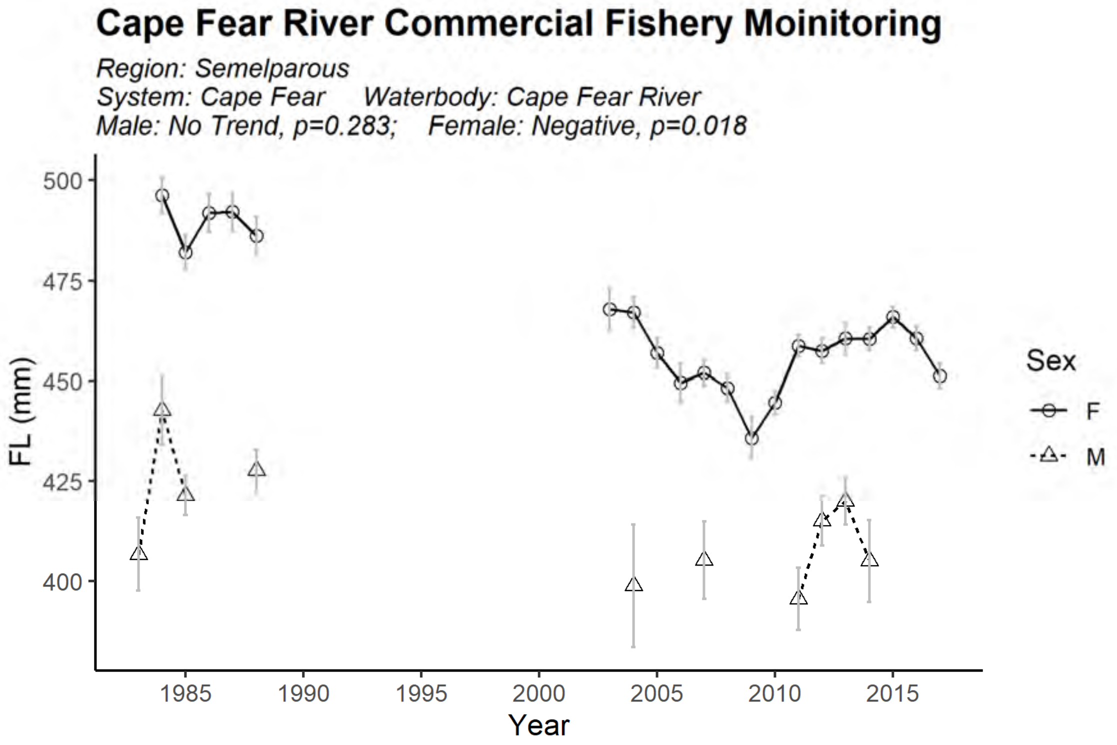


Figure 306. Mean fork length over time for the Cape Fear River Commercial Monitoring and Mann-Kendall results.

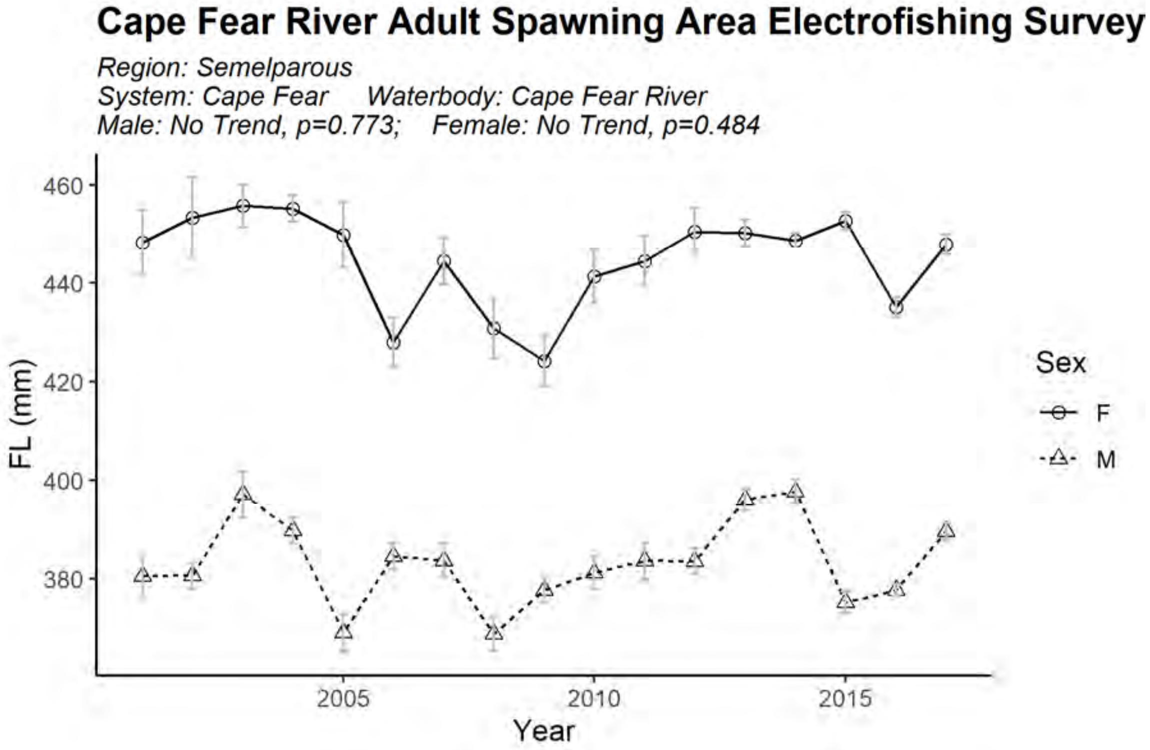


Figure 307. Mean fork length over time for the Cape Fear River Adult Spawning Area Electrofishing Survey and Mann-Kendall results.

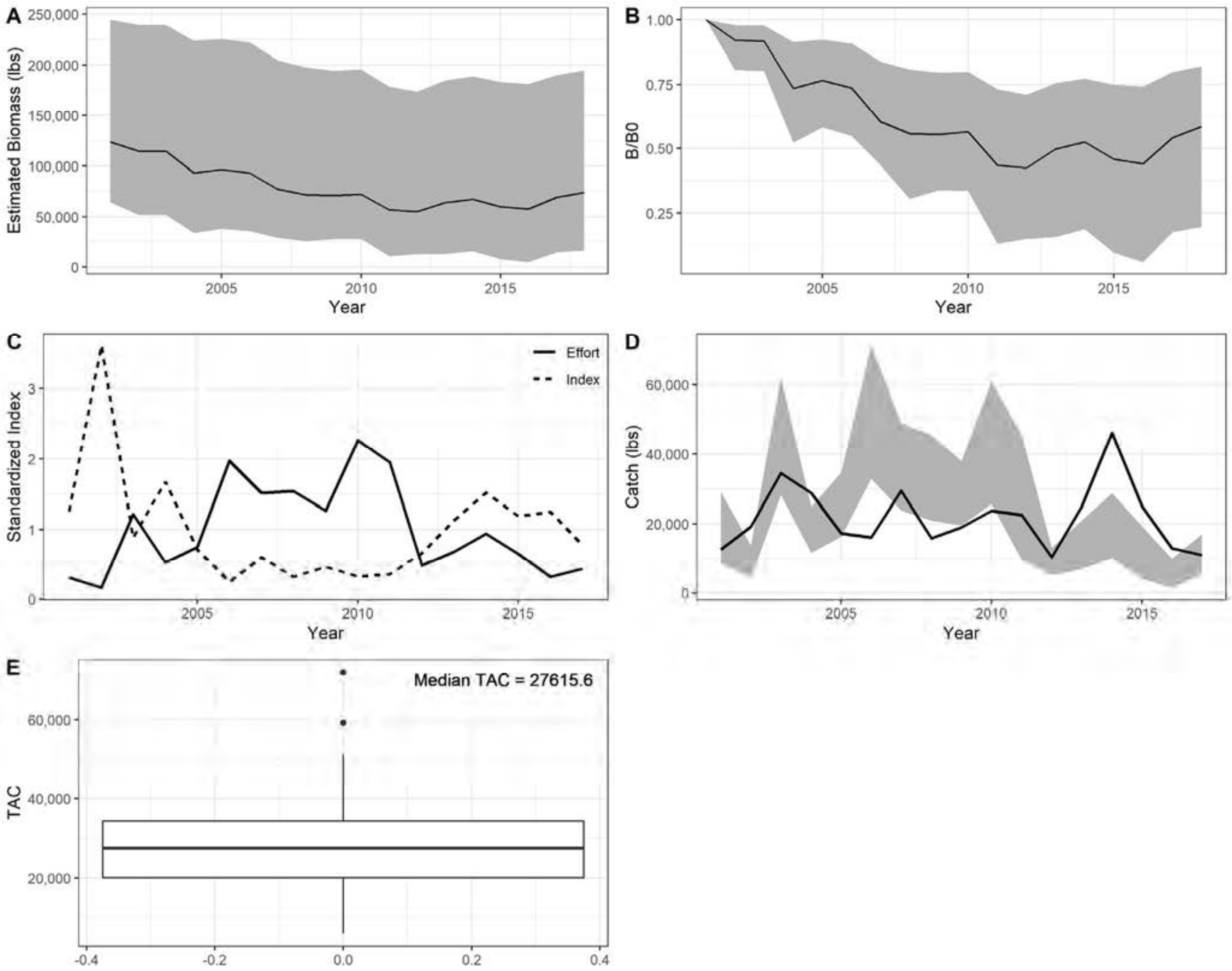


Figure 308. Output of delay-difference model for the Cape Fear American shad stock using the Cape Fear River Adult Spawning Area Electrofishing Survey index. (A) Estimated biomass of the population over time. The black line represents the median biomass over 100 simulations. (B) Ratio of estimated biomass to initial biomass. The black line represents the median biomass ratio over 100 simulations. (C) Standardized index and fishery effort over time. (D) Total catch over time. The black line represents the observed catch and the gray area represents estimates over 100 simulations. (E) Boxplot of Total Allowable Catch (TAC) estimates over 100 simulations.

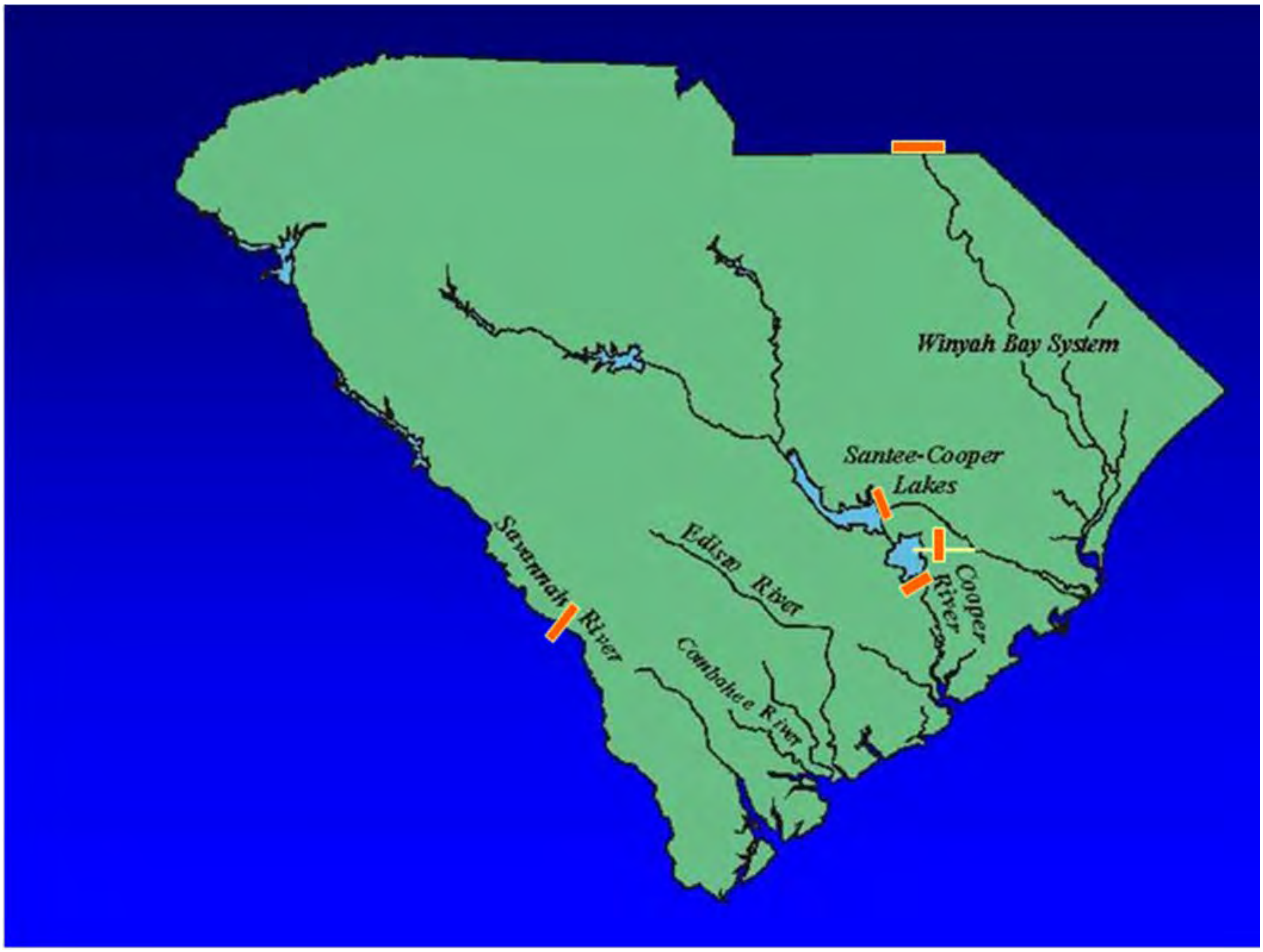


Figure 309. Map of major South Carolina drainage basins and river systems with American shad with first barriers to upstream migration shown.

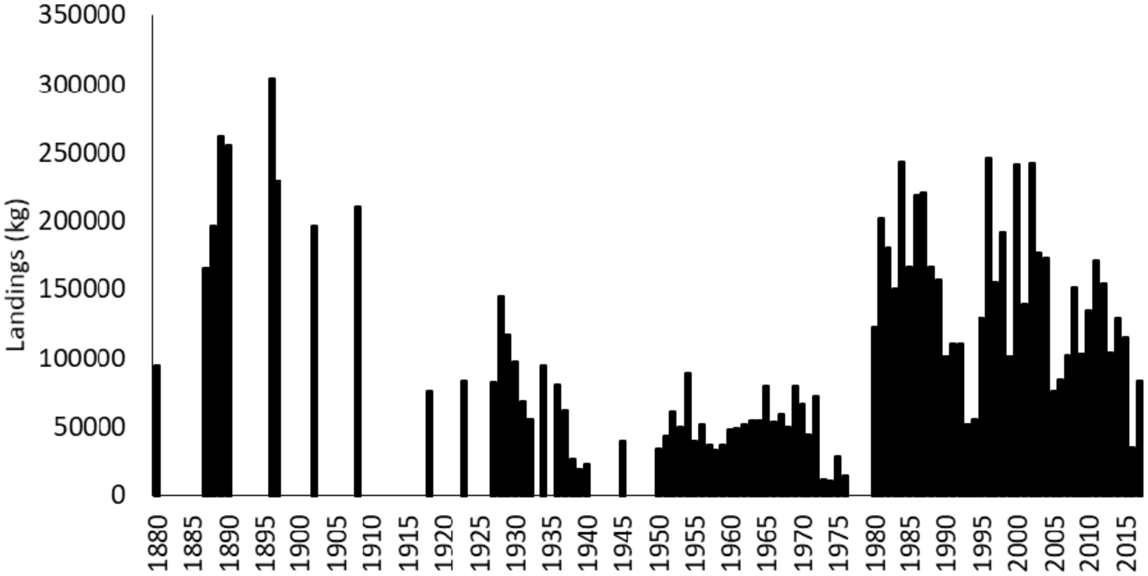
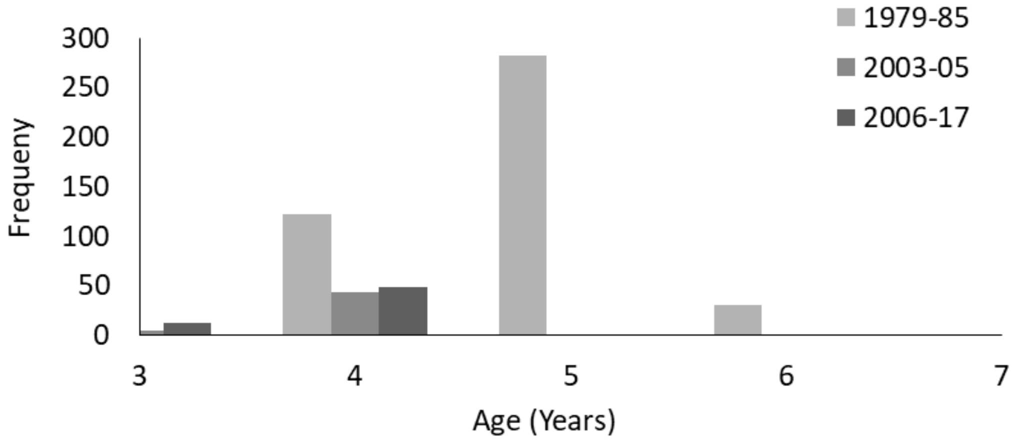


Figure 310. Historical landings of American shad in South Carolina. Landings from before 1979 are from: Statistics of the Fisheries of the [Middle and New England] Atlantic States. Division of Statistics and Methods of the Fisheries, United States Fish Commission. Obtained from NOAA Central Library Data Imaging Project (docs.lib.noaa.gov). Landings after 1979 are from South Carolina Department of Natural Resources.

(a)



(b)

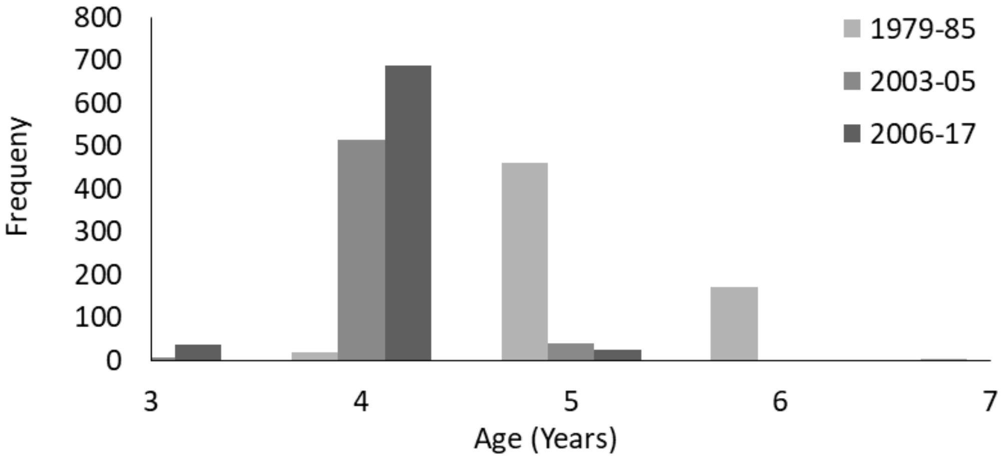
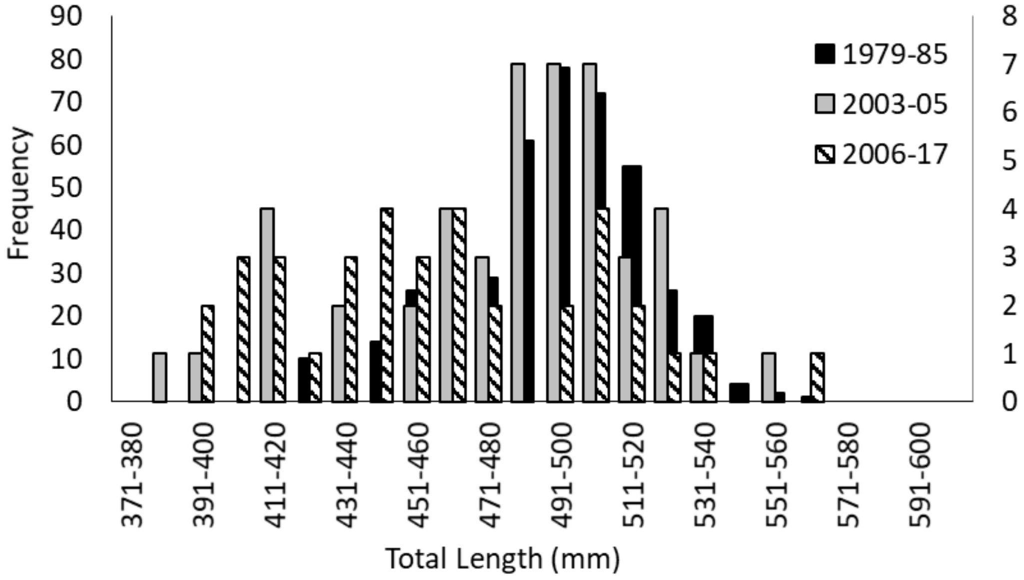


Figure 311. Age distribution of male (a) and female (b) American shad sampled in the Waccamaw River, South Carolina using gill nets in three periods (1979 to 1985, 2003 to 2005, and 2006 to 2017). Ages were determined from scales using Cating's (1953) method.

(a)



(b)

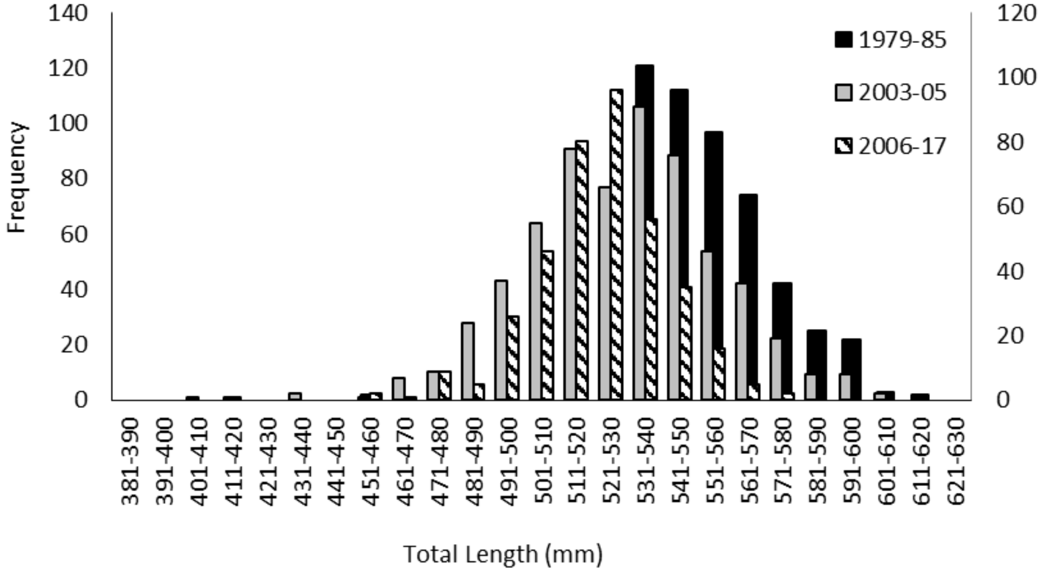


Figure 312. Length distribution of male (a) and female (b) American shad sampled in the Waccamaw River, South Carolina using gill nets in three periods, 1979 to 1985 (primary y-axis), 2003 to 2005, and 2006 to 2017 (secondary y-axis).

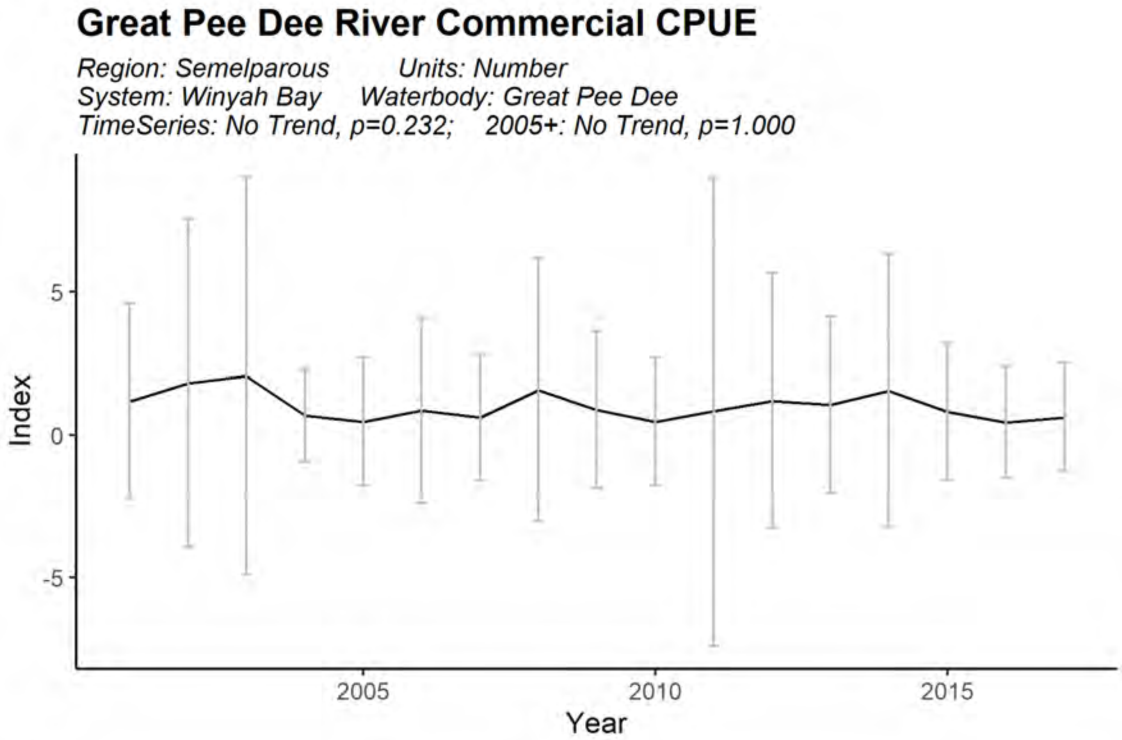


Figure 313. Abundance index developed from Great Pee Dee River Commercial CPUE and Mann-Kendall results.

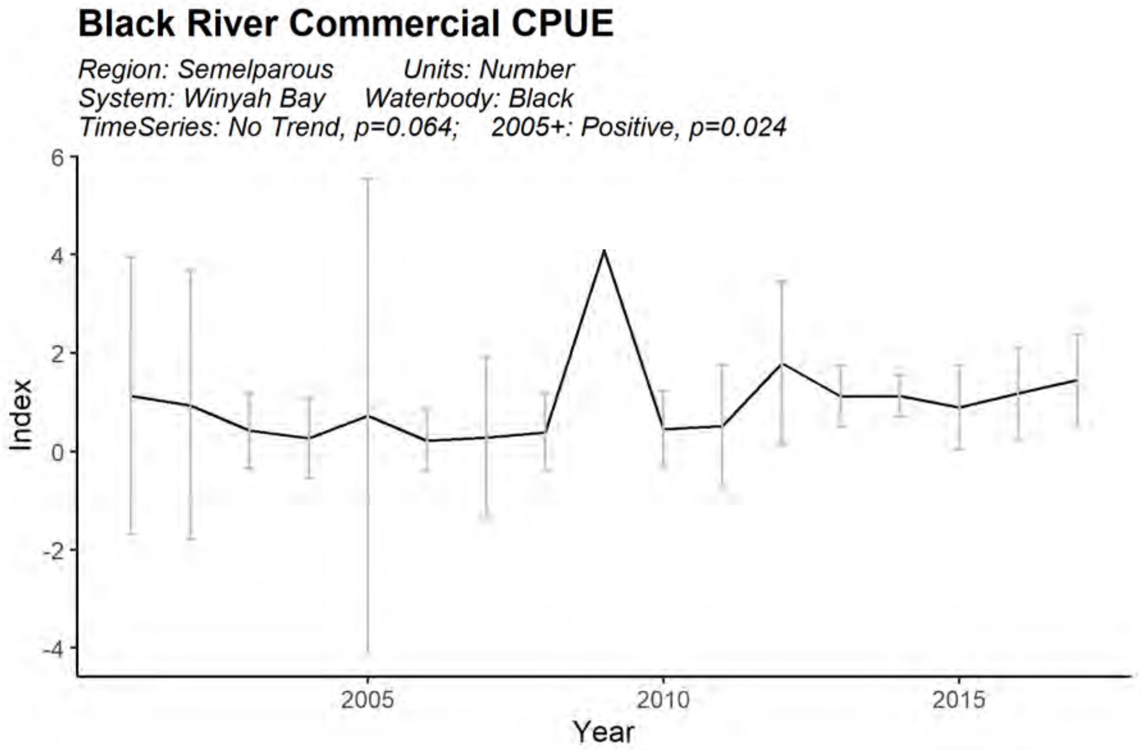


Figure 314. Abundance index developed from Black River Commercial CPUE and Mann-Kendall results.

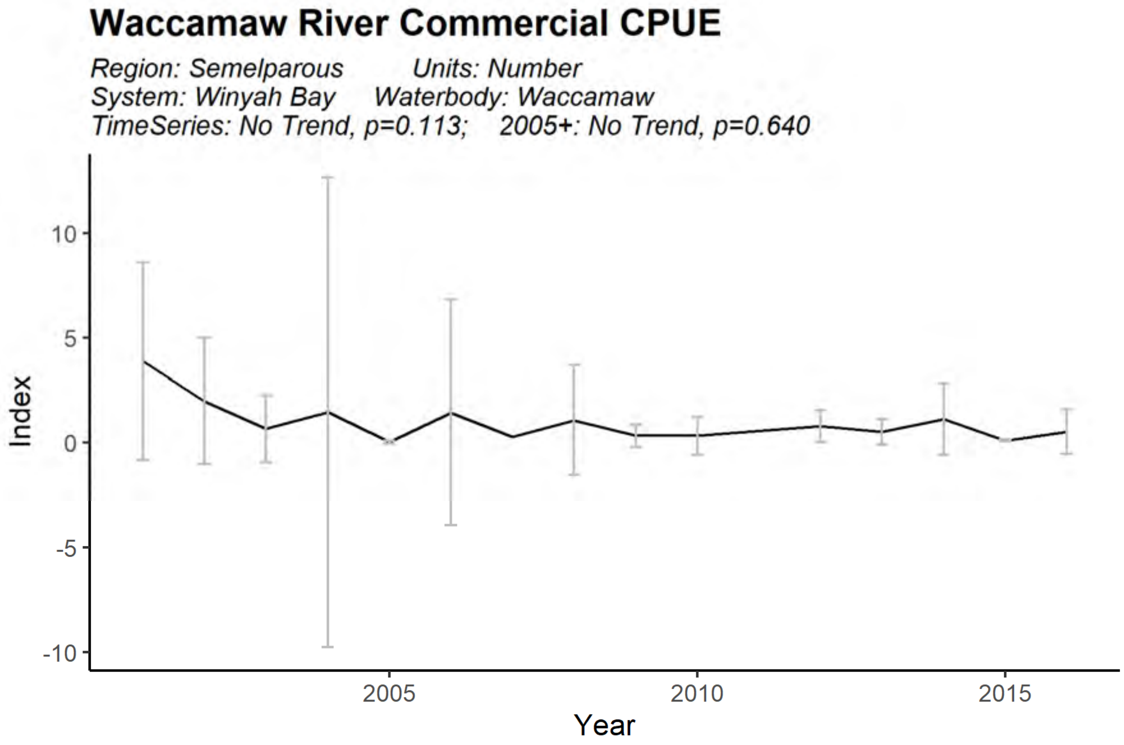


Figure 315. Abundance index developed from Waccamaw River Commercial CPUE and Mann-Kendall results.

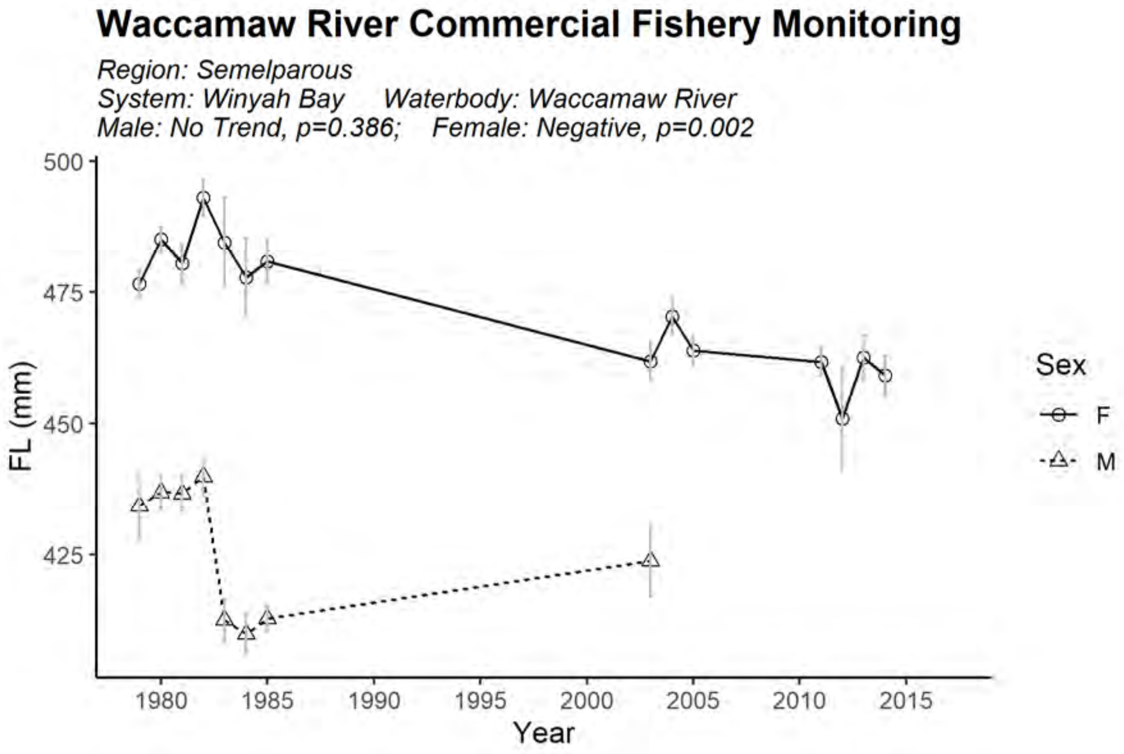


Figure 316. Mean fork length over time for the Waccamaw River Commercial Fishery Monitoring and Mann-Kendall results.

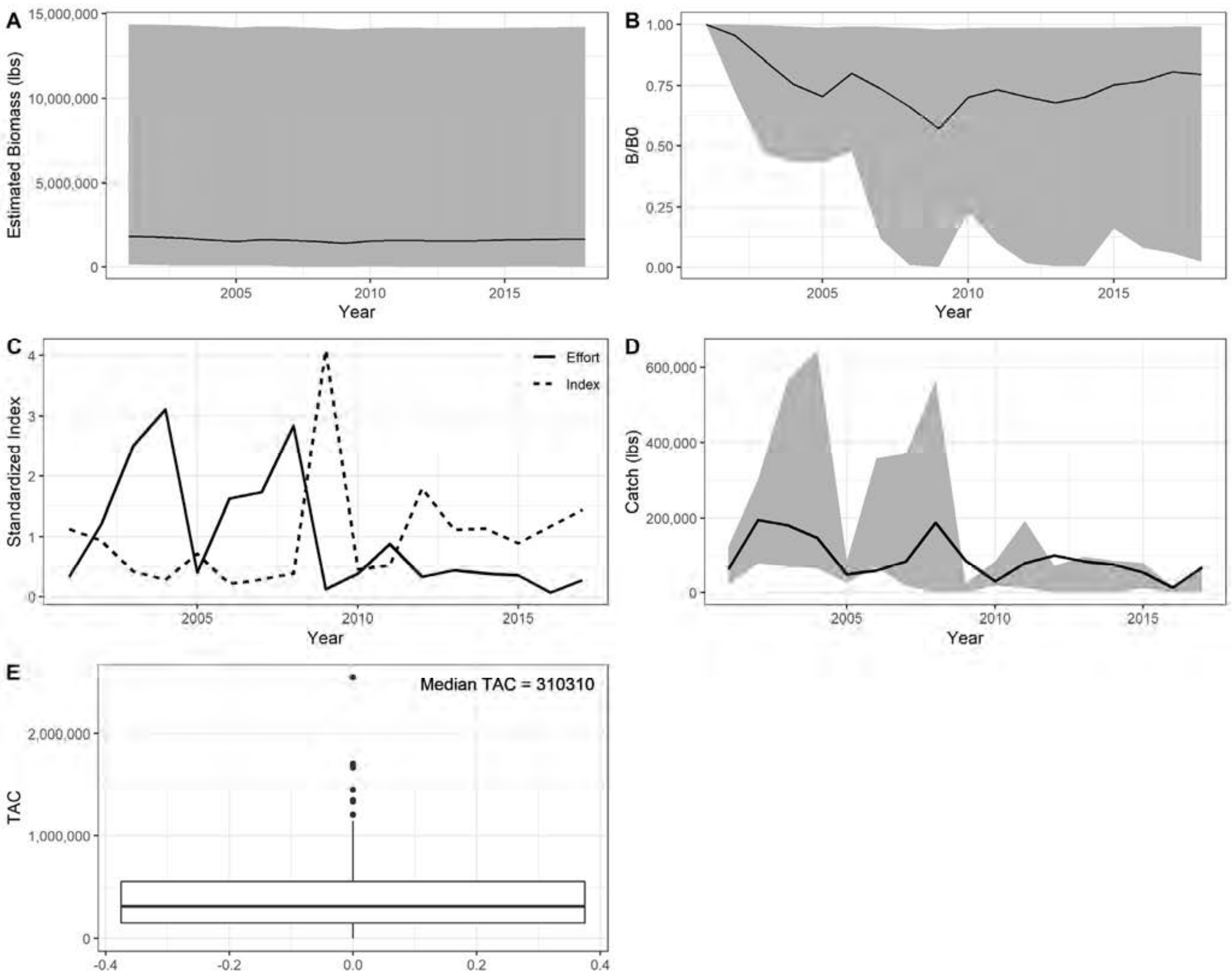


Figure 317. Output of delay-difference model for the Winyah Bay American shad stock using the Black River Commercial CPUE index. (A) Estimated biomass of the population over time. The black line represents the median biomass over 100 simulations. (B) Ratio of estimated biomass to initial biomass. The black line represents the median biomass ratio over 100 simulations. (C) Standardized index and fishery effort over time. (D) Total catch over time. The black line represents the observed catch and the gray area represents estimates over 100 simulations. (E) Boxplot of Total Allowable Catch (TAC) estimates over 100 simulations.

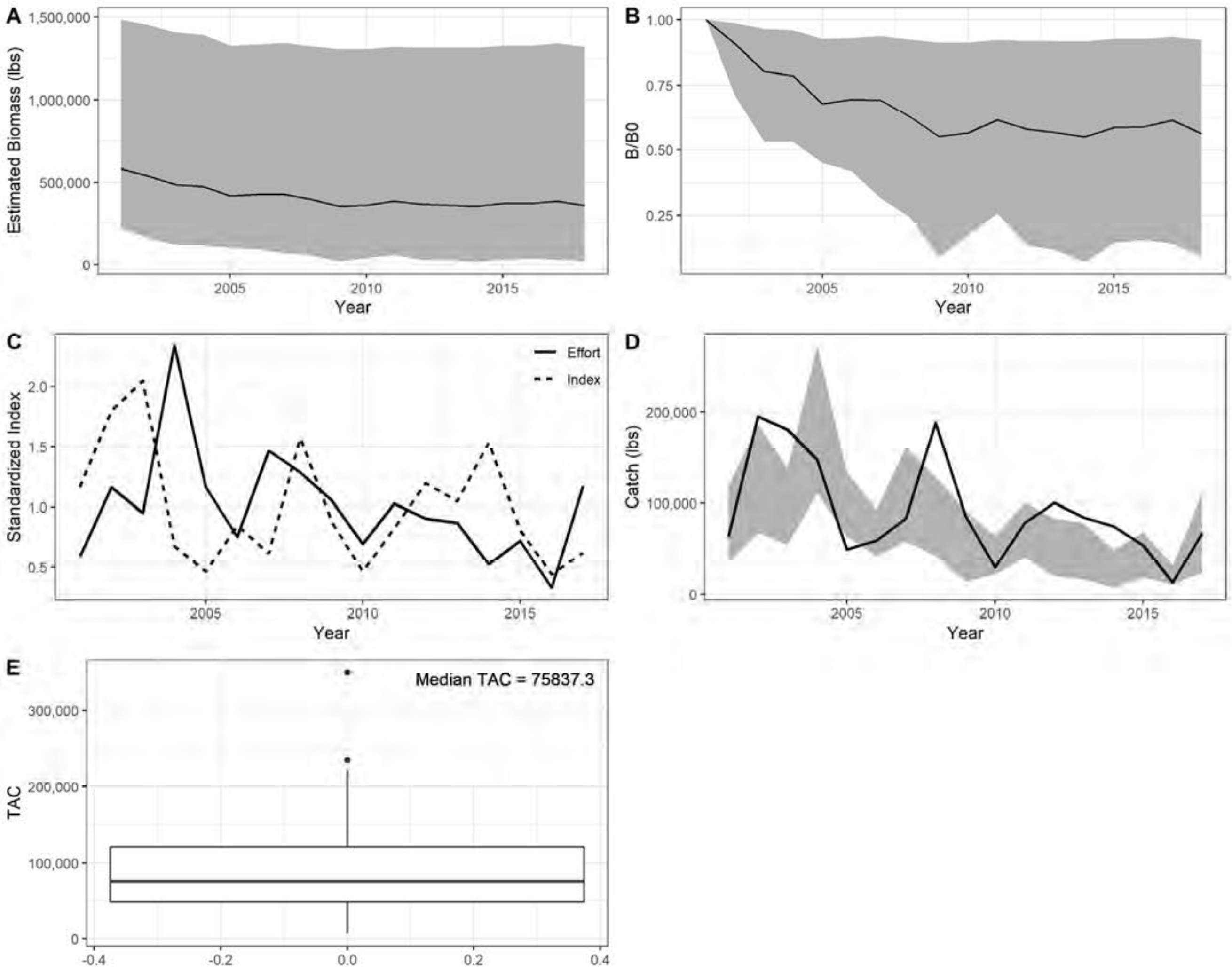


Figure 318. Output of delay-difference model for the Winyah Bay American shad stock using the Great Pee Dee River Commercial CPUE index. (A) Estimated biomass of the population over time. The black line represents the median biomass over 100 simulations. (B) Ratio of estimated biomass to initial biomass. The black line represents the median biomass ratio over 100 simulations. (C) Standardized index and fishery effort over time. (D) Total catch over time. The black line represents the observed catch and the gray area represents estimates over 100 simulations. (E) Boxplot of Total Allowable Catch (TAC) estimates over 100 simulations.

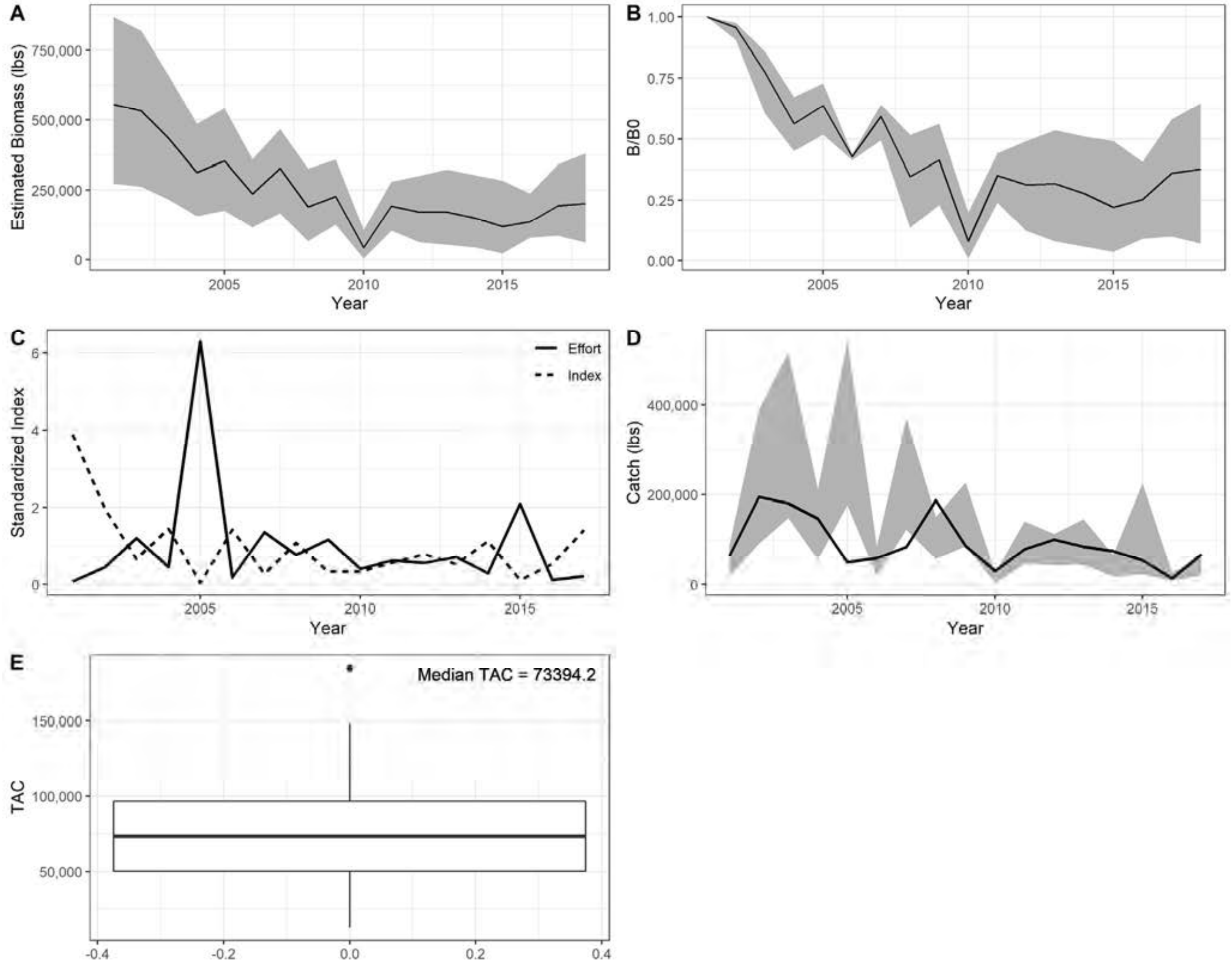
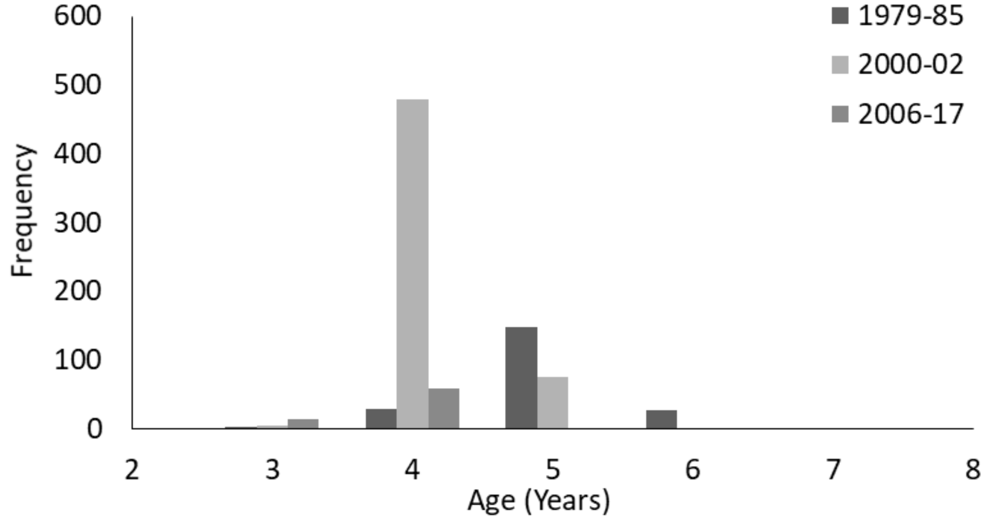


Figure 319. Output of delay-difference model for the Winyah Bay American shad stock using the Waccamaw River Commercial CPUE index. (A) Estimated biomass of the population over time. The black line represents the median biomass over 100 simulations. (B) Ratio of estimated biomass to initial biomass. The black line represents the median biomass ratio over 100 simulations. (C) Standardized index and fishery effort over time. (D) Total catch over time. The black line represents the observed catch and the gray area represents estimates over 100 simulations. (E) Boxplot of Total Allowable Catch (TAC) estimates over 100 simulations.

(a)



(b)

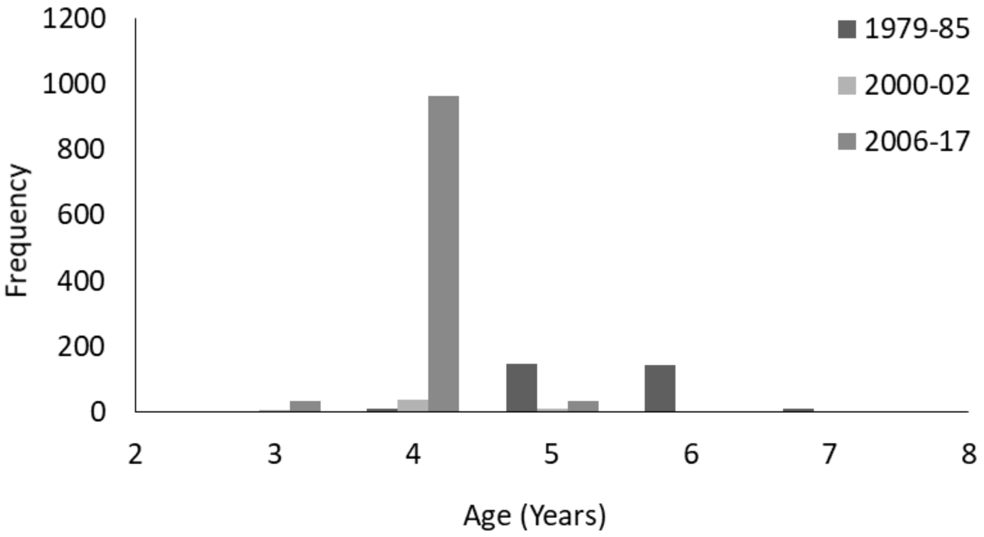
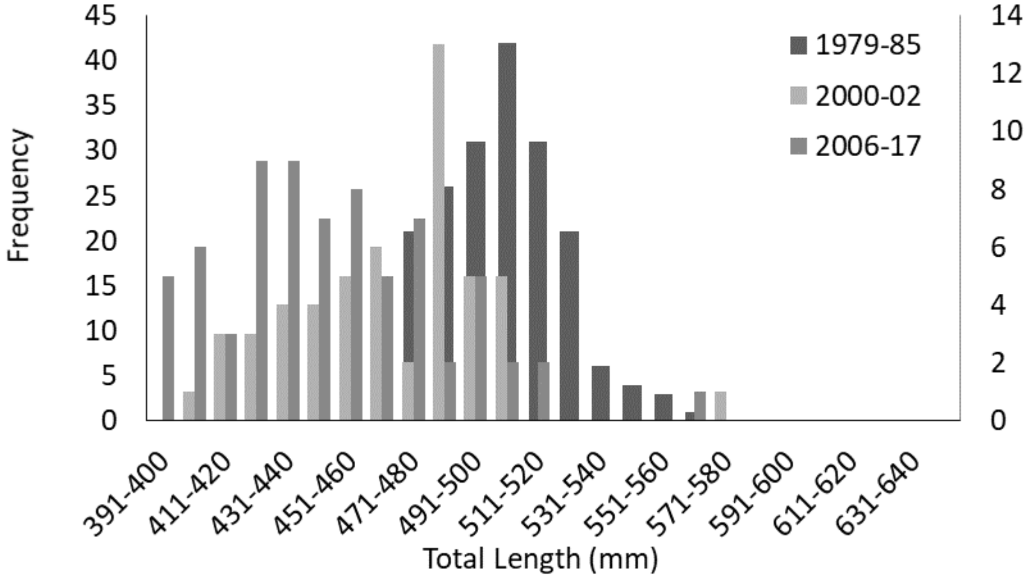


Figure 320. Age distribution of male (a) and female (b) American shad sampled in the N. Santee River, South Carolina using gill nets in three periods, 1979 to 1985, 2000 to 2002, and 2006 to 2017. Ages were determined from scales using Cating's (1953) method.

(a)



(b)

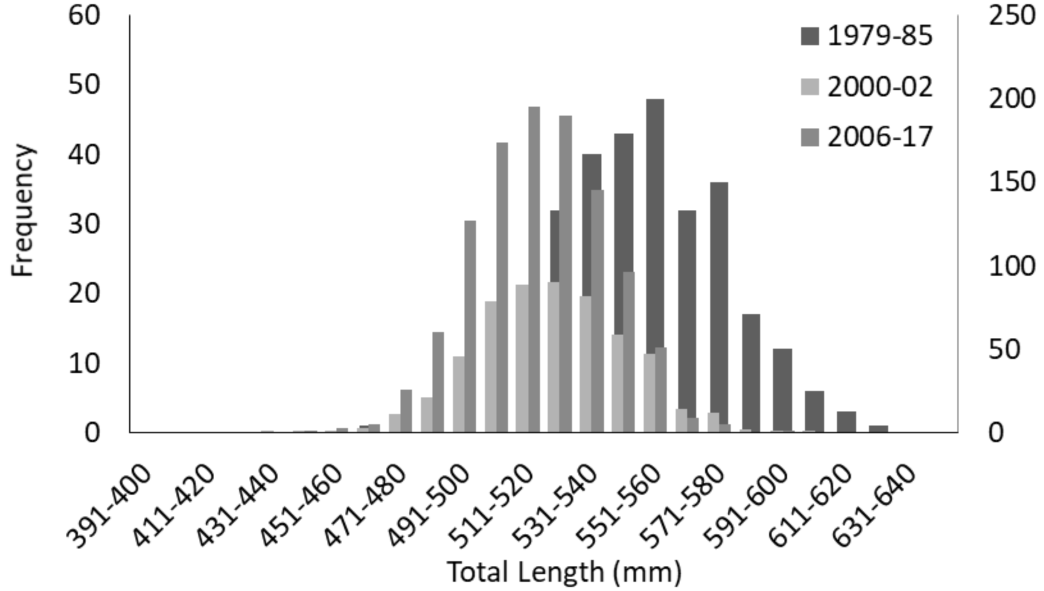


Figure 321. Length (total length) distribution of male (a) and female (b) American shad sampled in the N. Santee River, South Carolina using gill nets in three periods, 1979 to 1985 (primary y-axis), 2000 to 2002, and 2006 to 2017 (secondary y-axis).

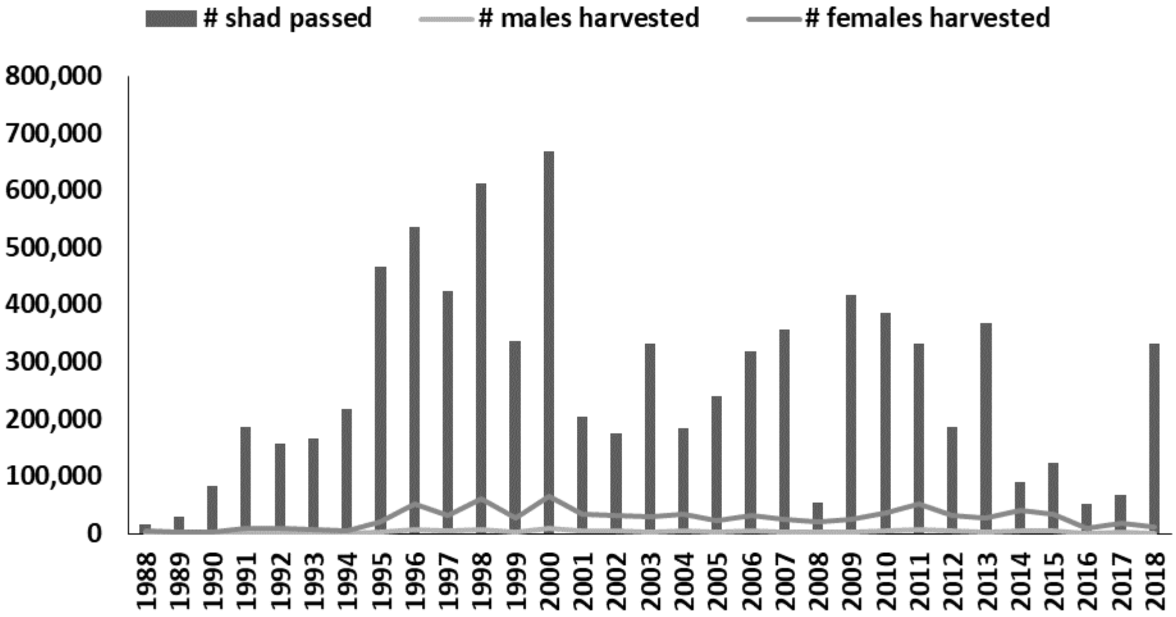


Figure 322. Annual total number of American shad passed at St. Stephens Fish Lock from 1988 to 2018. Counts made by real time counts (1988 to 1994) and counts from video recordings (1995 to 2005).

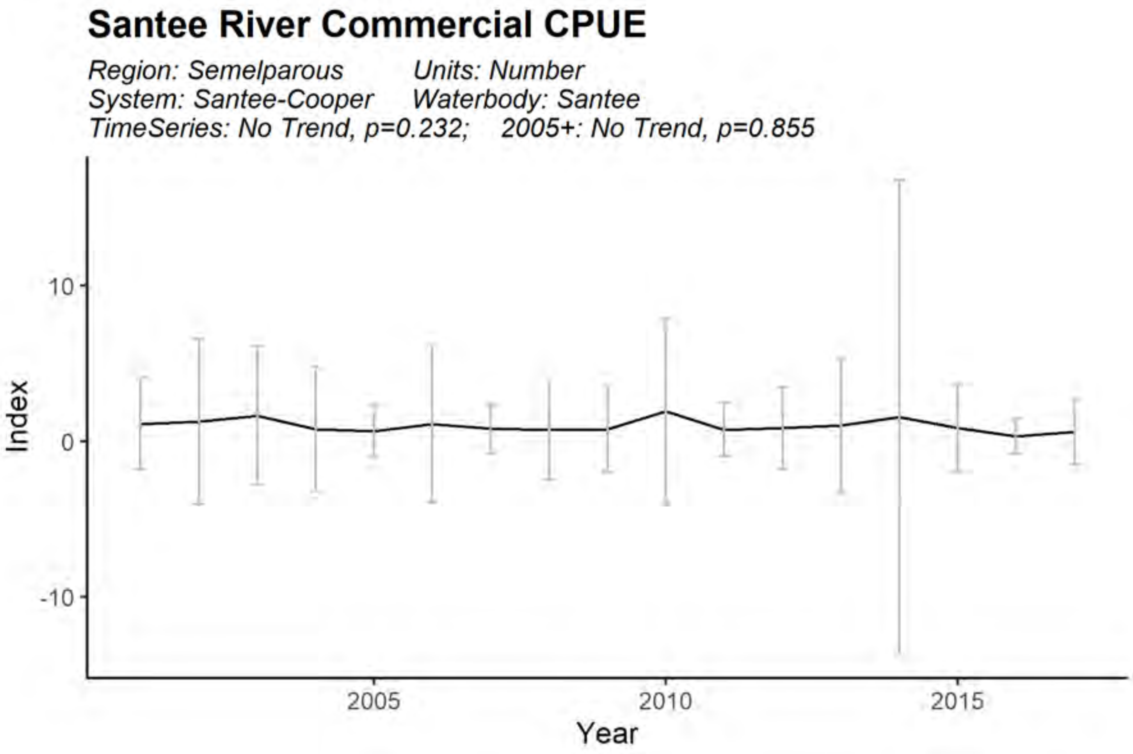


Figure 323. Abundance index developed from Santee River Commercial CPUE and Mann-Kendall results.

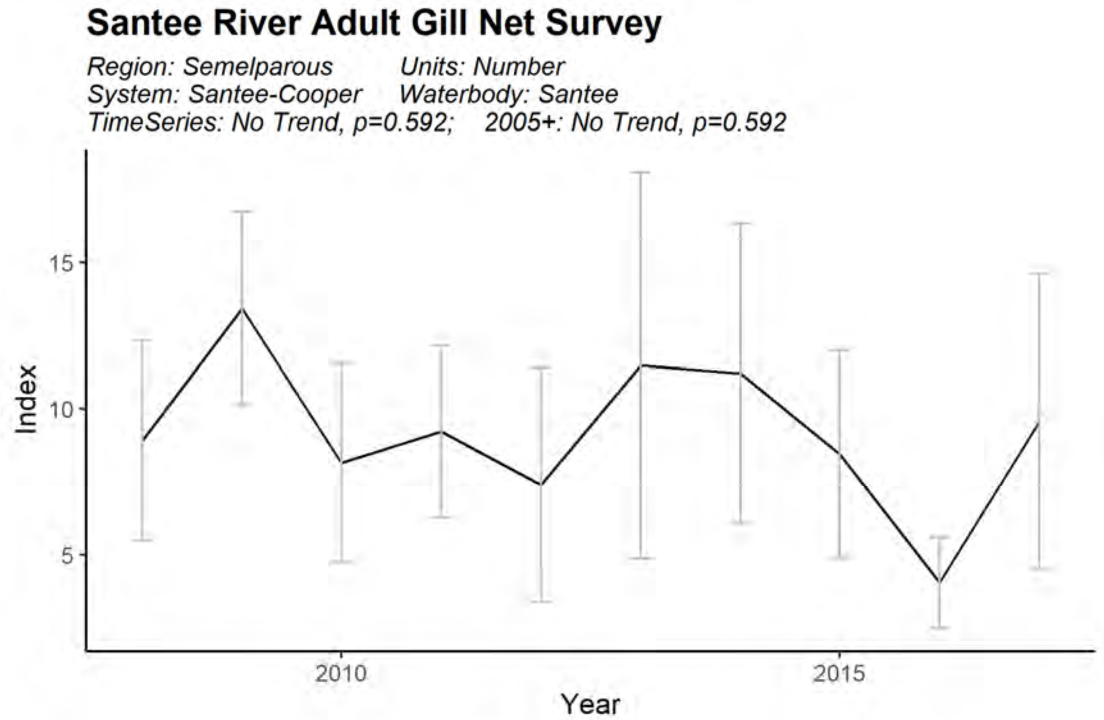


Figure 324. Abundance index developed from the Santee River Adult Gill Net Survey and Mann-Kendall results.

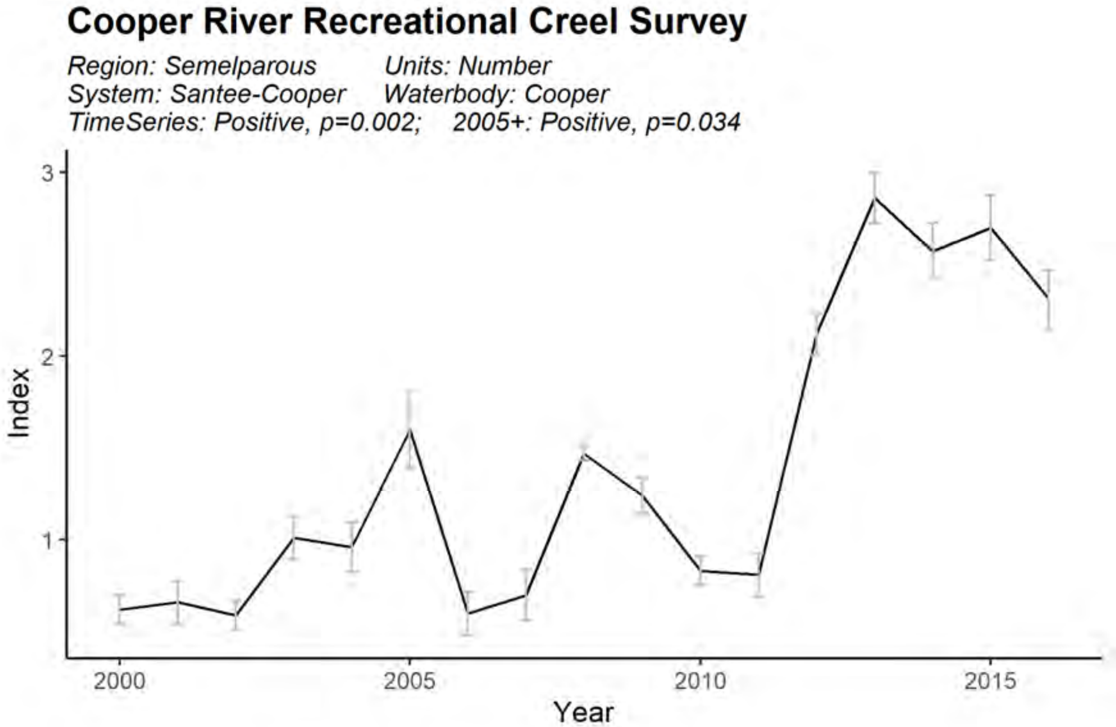


Figure 325. Abundance index developed from the Cooper River Recreational Creel Survey and Mann-Kendall results.

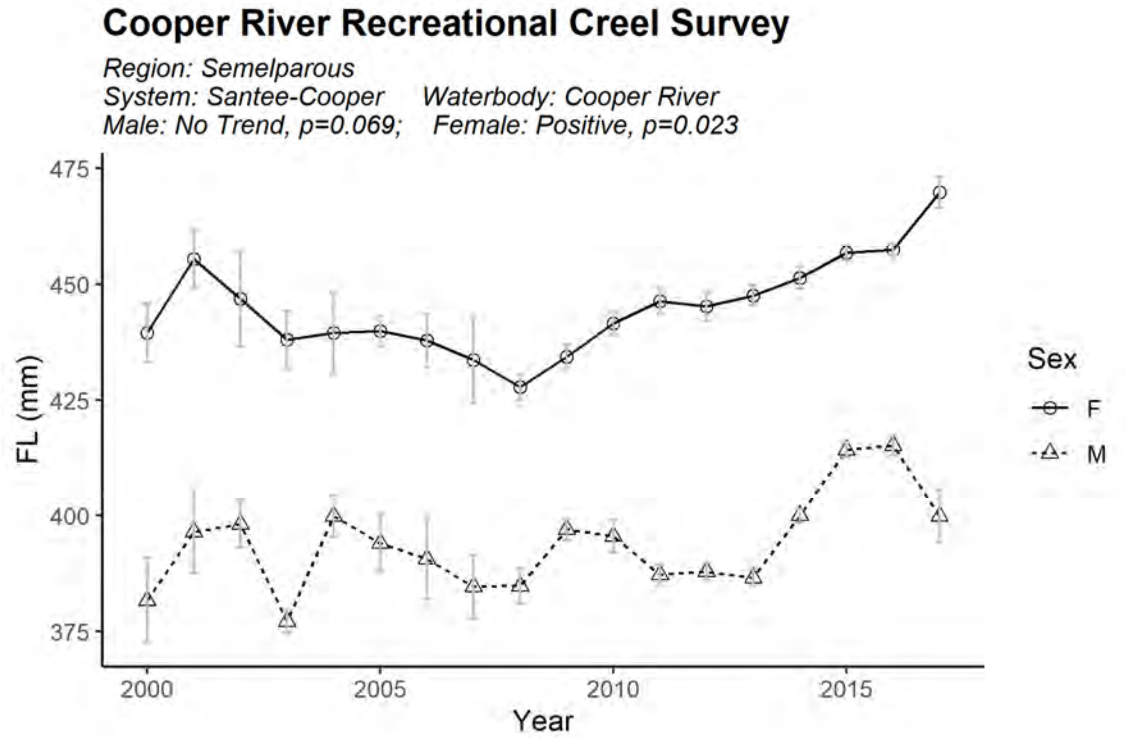


Figure 326. Mean fork length over time for the Cooper River Recreational Creel Survey and Mann-Kendall results.

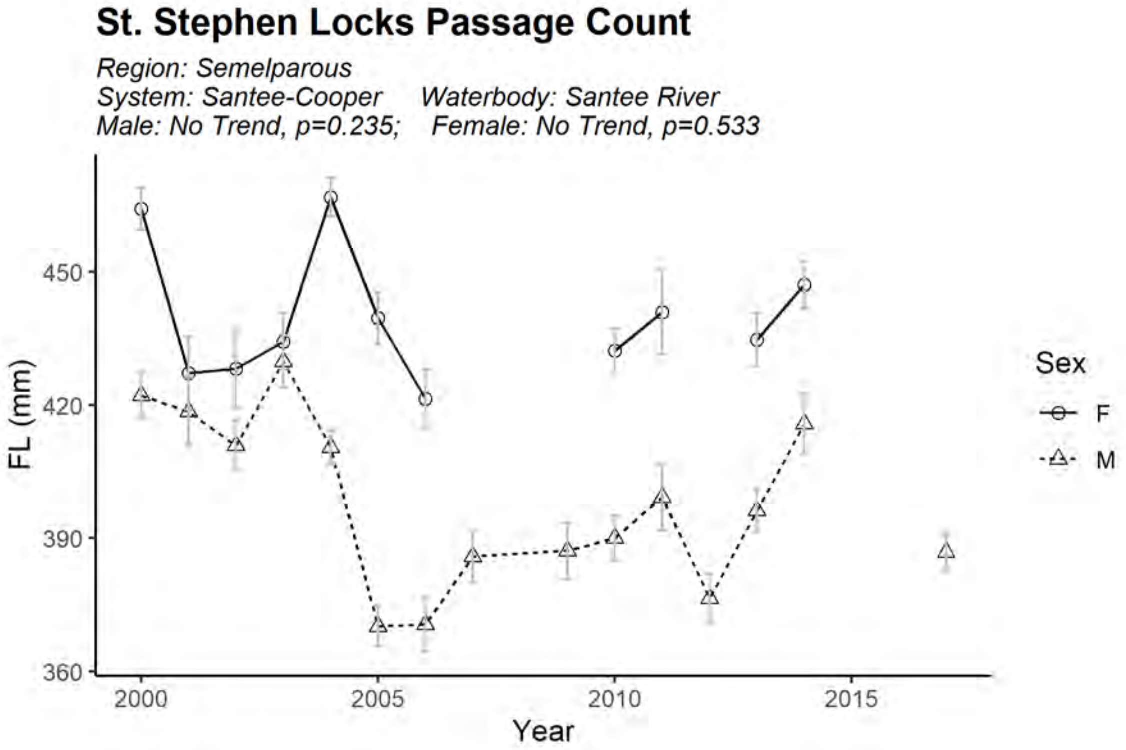


Figure 327. Mean fork length over time for the St. Stephen Locks Passage Count and Mann-Kendall results.

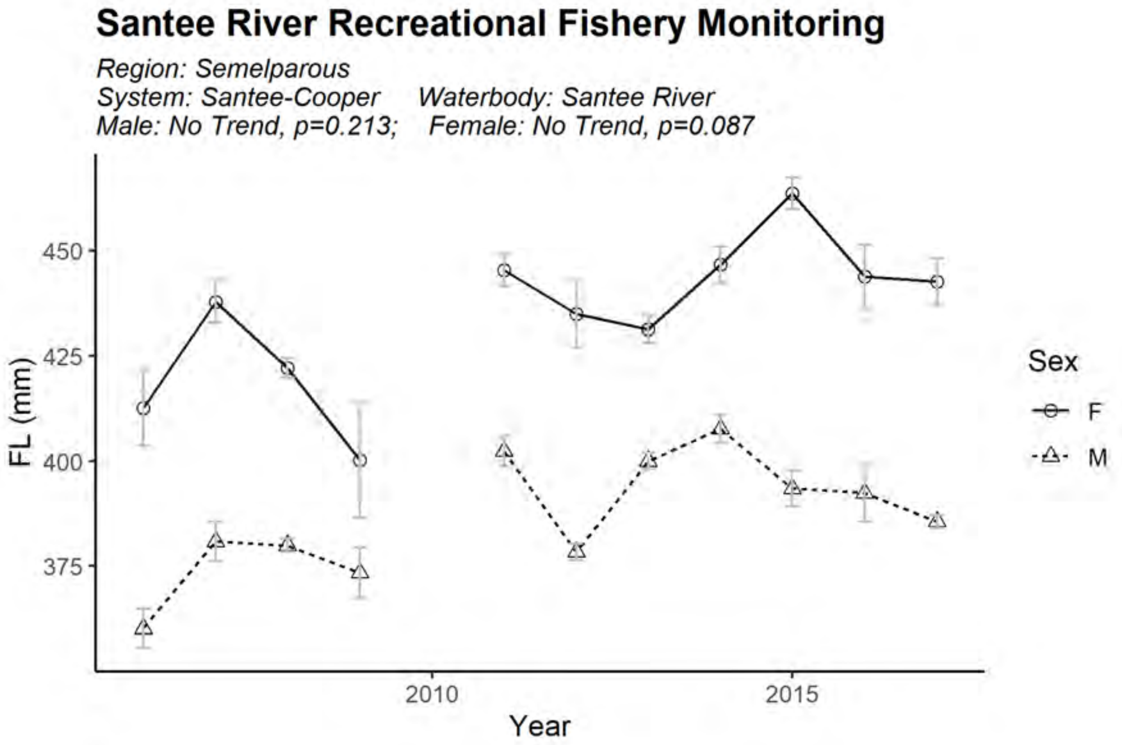


Figure 328. Mean fork length over time for the Santee River Recreational CPUE and Mann-Kendall results.

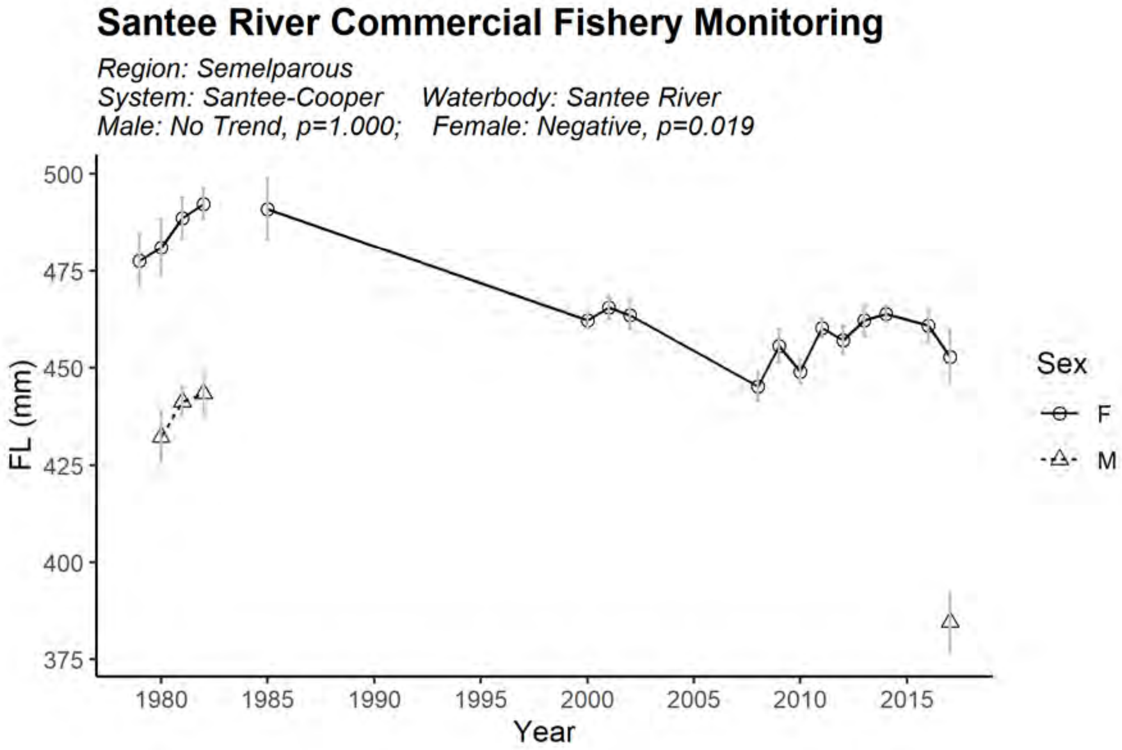


Figure 329. Mean fork length over time for the Santee River Commercial Fishery Monitoring and Mann-Kendall results.

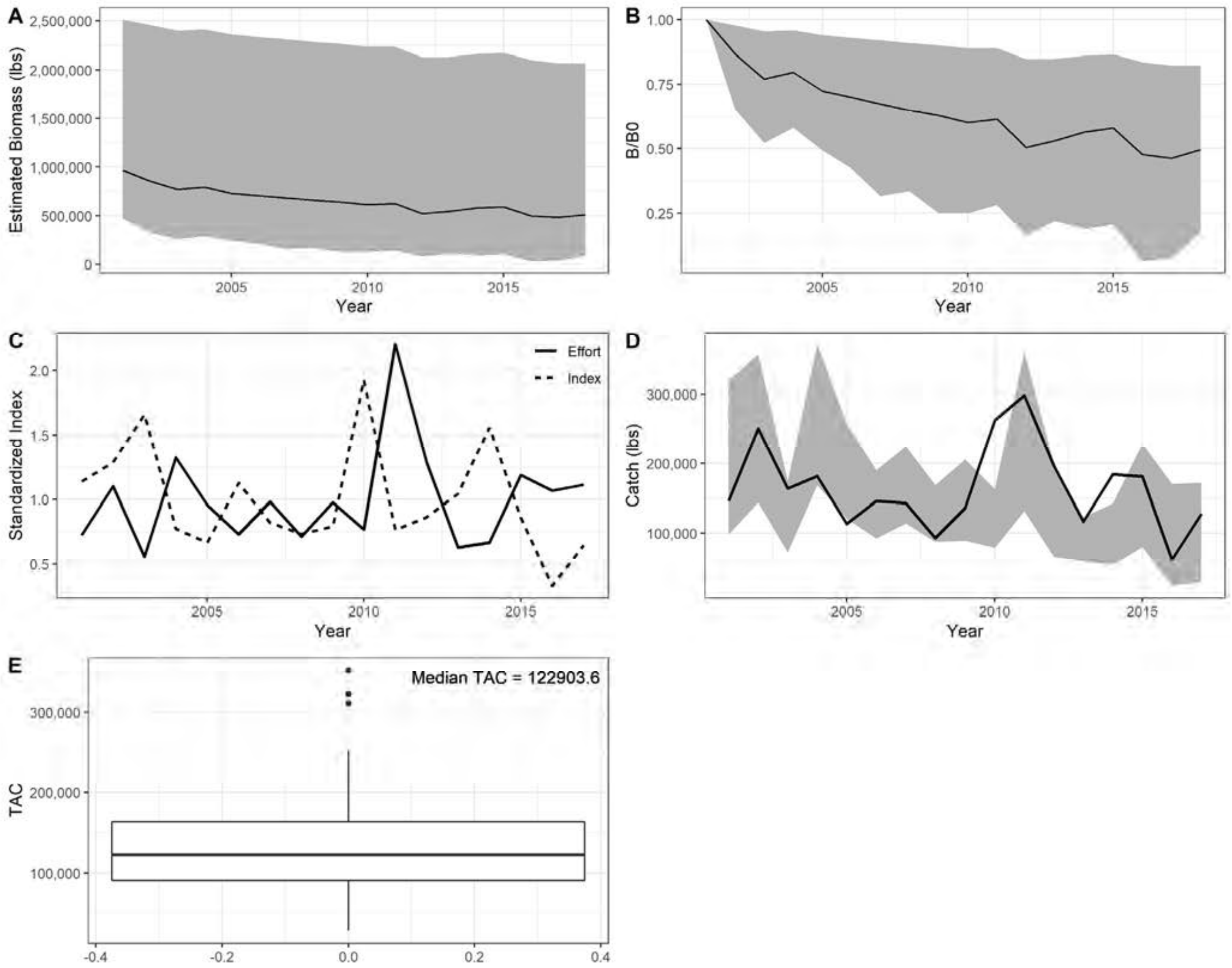


Figure 330. Output of delay-difference model for the Santee-Cooper American shad stock using the Santee River Commercial CPUE index. (A) Estimated biomass of the population over time. The black line represents the median biomass over 100 simulations. (B) Ratio of estimated biomass to initial biomass. The black line represents the median biomass ratio over 100 simulations. (C) Standardized index and fishery effort over time. (D) Total catch over time. The black line represents the observed catch and the gray area represents estimates over 100 simulations. (E) Boxplot of Total Allowable Catch (TAC) estimates over 100 simulations.

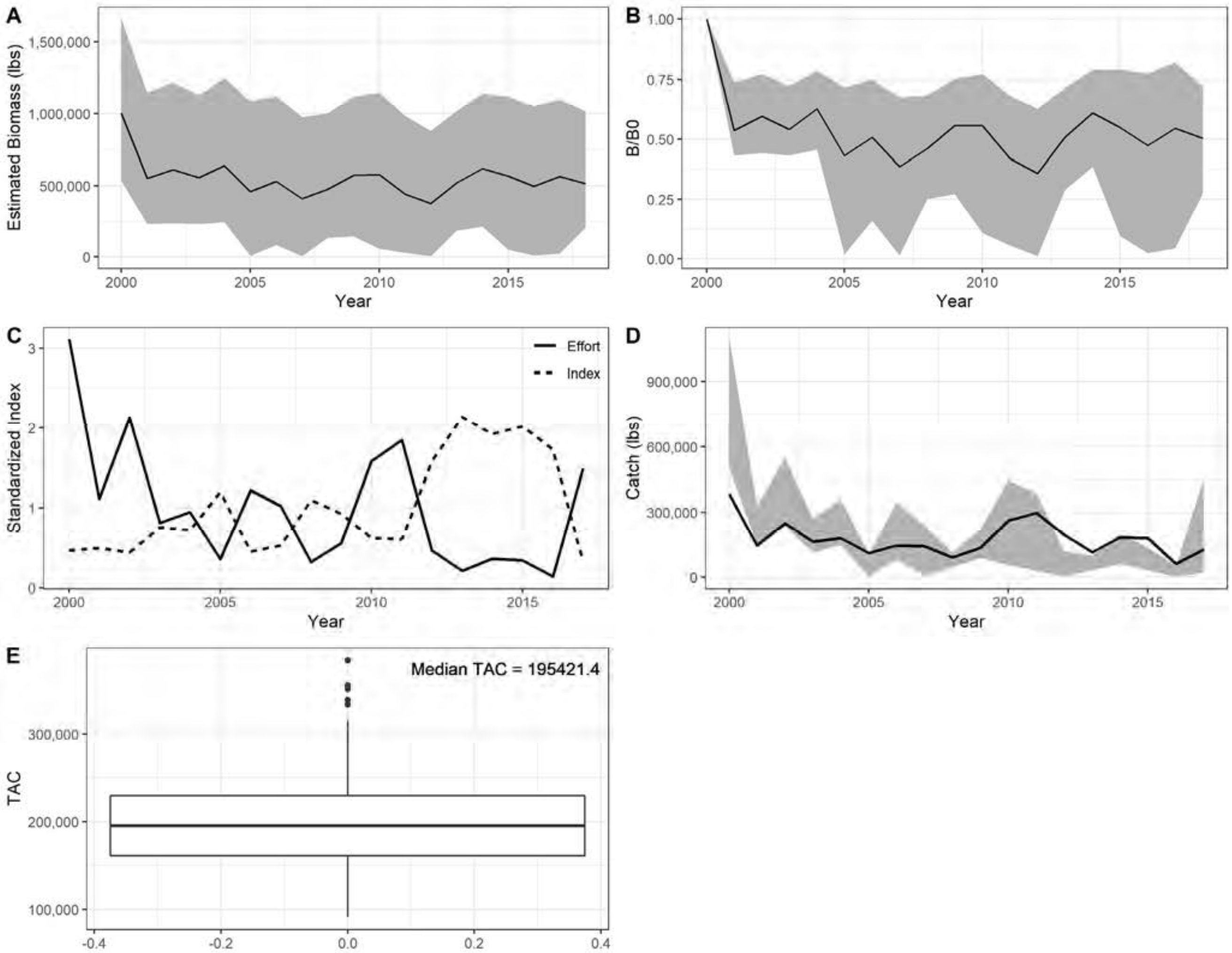
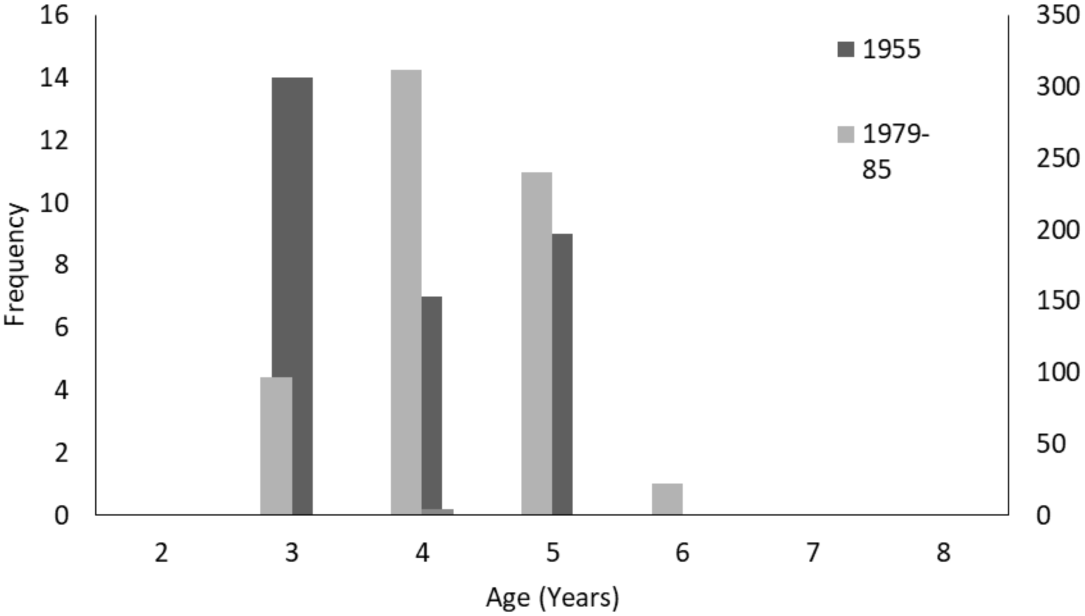


Figure 331. Output of delay-difference model for the Santee-Cooper American shad stock using the Cooper River Recreational Creel Survey index. (A) Estimated biomass of the population over time. The black line represents the median biomass over 100 simulations. (B) Ratio of estimated biomass to initial biomass. The black line represents the median biomass ratio over 100 simulations. (C) Standardized index and fishery effort over time. (D) Total catch over time. The black line represents the observed catch and the gray area represents estimates over 100 simulations. (E) Boxplot of Total Allowable Catch (TAC) estimates over 100 simulations.

(a)



(b)

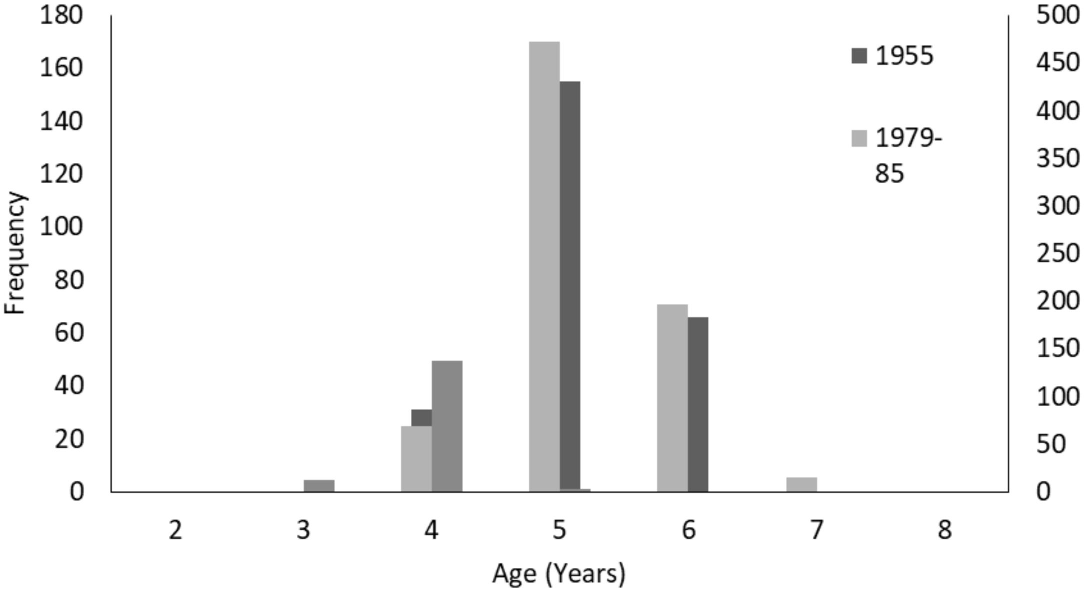


Figure 332. Age distribution of male (a) and female (b) American shad sampled in the Edisto River, South Carolina using gill nets in three periods, 1955 (primary y-axis), 1979 to 1985, and 2006 to 2007 (secondary y-axis). Ages were determined from scales using Cating's (1953) method.

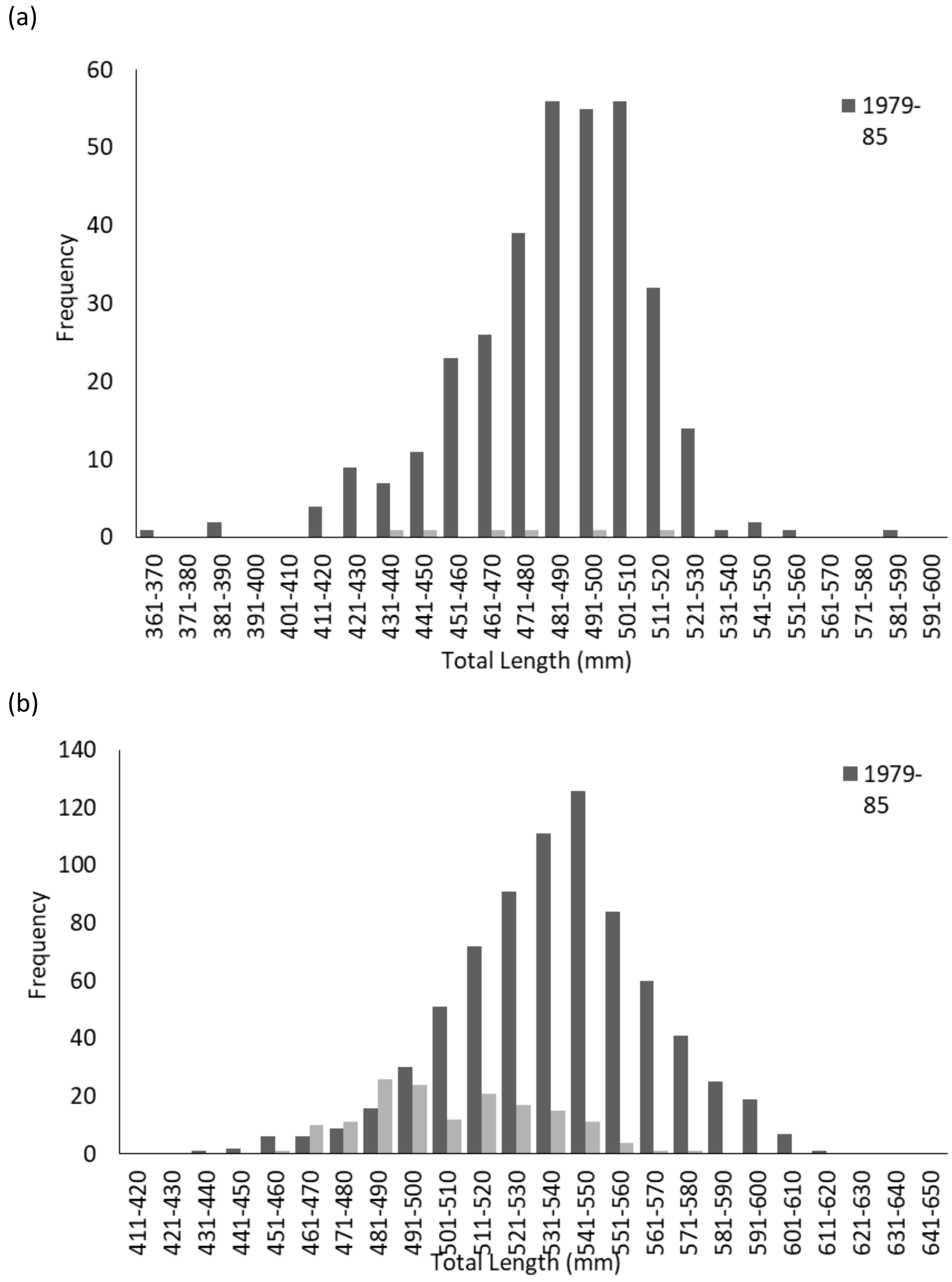


Figure 333. Length distribution of male (a) and female (b) American shad sampled in the Edisto River, South Carolina using gill nets in two periods, 1979 to 1985 (primary y-axis), and 2006 to 2007 (secondary y-axis).

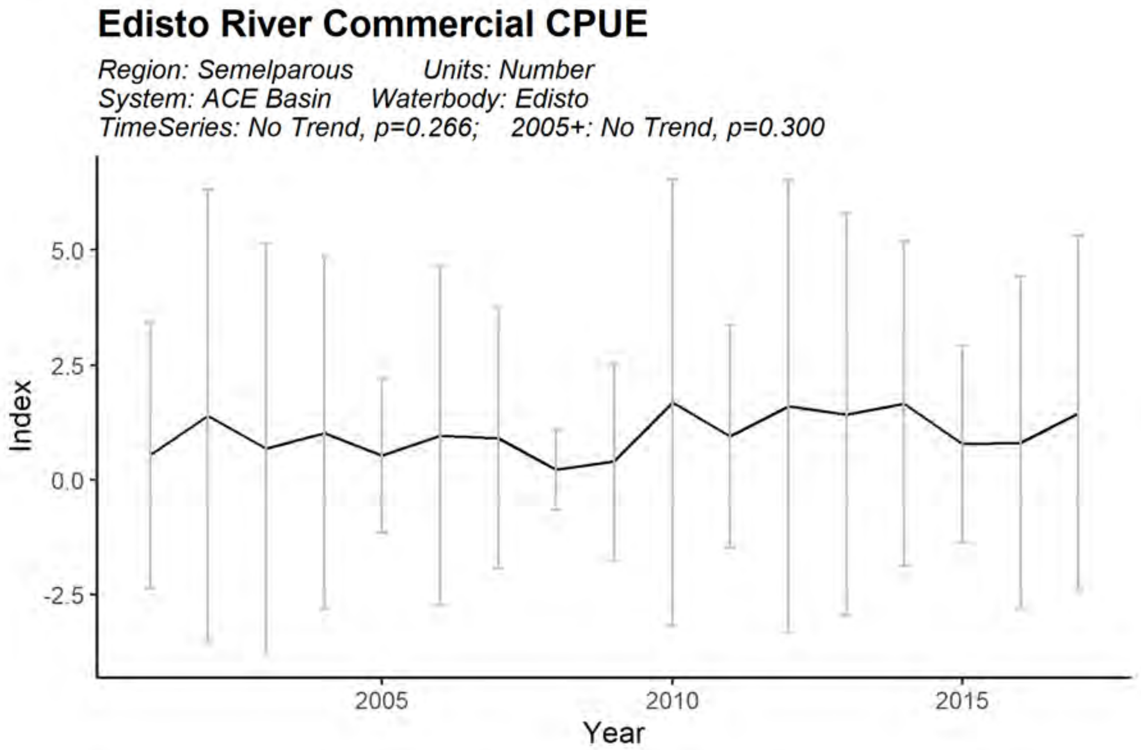


Figure 334. Abundance index developed from the Edisto River Commercial CPUE and Mann-Kendall results.

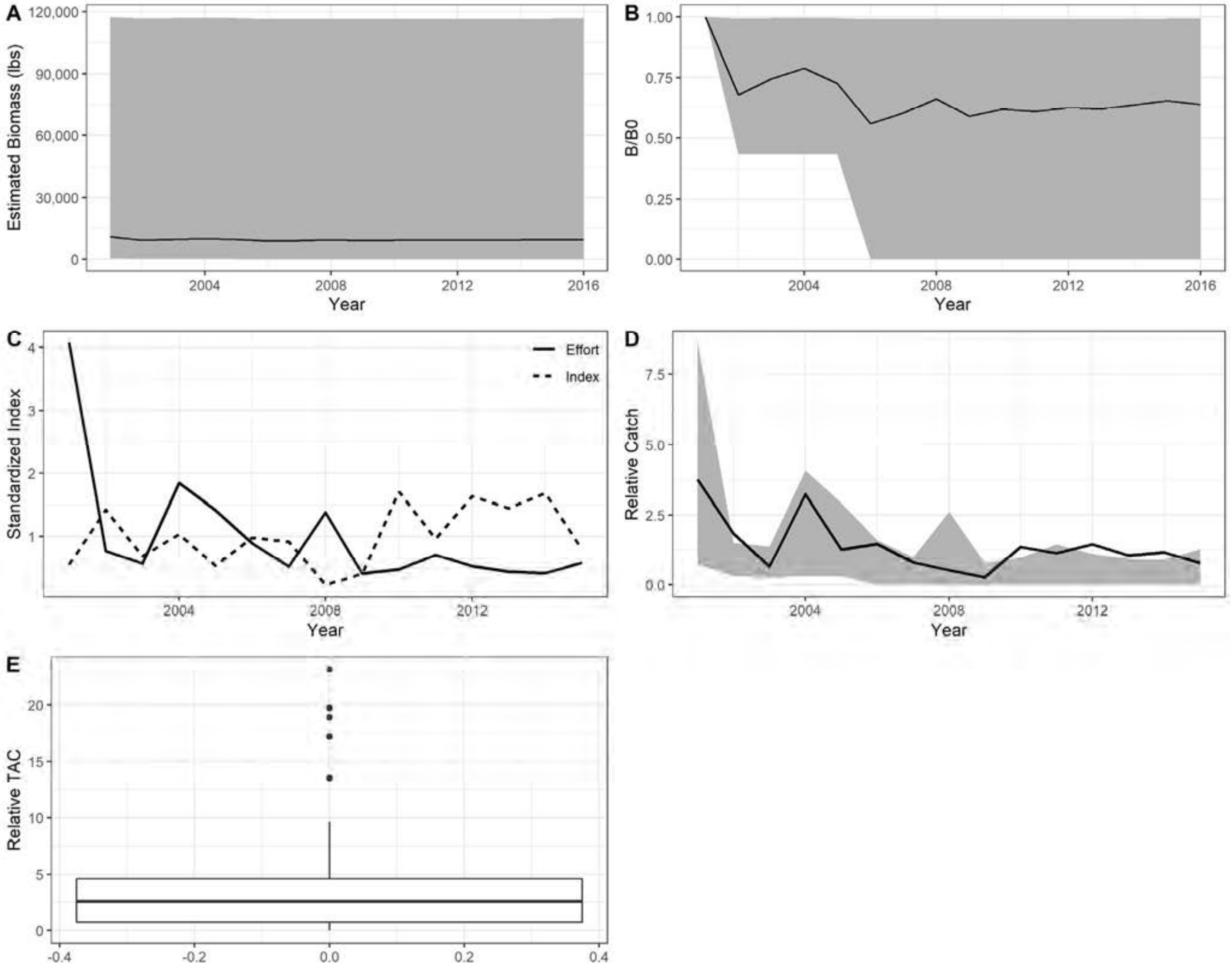


Figure 335. Output of delay-difference model for the ACE Basin American shad stock using the Edisto River Commercial CPUE index. (A) Estimated biomass of the population over time. The black line represents the median biomass over 100 simulations. (B) Ratio of estimated biomass to initial biomass. The black line represents the median biomass ratio over 100 simulations. (C) Standardized index and fishery effort over time. (D) Relative total catch over time. The black line represents the observed catch and the gray area represents estimates over 100 simulations. (E) Boxplot of Total Allowable Catch (TAC) estimates over 100 simulations on a relative scale. Due to confidentiality concerns, catch and TAC figures are plotted relative to the average catch of the final three years of the time series.

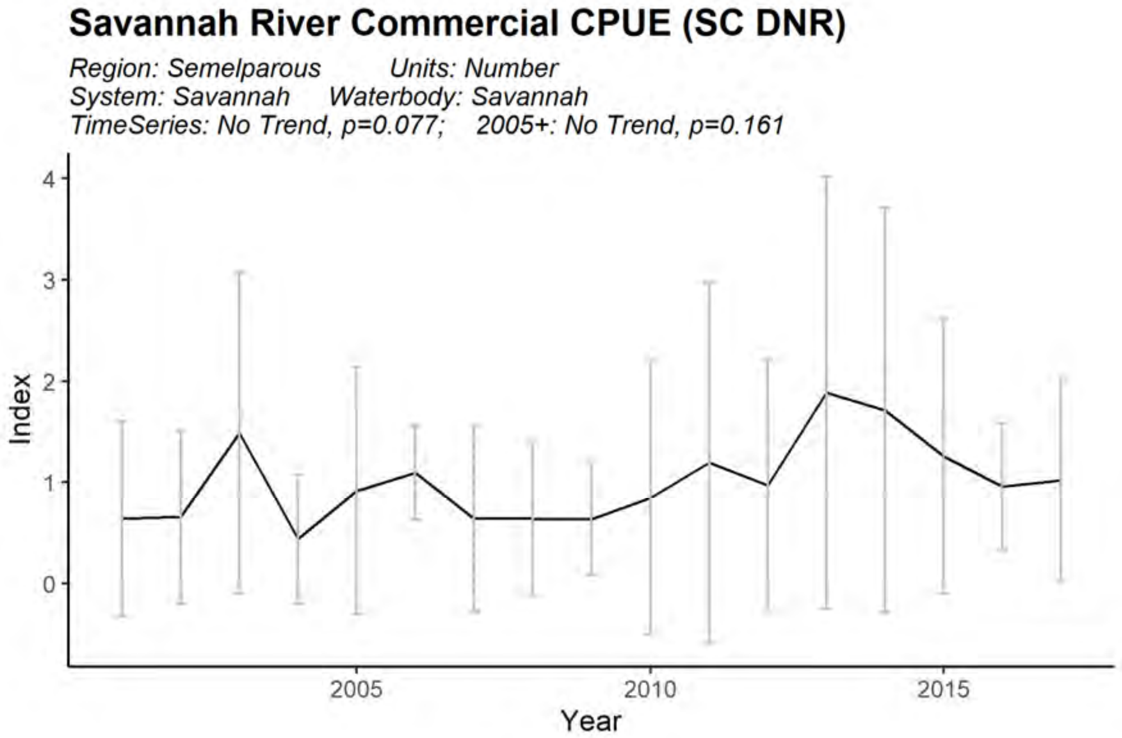


Figure 336. Abundance index developed from Savannah River Commercial CPUE (SC DNR) and Mann-Kendall results.

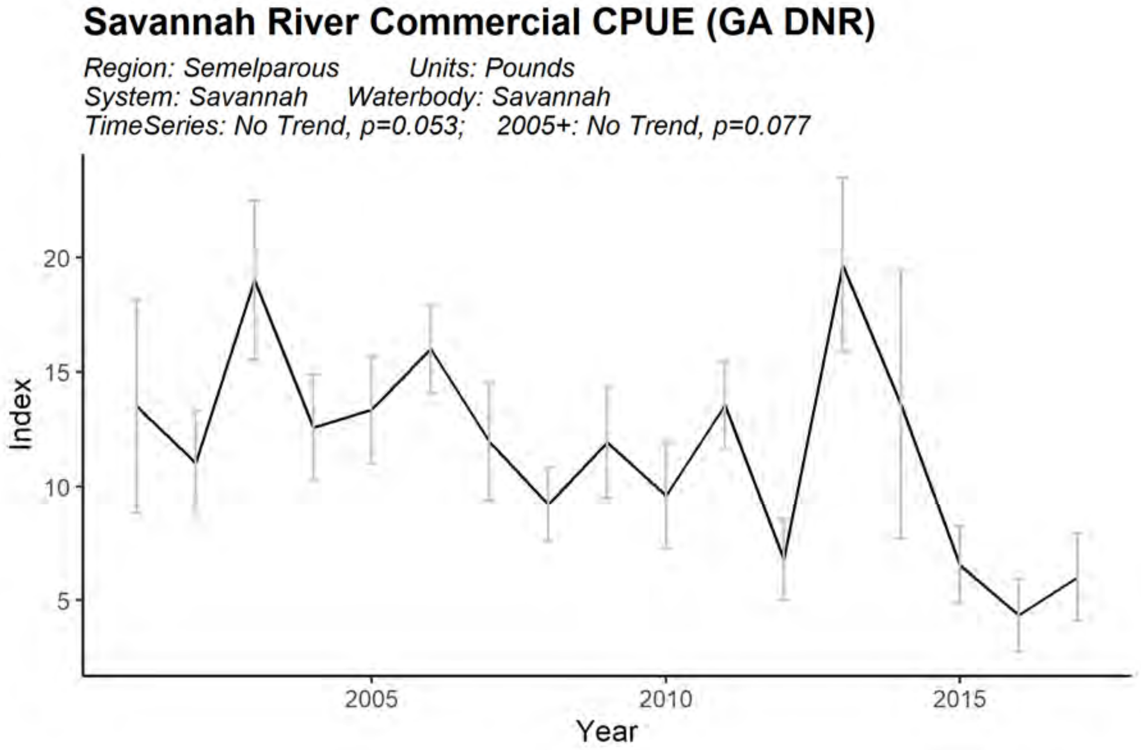


Figure 337. Abundance index developed from Savannah River Commercial CPUE (GA DNR) and Mann-Kendall results.

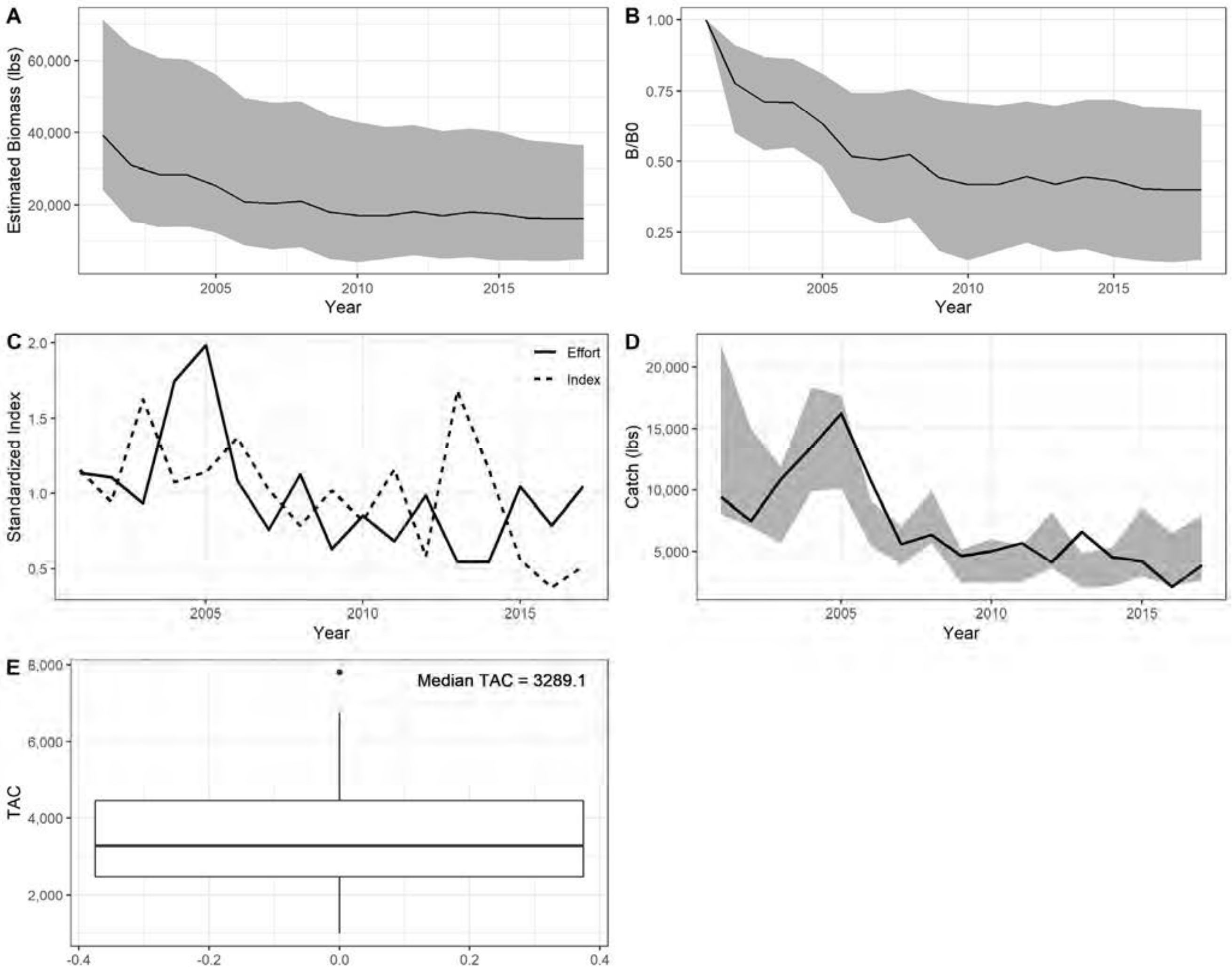


Figure 338. Output of delay-difference model for the Savannah American shad stock using the Savannah River Commercial CPUE (GADNR) index. (A) Estimated biomass of the population over time. The black line represents the median biomass over 100 simulations. (B) Ratio of estimated biomass to initial biomass. The black line represents the median biomass ratio over 100 simulations. (C) Standardized index and fishery effort over time. (D) Total catch over time. The black line represents the observed catch and the gray area represents estimates over 100 simulations. (E) Boxplot of Total Allowable Catch (TAC) estimates over 100 simulations.

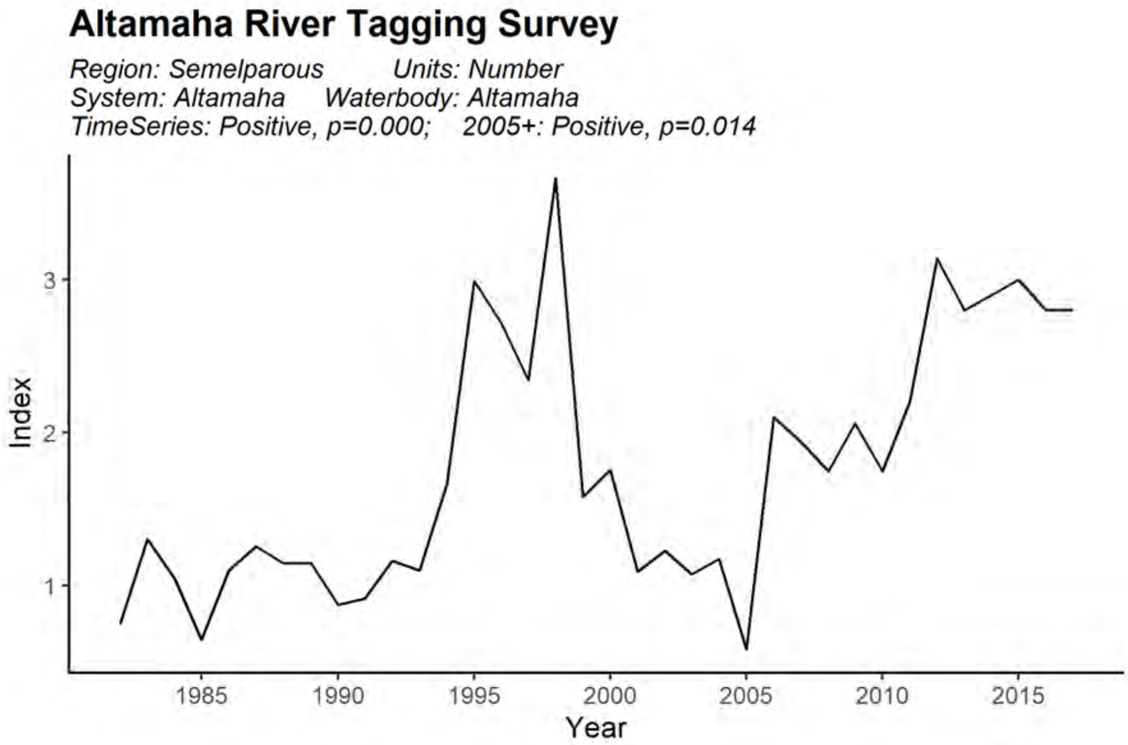


Figure 339. Abundance index developed from the Altamaha River Tagging Survey and Mann-Kendall results.

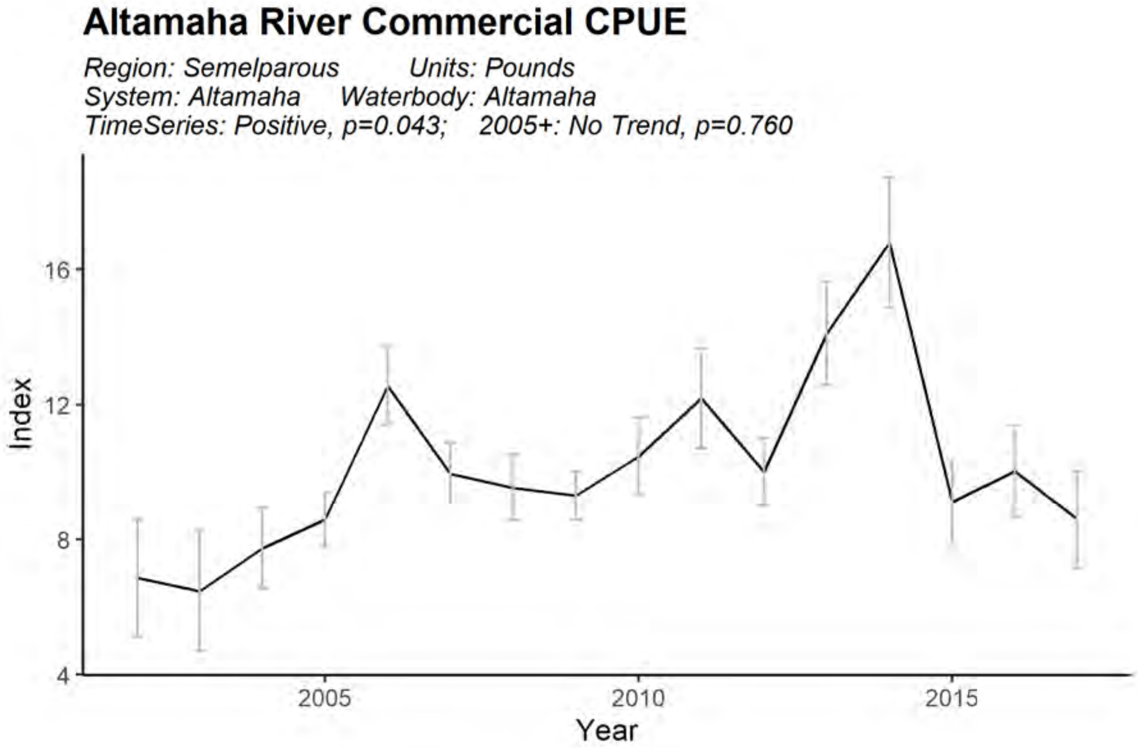


Figure 340. Abundance index developed from Altamaha River Commercial CPUE and Mann-Kendall results.

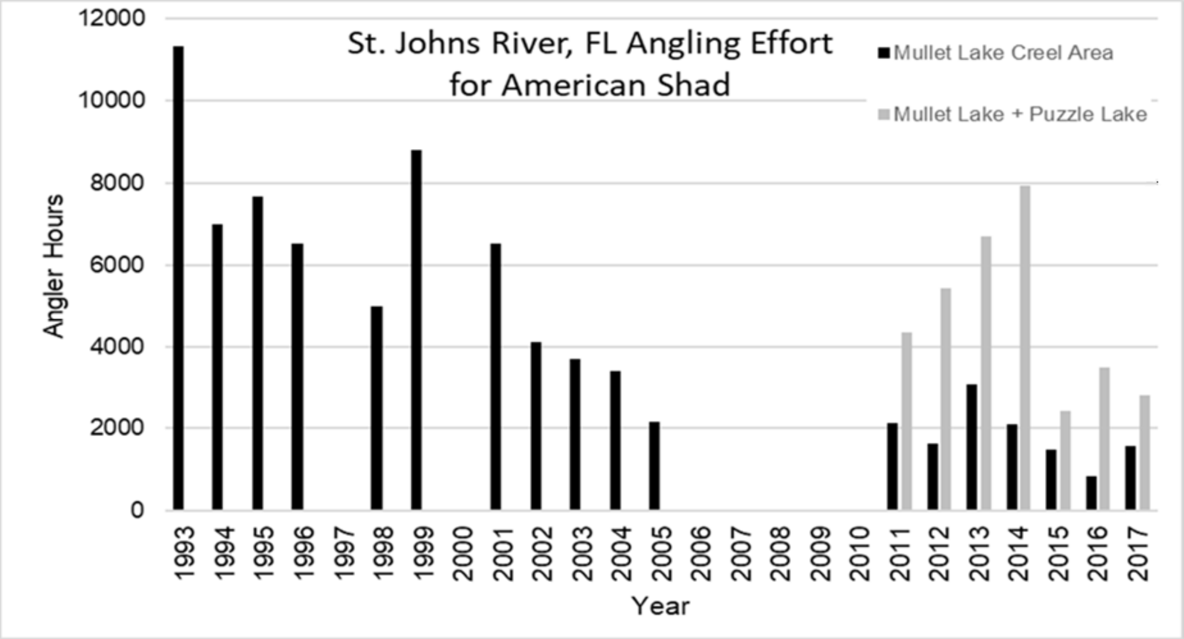


Figure 341. Recreation effort for American shad in the St. Johns River, Florida expressed as angler-hours. An additional stratum was added in 2011 as effort shifted away from the original area. "Mullet Lake Creel Area" is still treated as a unique stratum for comparison to the 1993 to 2005 data. Total effort is the combined effort from the "Mullet Lake Creel Area" stratum and the "Puzzle Lake Creel Area" stratum.

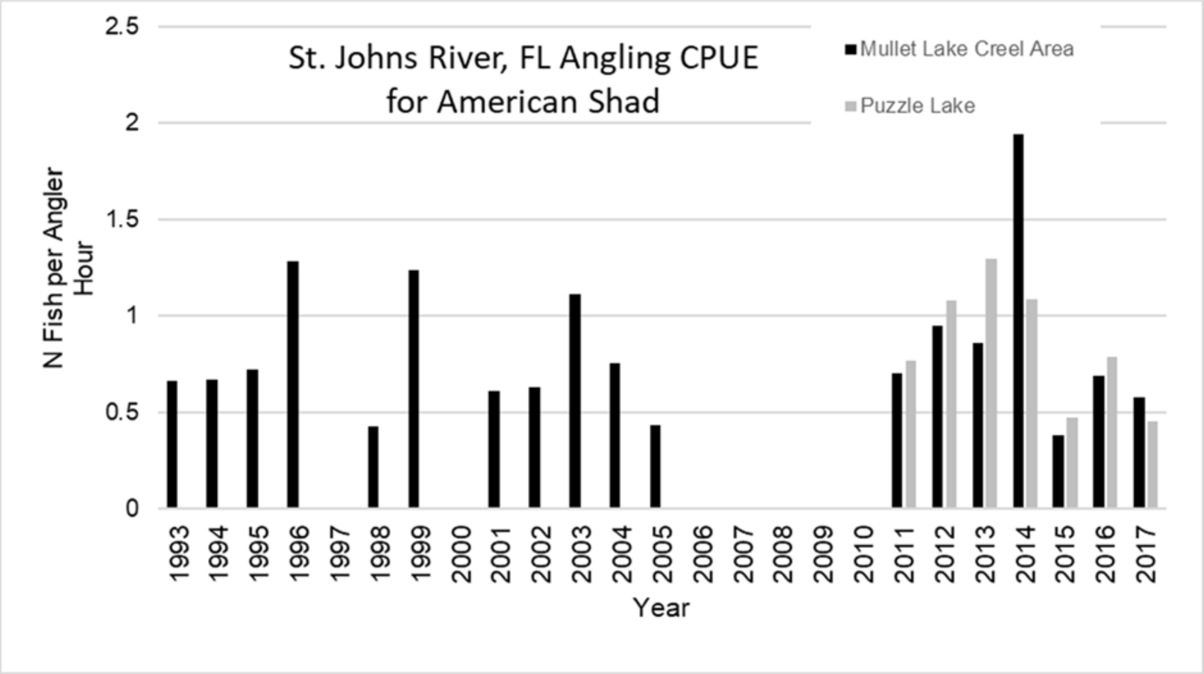


Figure 342. The catch per unit effort of American shad from the recreational fishery in the St. Johns River, Florida from the Mullet Lake Creel Area stratum and the Puzzle Lake stratum.

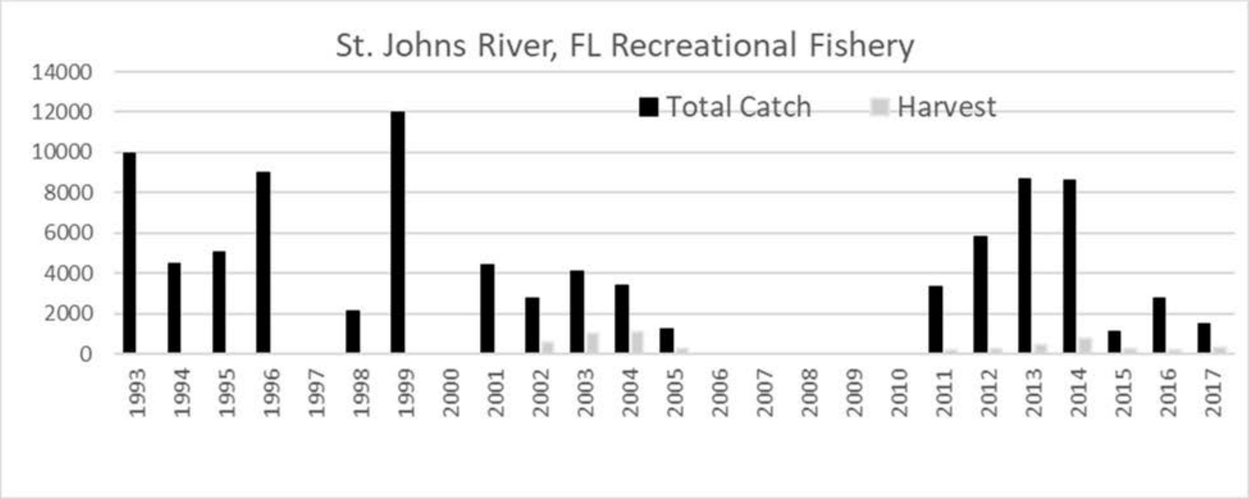


Figure 343. The total catch and harvest of American shad in the recreational fishery in the St. Johns River, Florida.

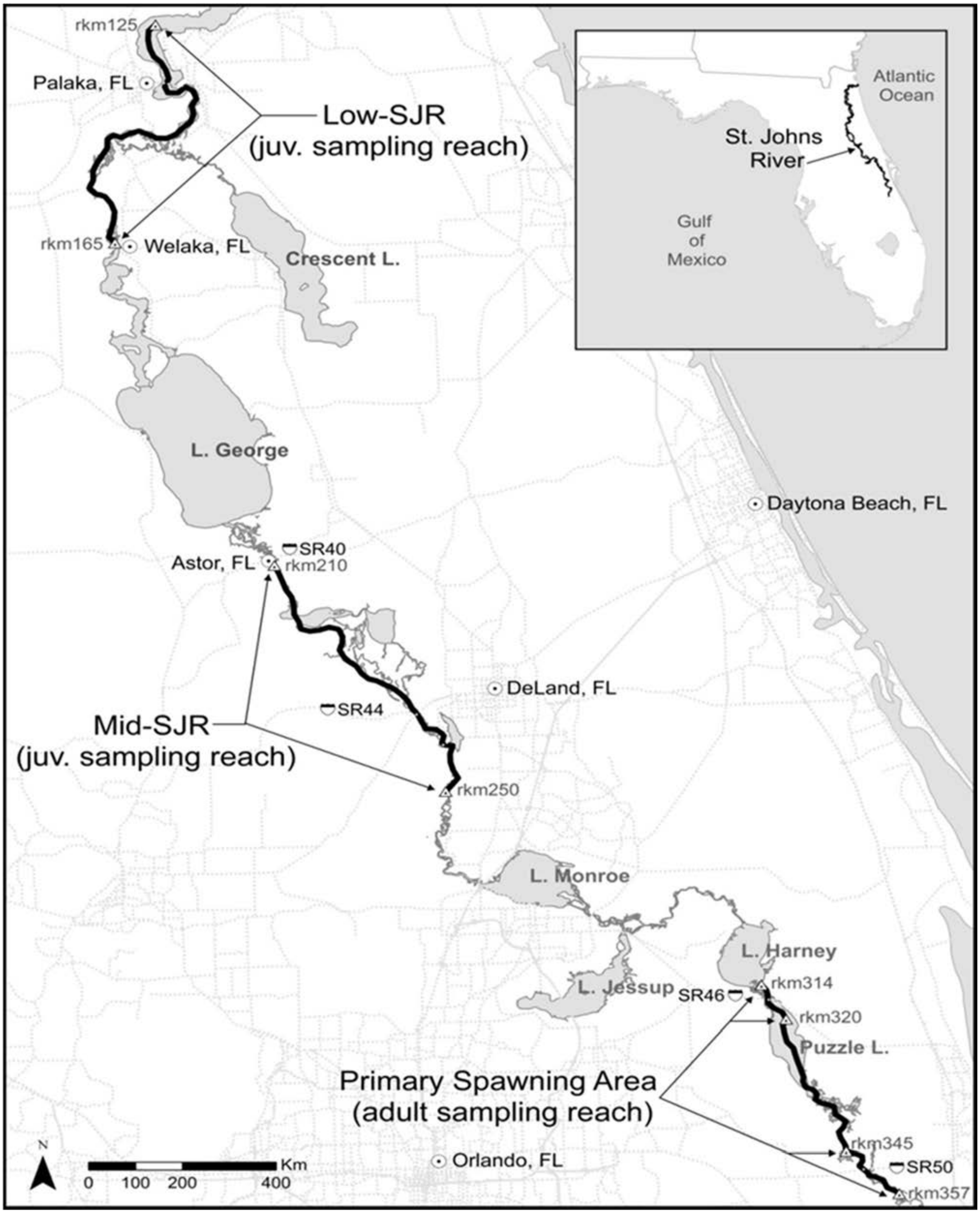


Figure 344. Overview of primary sample areas in the St. Johns River for American shad spawning stock and juvenile abundance monitoring.

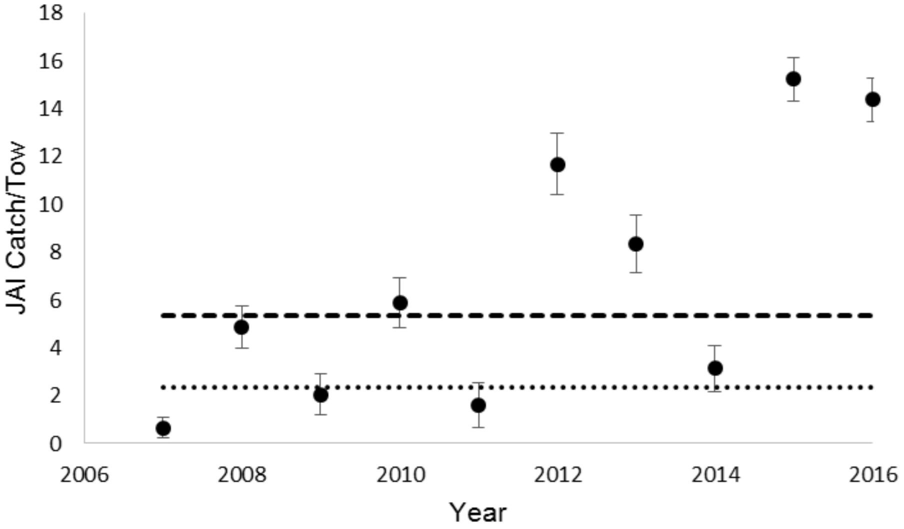
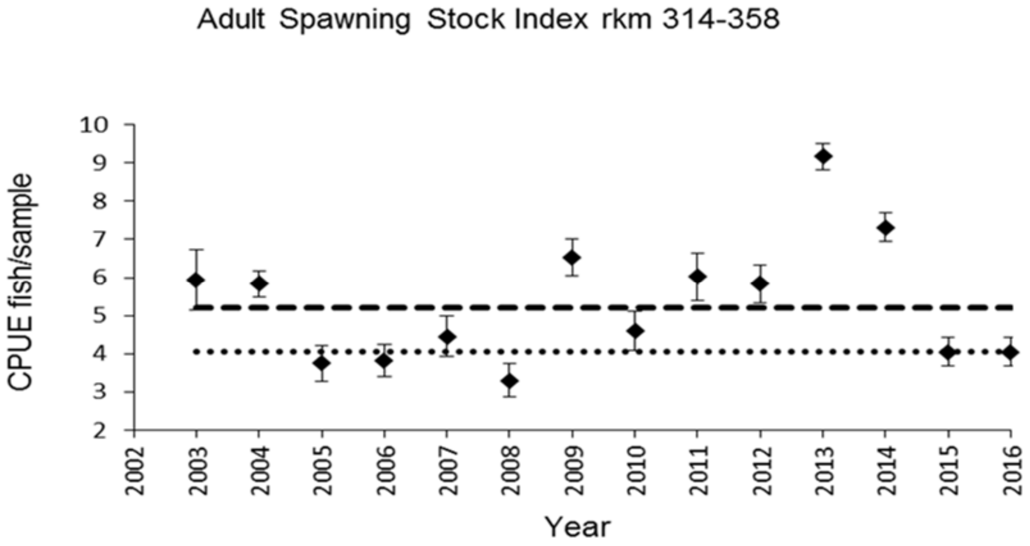


Figure 345. St. Johns River Florida SFMP metric for juvenile abundance. This is the peak nightly geometric mean of samples between river kilometer 125 – 164. A sample night consists of 12 standard samples within randomly selected river kilometers. The benchmark is currently set as the 25th percentile of indexes between 2007 and 2016.



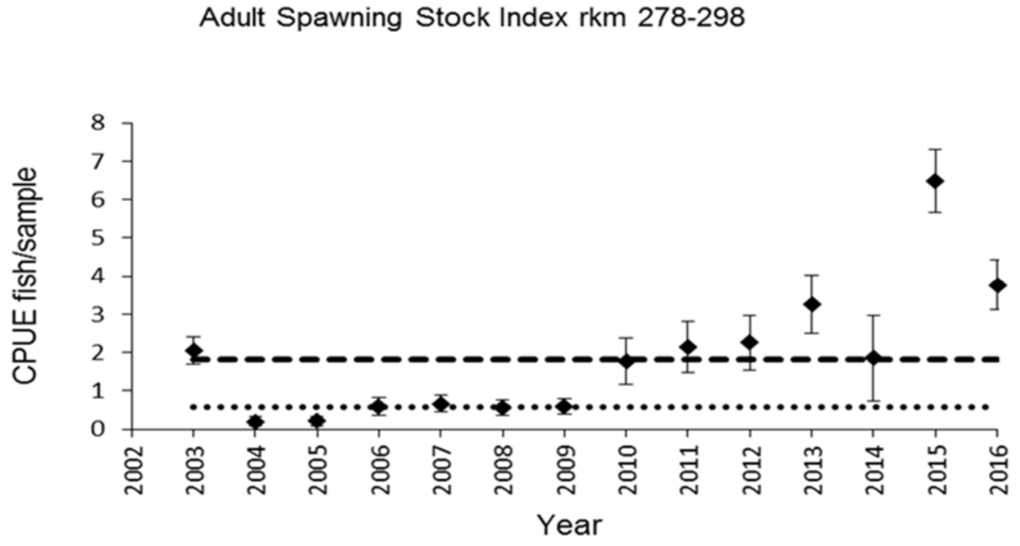


Figure 346. Electrofishing catch per unit effort (geometric mean catch per 10 minute transect) of American shad from the St. Johns River in each of two areas. Dashed line is the median. Dotted line is the 25th percentile. The 25th percentile of the spawning stock index from 2003 to 2016 in the rkm 314 – 358 reach is set as the current sustainability benchmark. The water level in 2015 and 2016 was above the 90th percentile of historic levels during the spawning season and may have impacted the electrofishing survey's ability to correctly index relative abundance by causing the distribution of fish on the spawning ground to shift downstream.

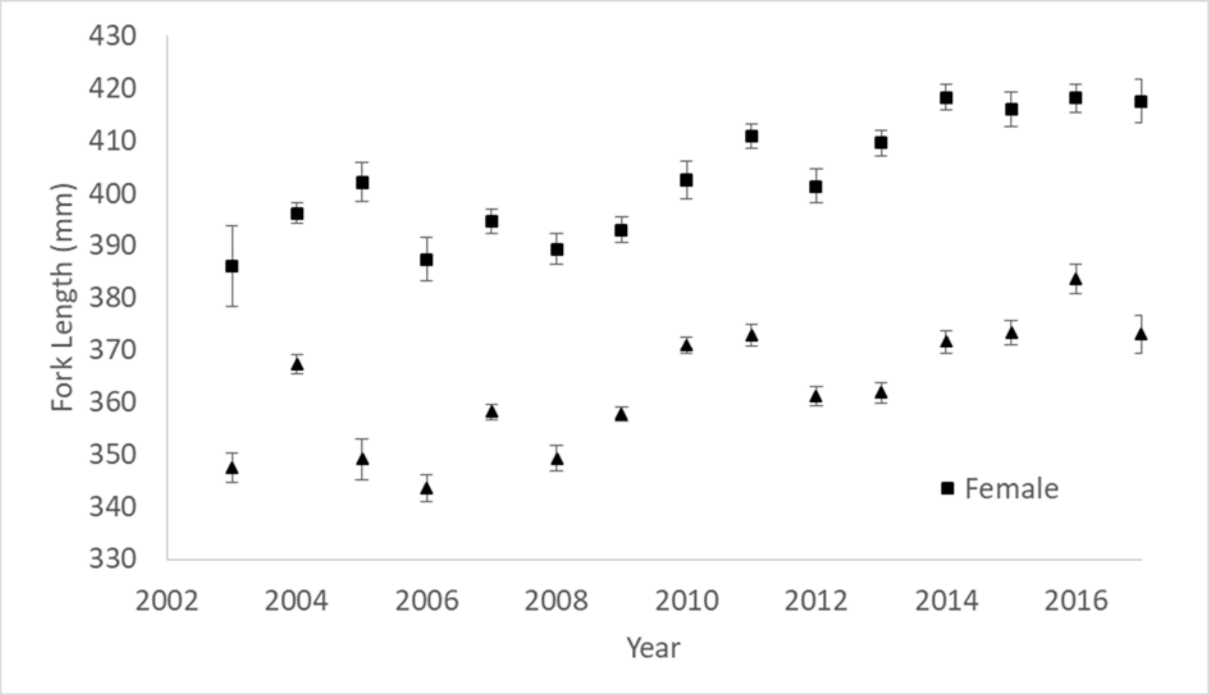


Figure 347. Mean length of female and male American shad on the spawning grounds of the St. Johns River from 2003 through 2017.

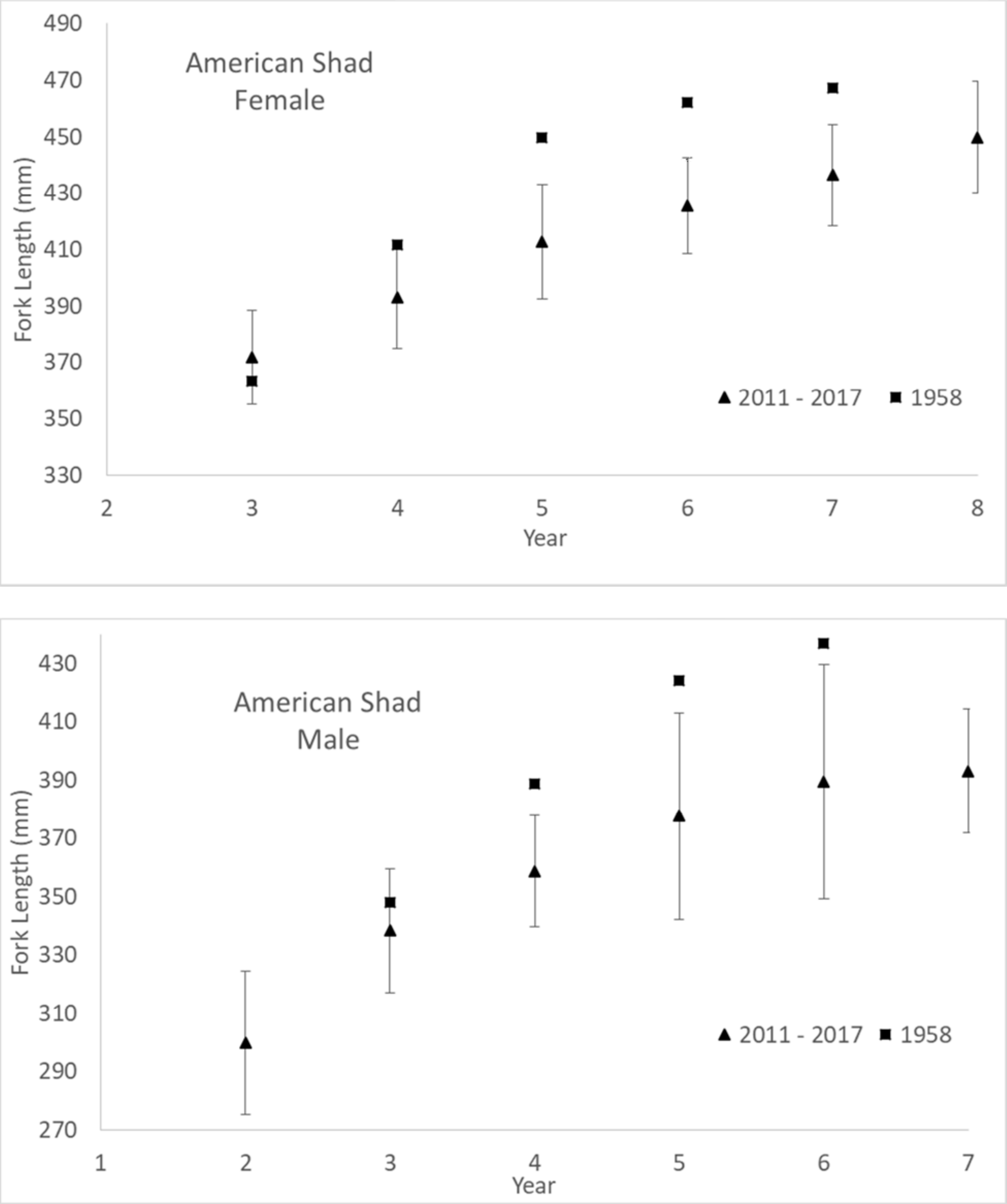


Figure 348. Length-at-age of American shad from the St. Johns River, Florida. 1958 data are scale-based ages from Walburg 1960. The 2011 – 2017 data are from otolith-based age data from the current monitoring program.

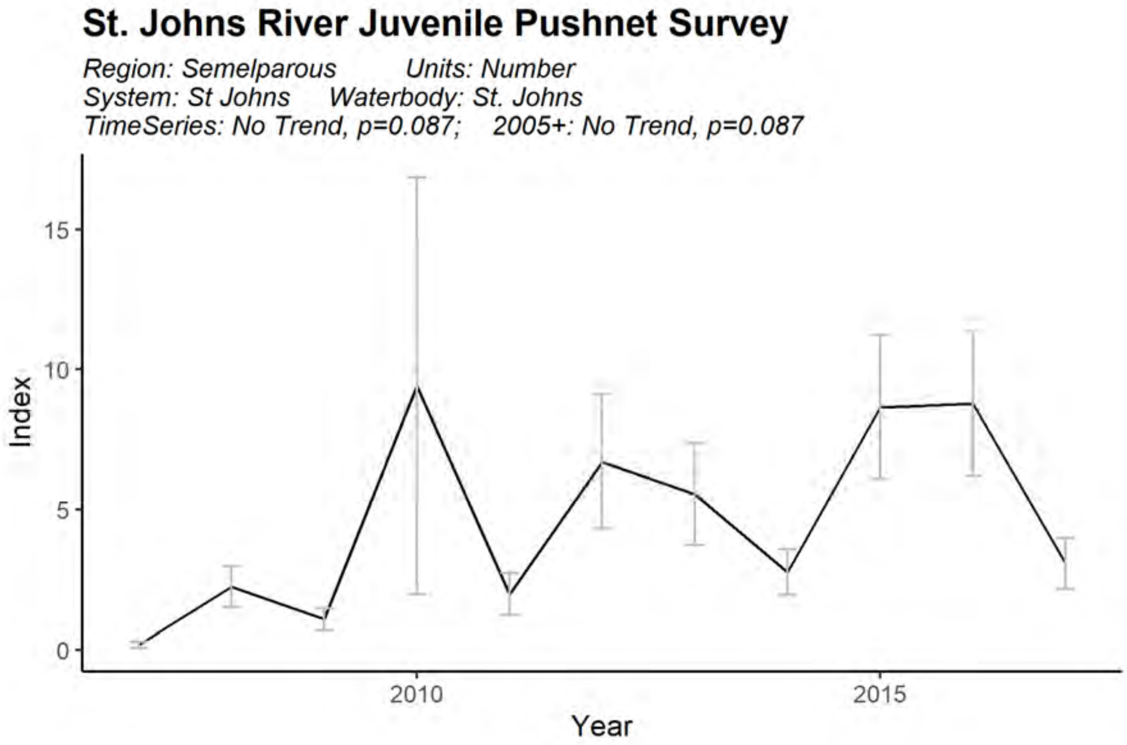


Figure 349. YOY index developed from the St. Johns River Juvenile Pushnet Survey and Mann-Kendall results.

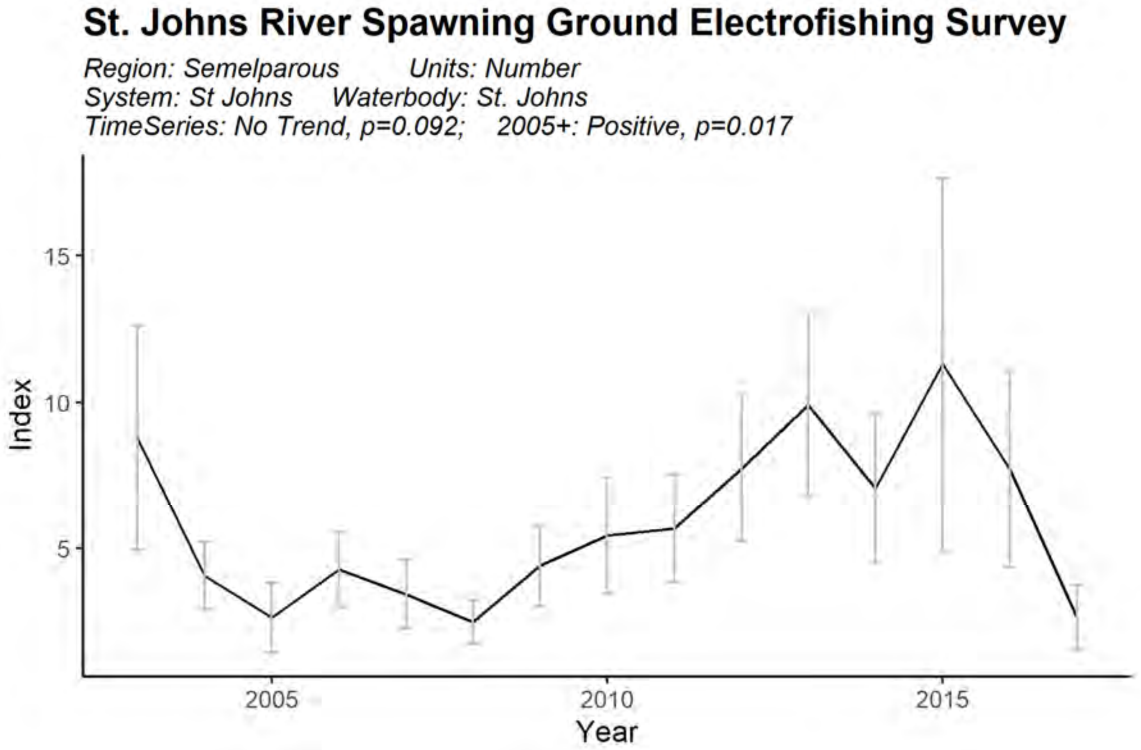


Figure 350. Abundance index developed from the St. Johns River Spawning Ground Electrofishing Survey and Mann Kendall results.

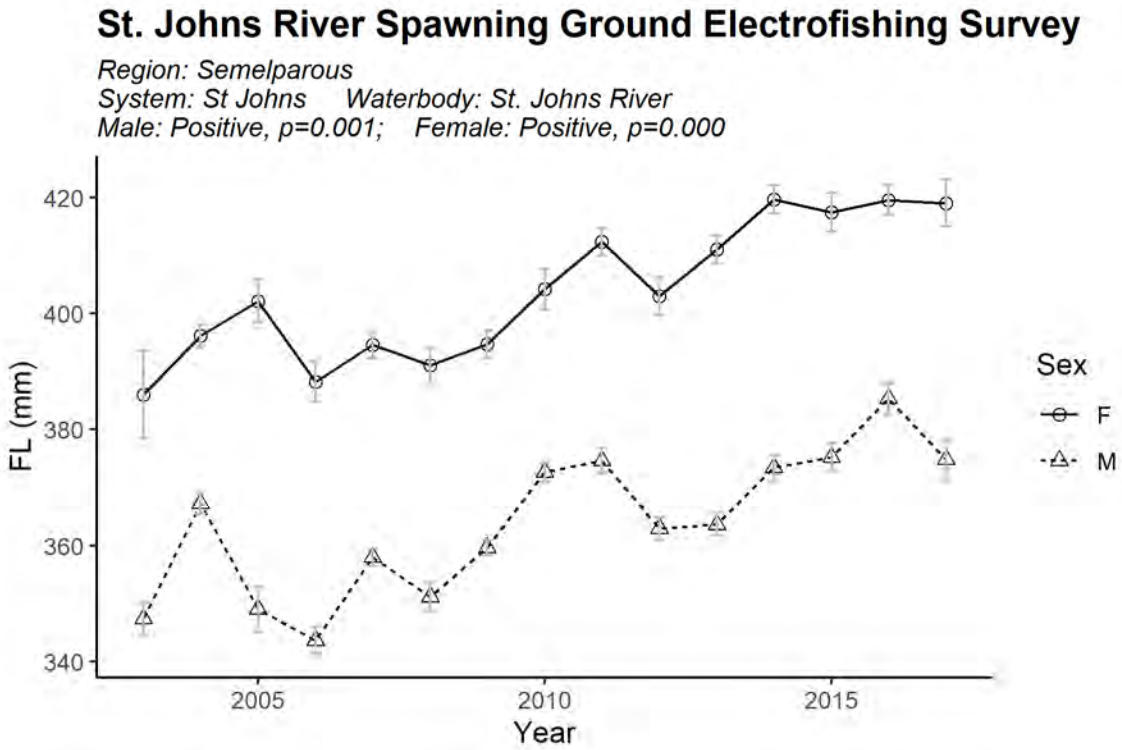


Figure 351. Mean fork length over time from the St. Johns River Spawning Ground Electrofishing Survey and Mann Kendall results.

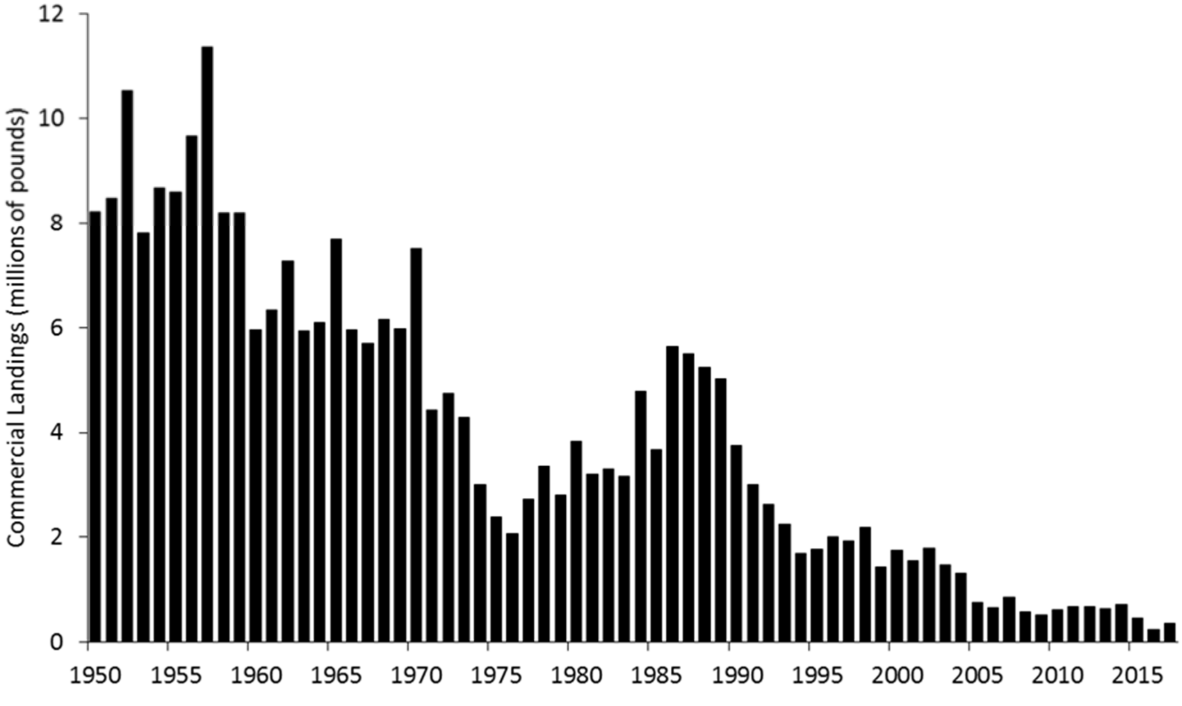


Figure 352. U.S. Atlantic Coast commercial landings (millions of pounds) of American shad from 1950-2017.

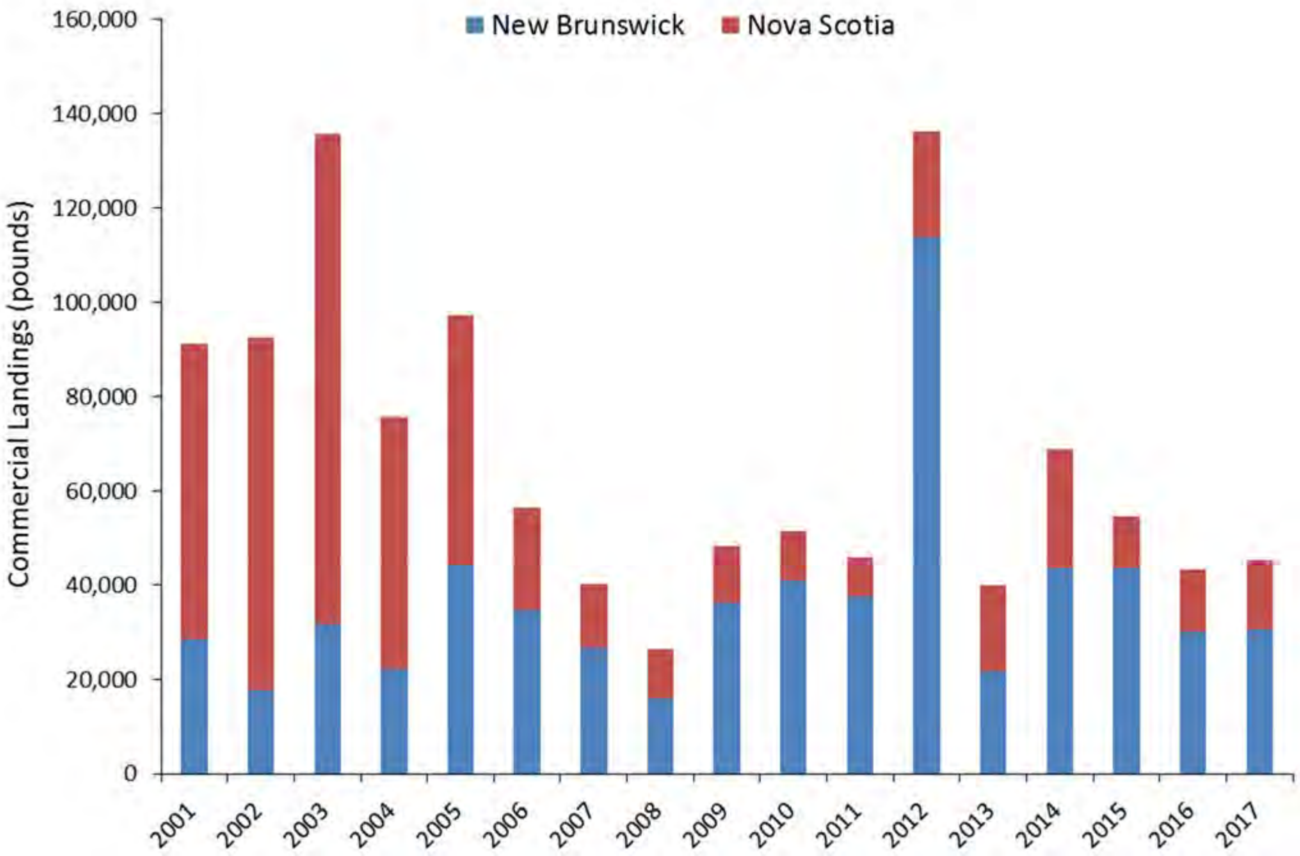


Figure 353. Canadian Maritimes region commercial landings of American shad from 2001-2017. Data from 2016-2017 are considered preliminary and subject to change.

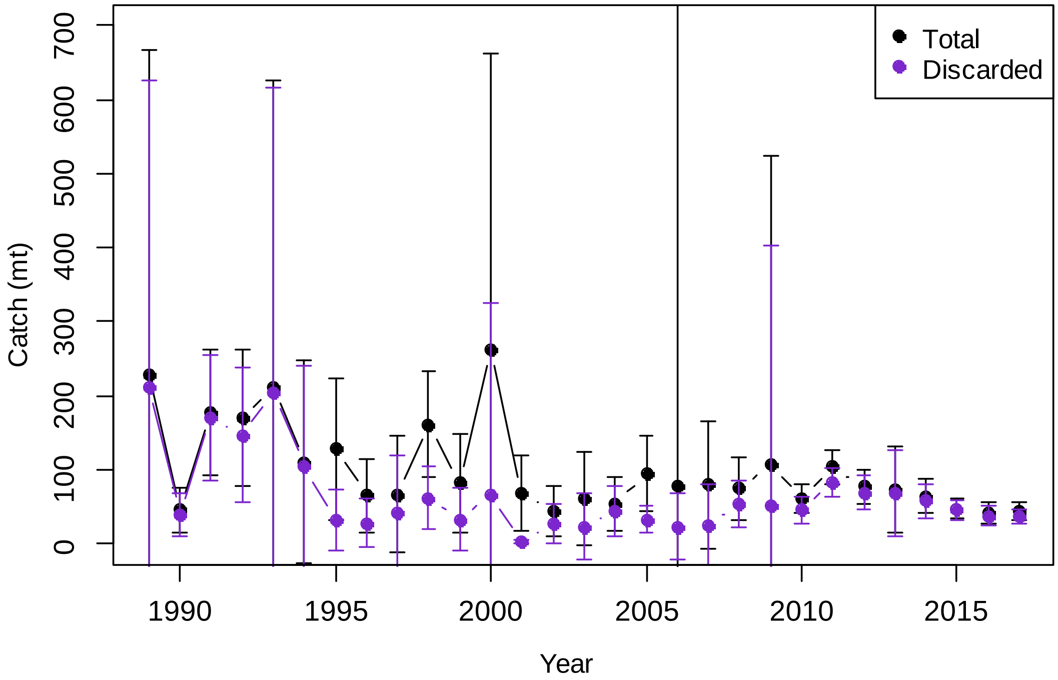
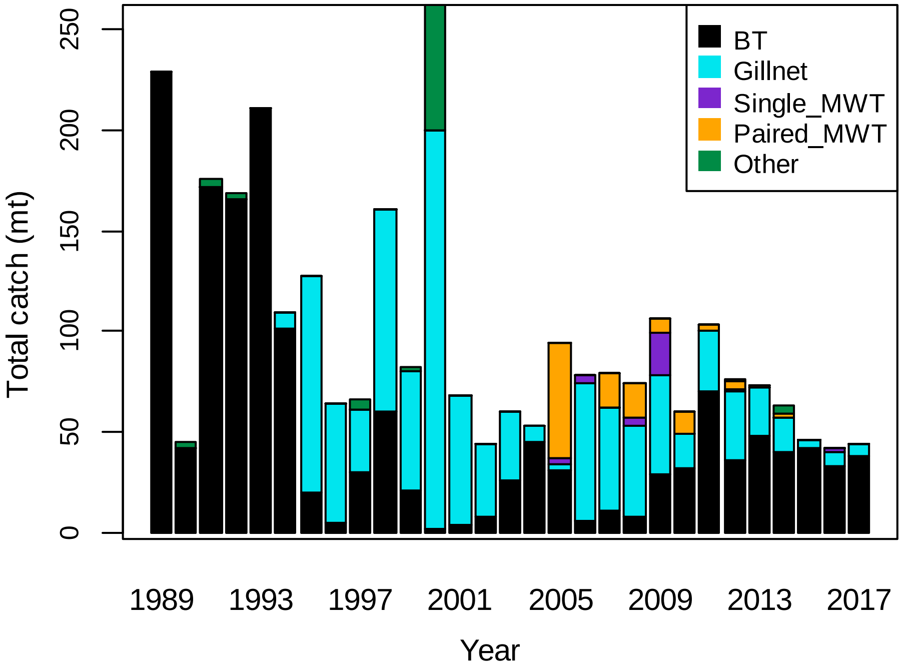


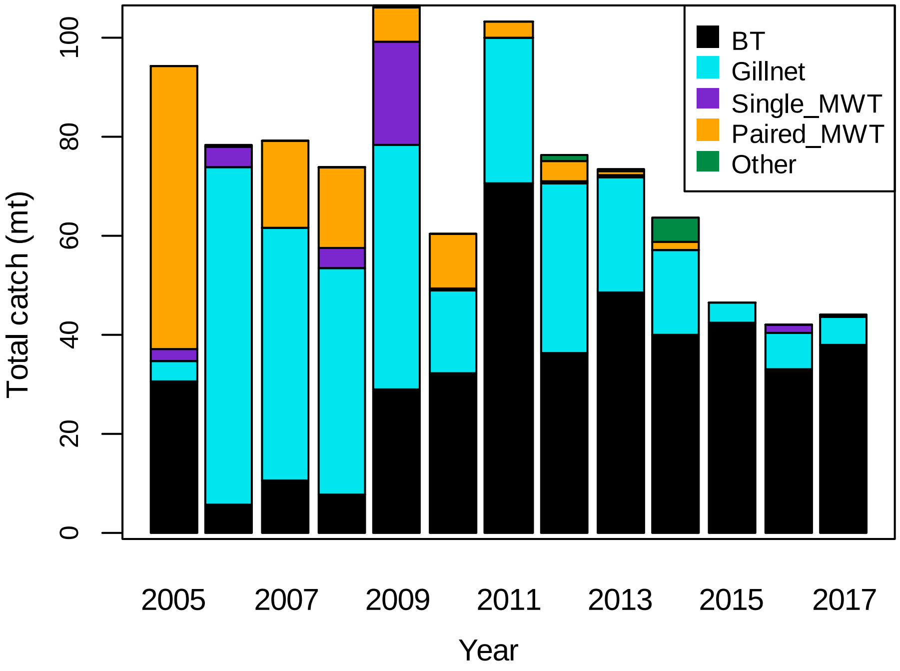
Figure 354. American shad total incidental catch and discarded catch (metric tons) from 1989-2017. Catches from MWT fleets are only included beginning in 2005.

a)



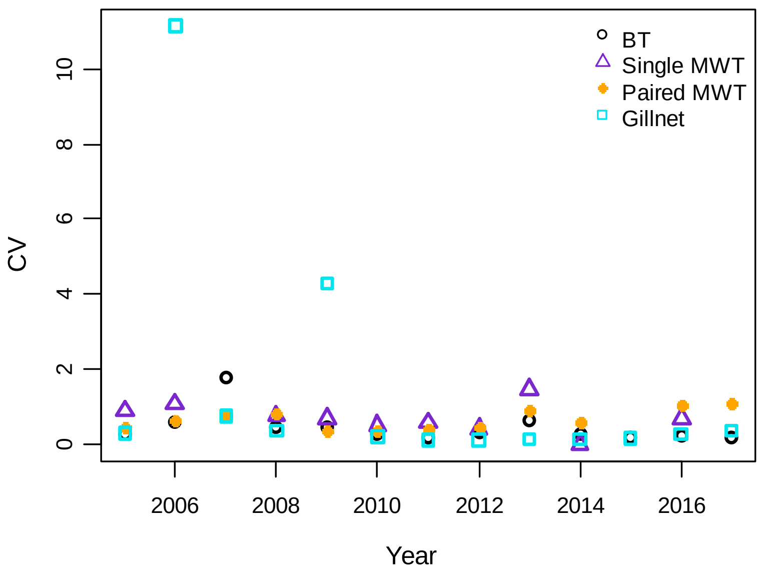
Total catch (mt)
0
50
100
150
200
250
1989
1993
1997
2001
2005
2009
2013
2017
Year
BT
Gillnet
Single_MWT
Paired_MWT
Other

b)



Total catch (mt)
0
20
40
60
80
100
2005
2007
2009
2011
2013
2015
2017
Year
BT
Gillnet
Single_MWT
Paired_MWT
Other

c)



d)

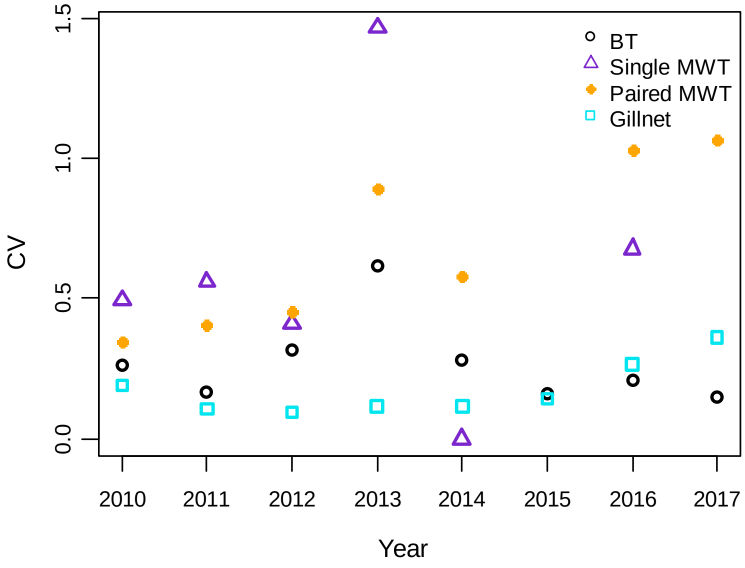


Figure 355. American shad total (retained + discarded) annual incidental catch (metric tons) for the four gears with the largest catches from 1989-2017 (a) and 2005-2017 (b), and the corresponding estimates of precision for 2005-2017 (c) and since 2010 (d).

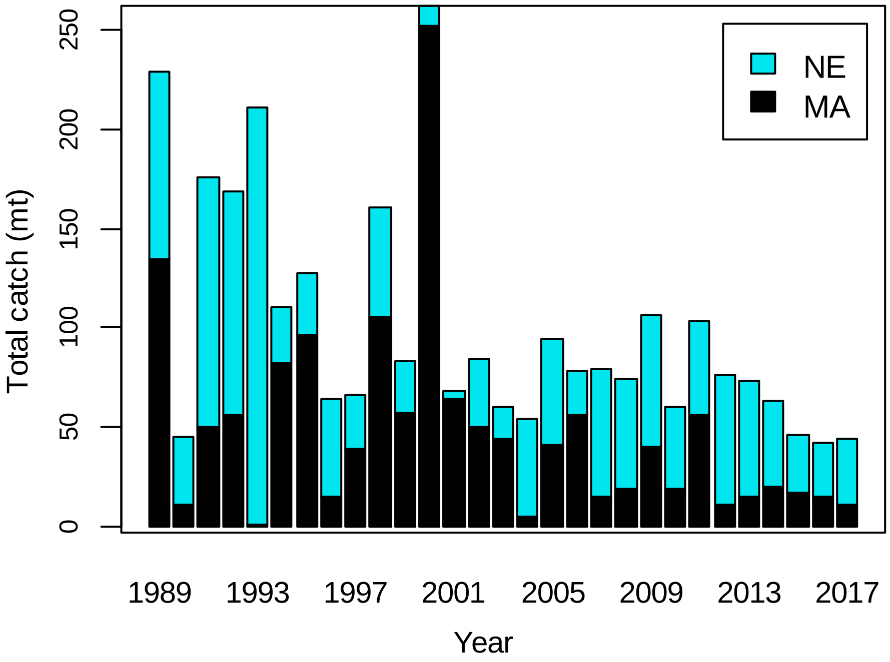


Figure 356. American shad total (retained + discarded) annual incidental catch (metric tons) by fishing region from 1989-2017.

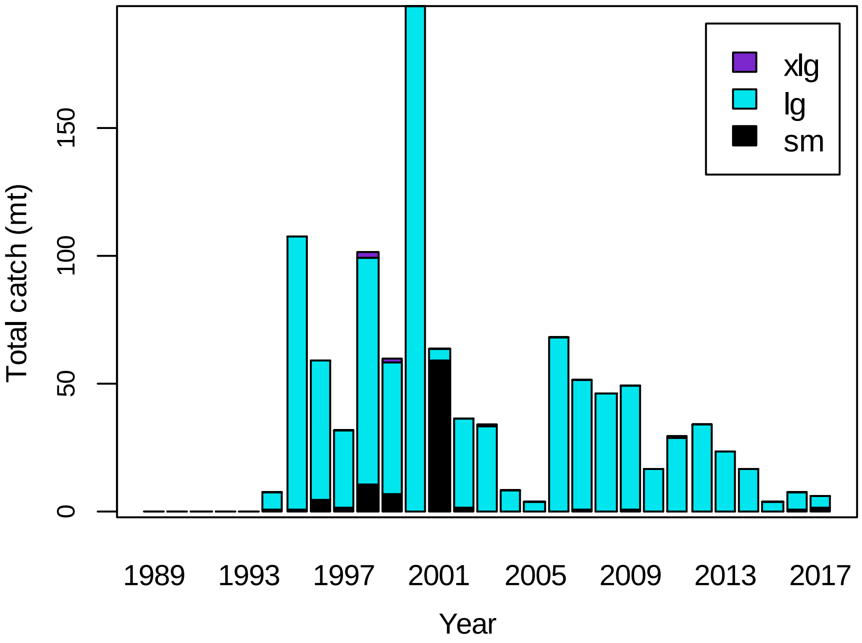


Figure 357. American shad total (retained + discarded) annual incidental gill net catch (metric tons) by mesh category from 1989-2017.

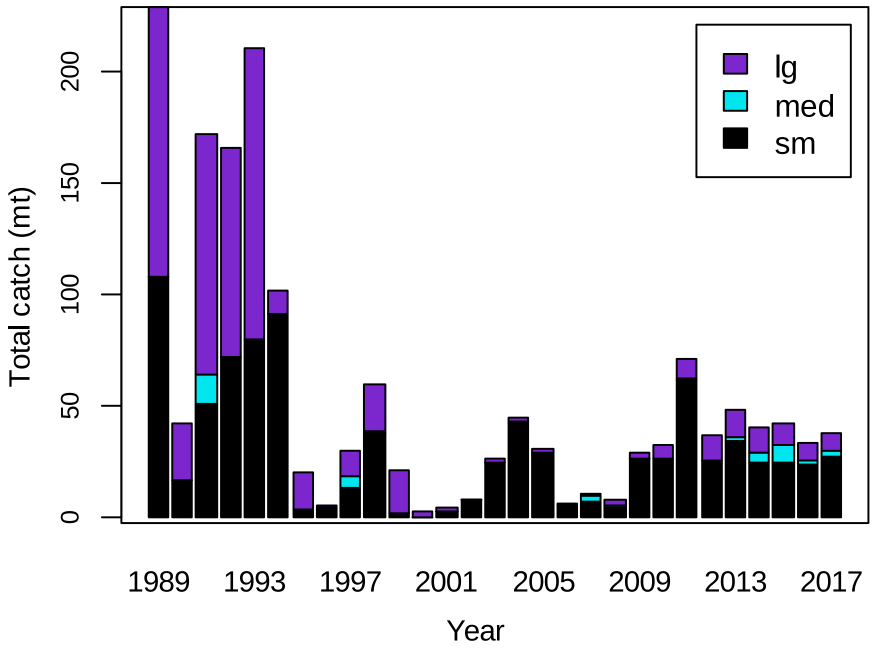


Figure 358. American shad total (retained + discarded) annual incidental bottom trawl catch (metric tons) by mesh category from 1989-2017.

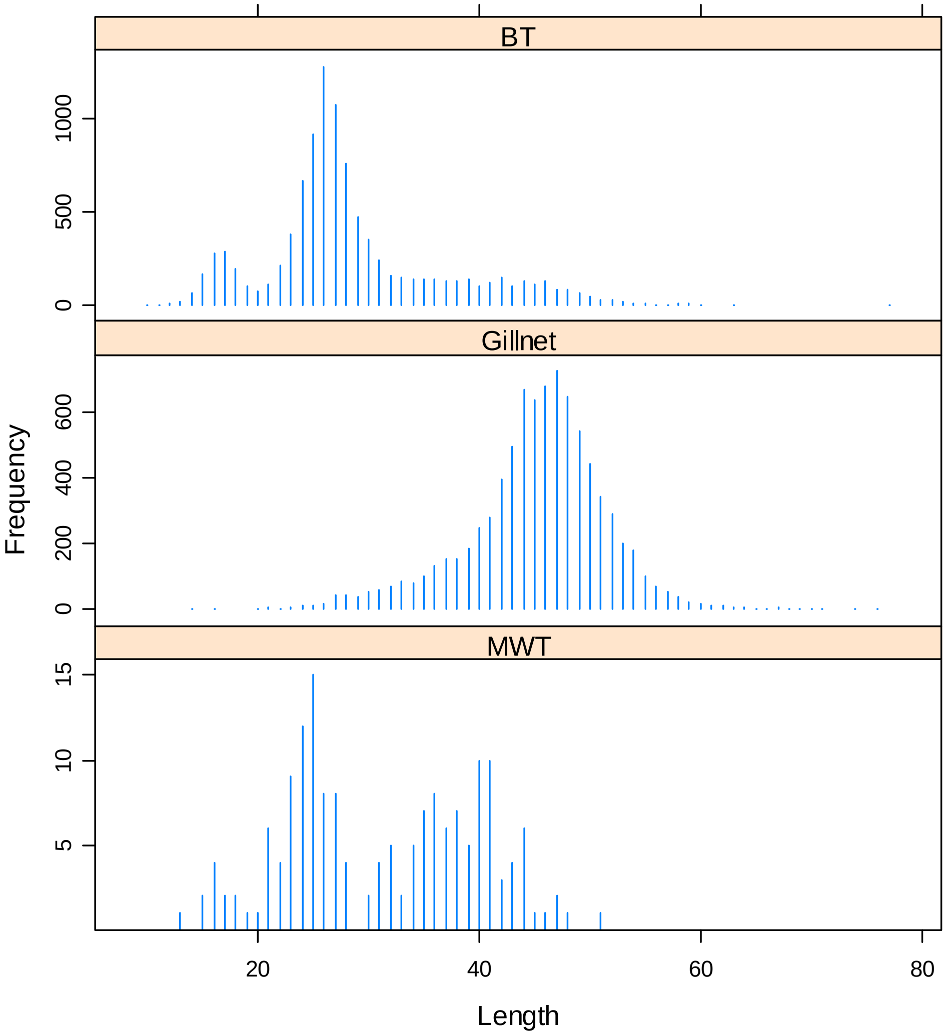


Figure 359. Average length frequency distribution of American shad total incidental catch during 1989-2017 for the three most dominant gears.

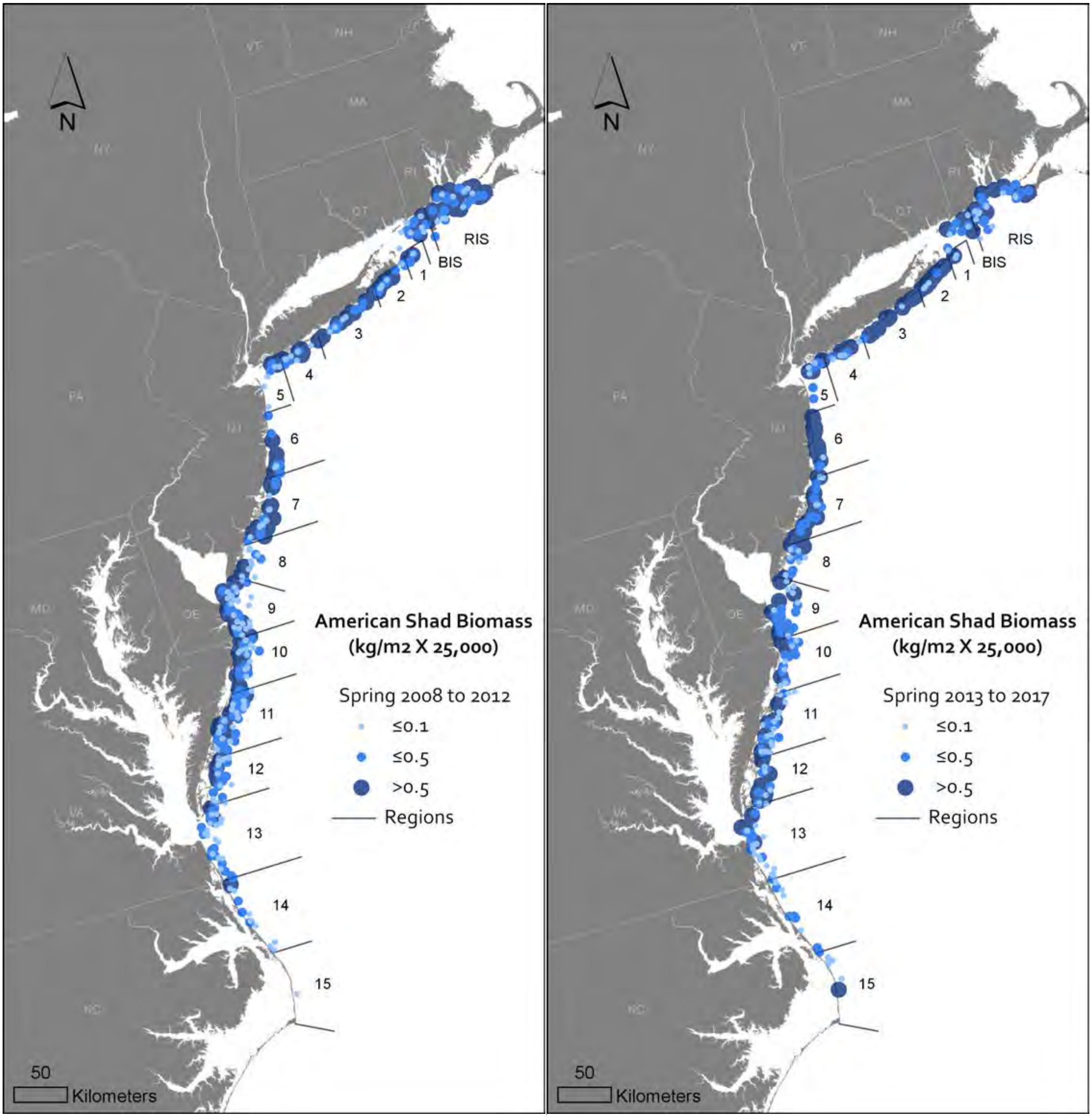


Figure 360. American shad 2008-2012 (left) and 2013-2017 (right) catch rates during the Northeast Area Monitoring and Assessment Program Trawl Survey (Spring).

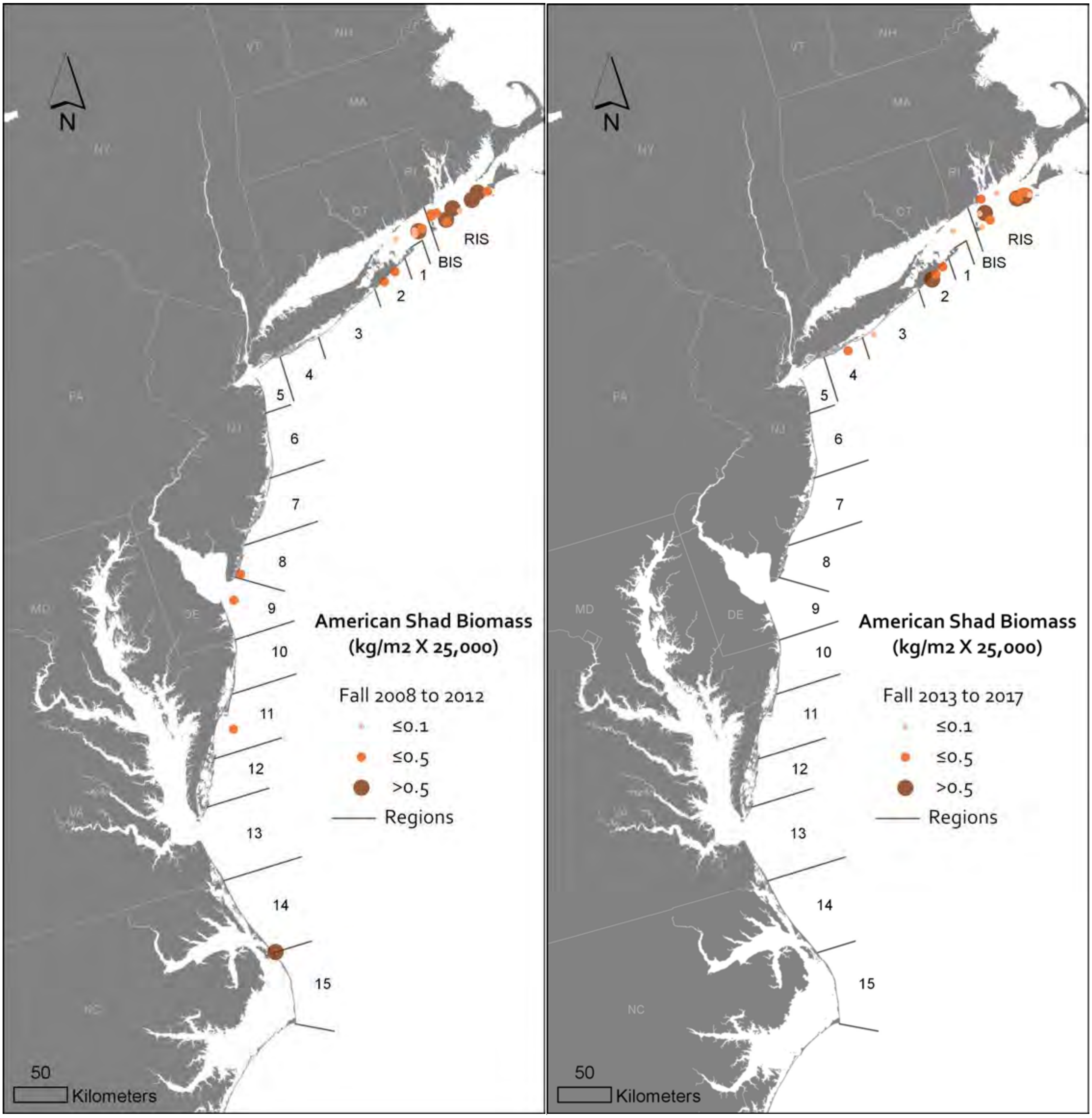


Figure 361. American shad 2008-2012 (left) and 2013-2017 (right) catch rates during the Northeast Area Monitoring and Assessment Program Trawl Survey (Fall).

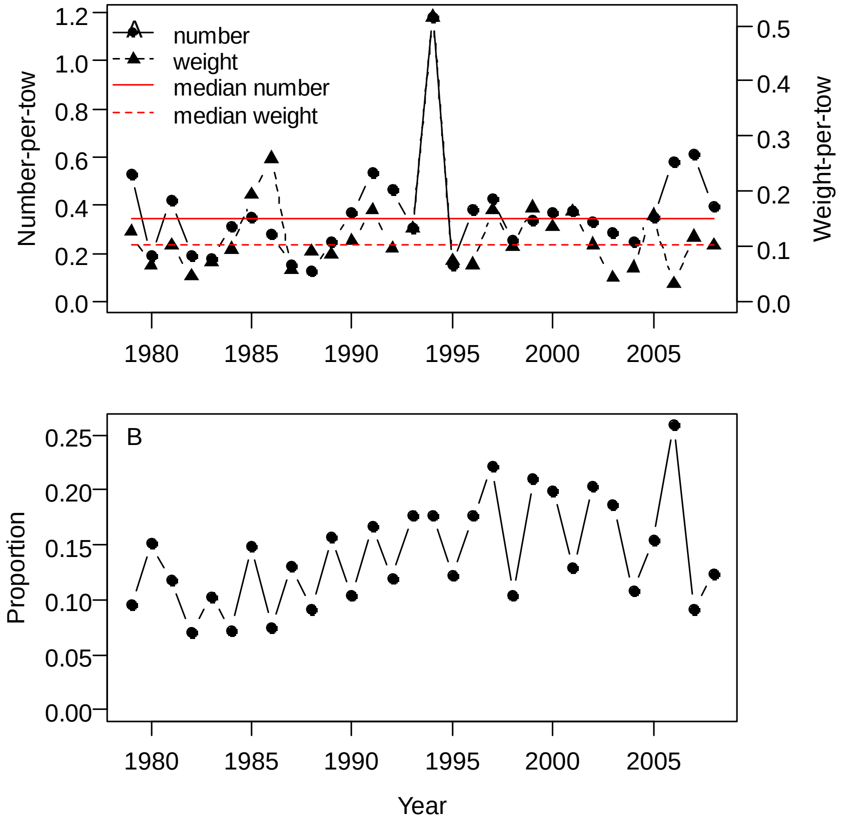


Figure 362. American shad relative abundance (stratified mean number-per-tow) and biomass (stratified mean kg-per-tow) indices (A) and the proportion of positive tows (B) derived from the NEFSC Bottom Trawl Survey (R/V Albatross; Spring) 1979-2008. The median number- and weight-per-tow values represent the median indices over 1979-2008.

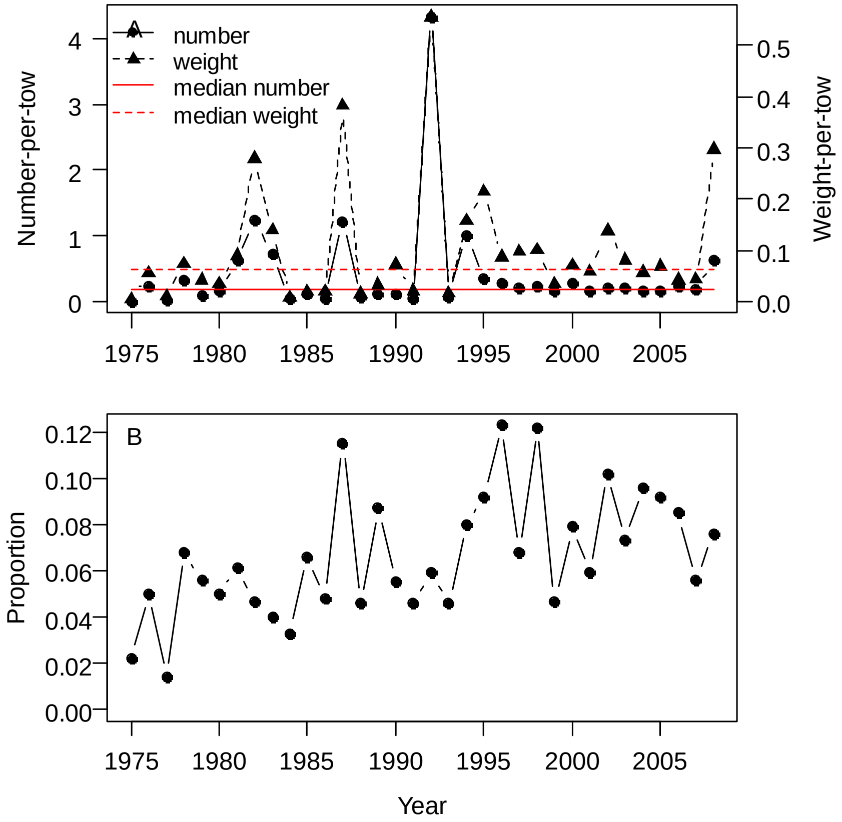


Figure 363. **American shad relative abundance (stratified mean number-per-tow) and biomass (stratified mean kg-per-tow) indices (A) and the proportion of positive tows (B) derived from the NEFSC Bottom Trawl Survey (R/V Albatross; Fall) 1979-2008. The median number- and weight-per-tow values represent the median indices over 1979-2008.**

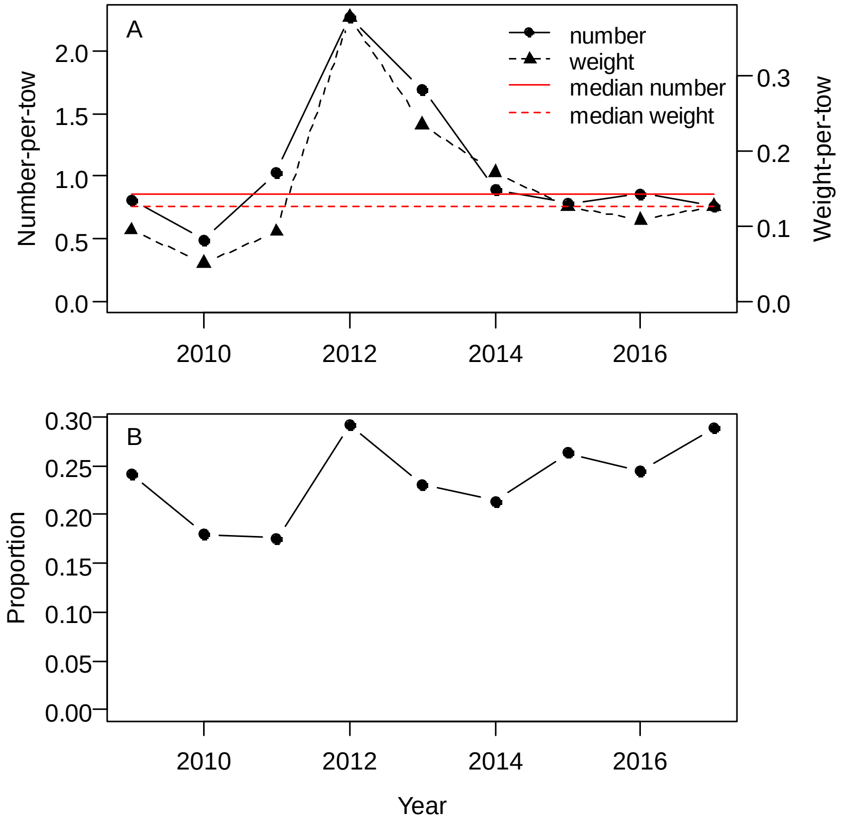


Figure 364. American shad relative abundance (stratified mean number-per-tow) and biomass (stratified mean kg-per-tow) indices (A) and the proportion of positive tows (B) derived from the NEFSC Bottom Trawl Survey (R/V Bigelow; Spring) 2009-2017. The median number- and weight-per-tow values represent the median indices over 2009-2017. The full strata set was not sampled in 2014 due to delays in the survey (offshore strata 61-68 south of Maryland were not sampled).

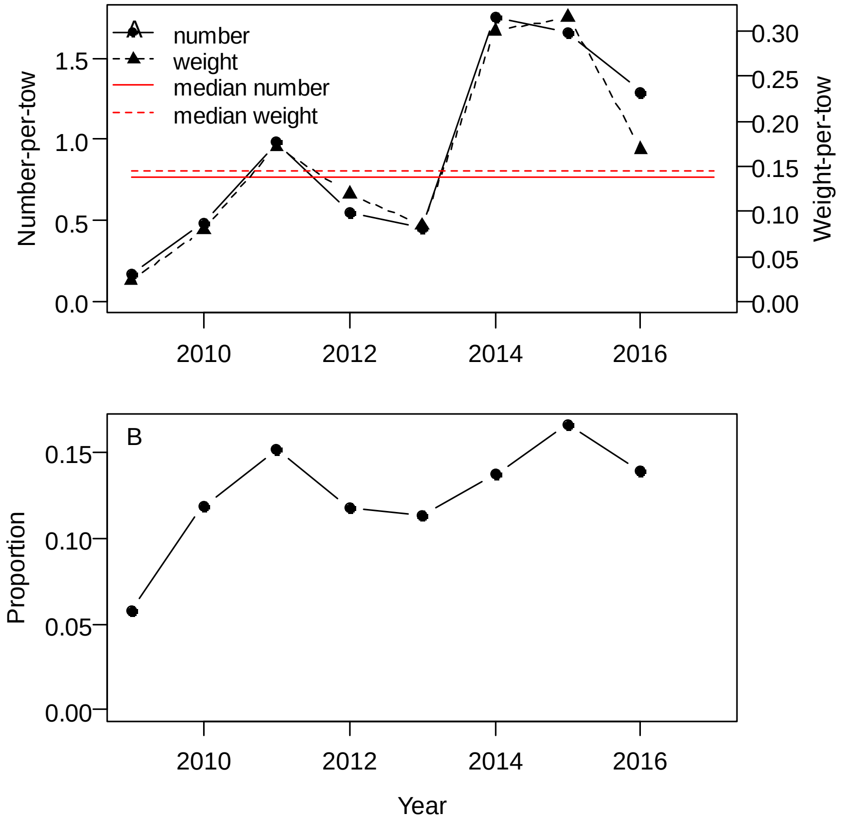


Figure 365. American shad relative abundance (stratified mean number-per-tow) and biomass (stratified mean kg-per-tow) indices (A) and the proportion of positive tows (B) derived from the NEFSC Bottom Trawl Survey (R/V Bigelow; Fall) 2009-2017. The median number- and weight-per-tow values represent the median indices over 2009-2017. Indices from the 2017 fall bottom trawl survey are treated as missing because the full survey was not completed due to vessel mechanical issues.

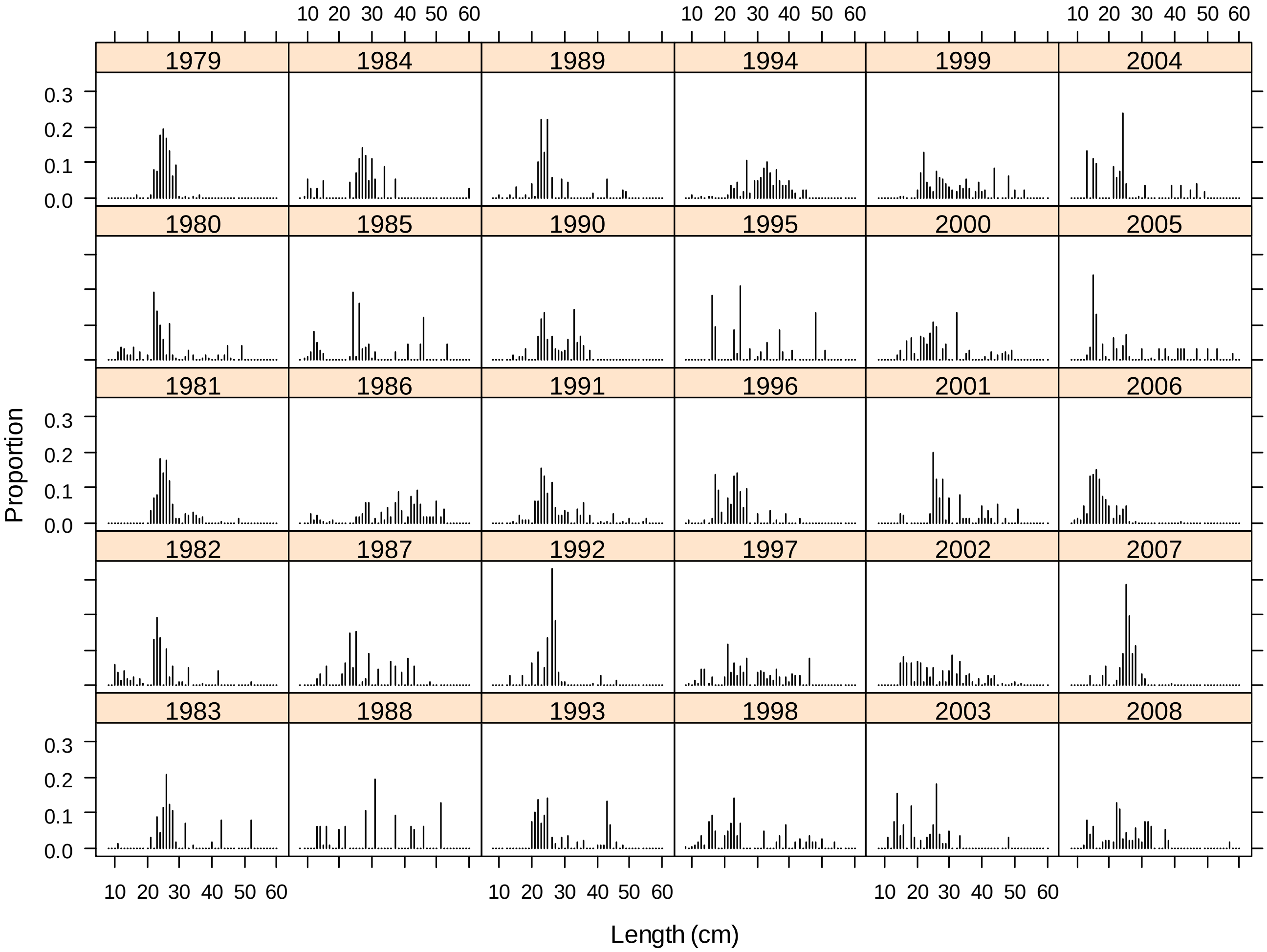


Figure 366. Annual American shad length compositions from the NEFSC Bottom Trawl Survey (R/V Albatross; Spring) 1979-2008.

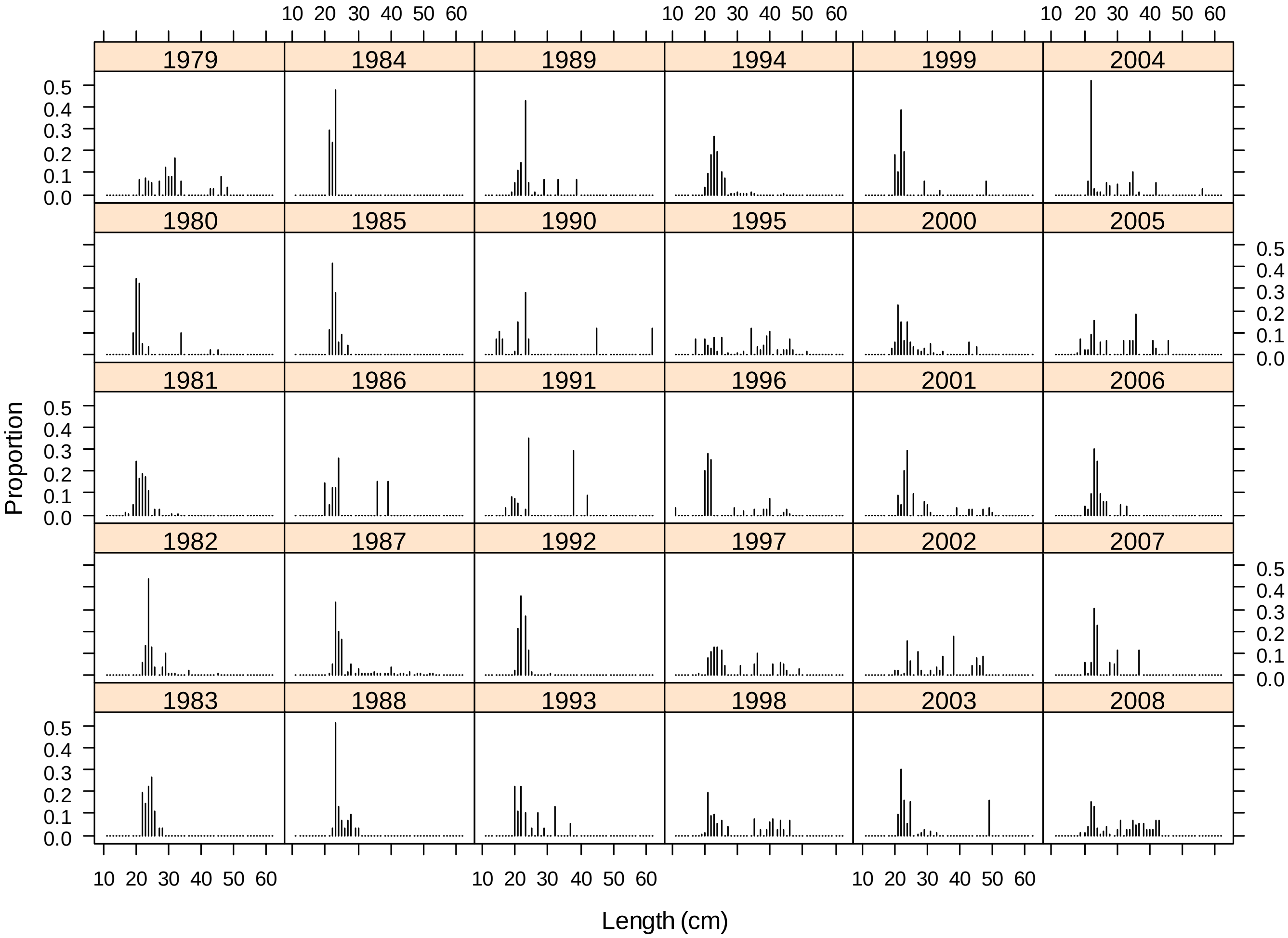


Figure 367. Annual American shad length compositions from the NEFSC Bottom Trawl Survey (R/V Albatross; Fall) 1979-2008.

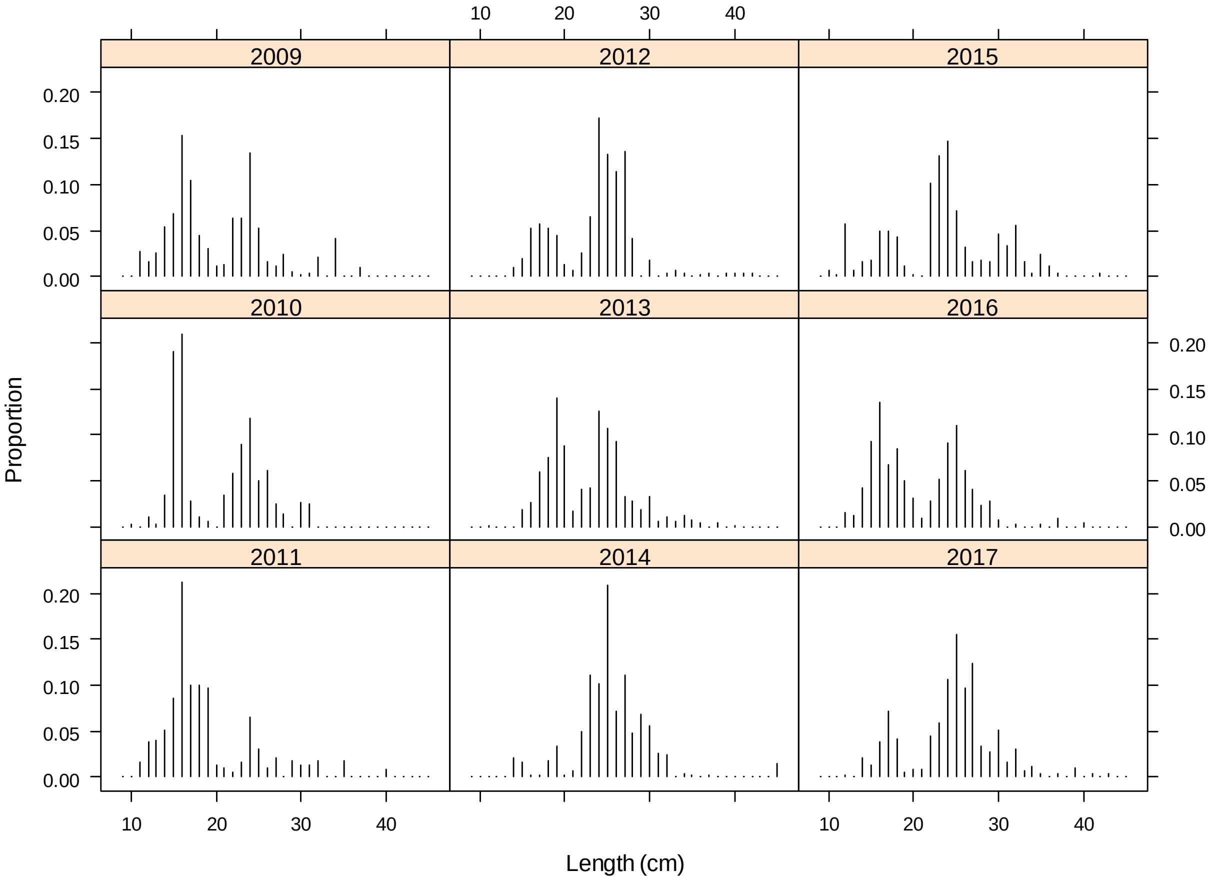


Figure 368. Annual American shad length compositions from the NEFSC Bottom Trawl Survey (R/V Bigelow; Spring) 2009-2017. The full strata set was not sampled in 2014 due to delays in the survey (offshore strata 61-68 south of Maryland were not sampled).

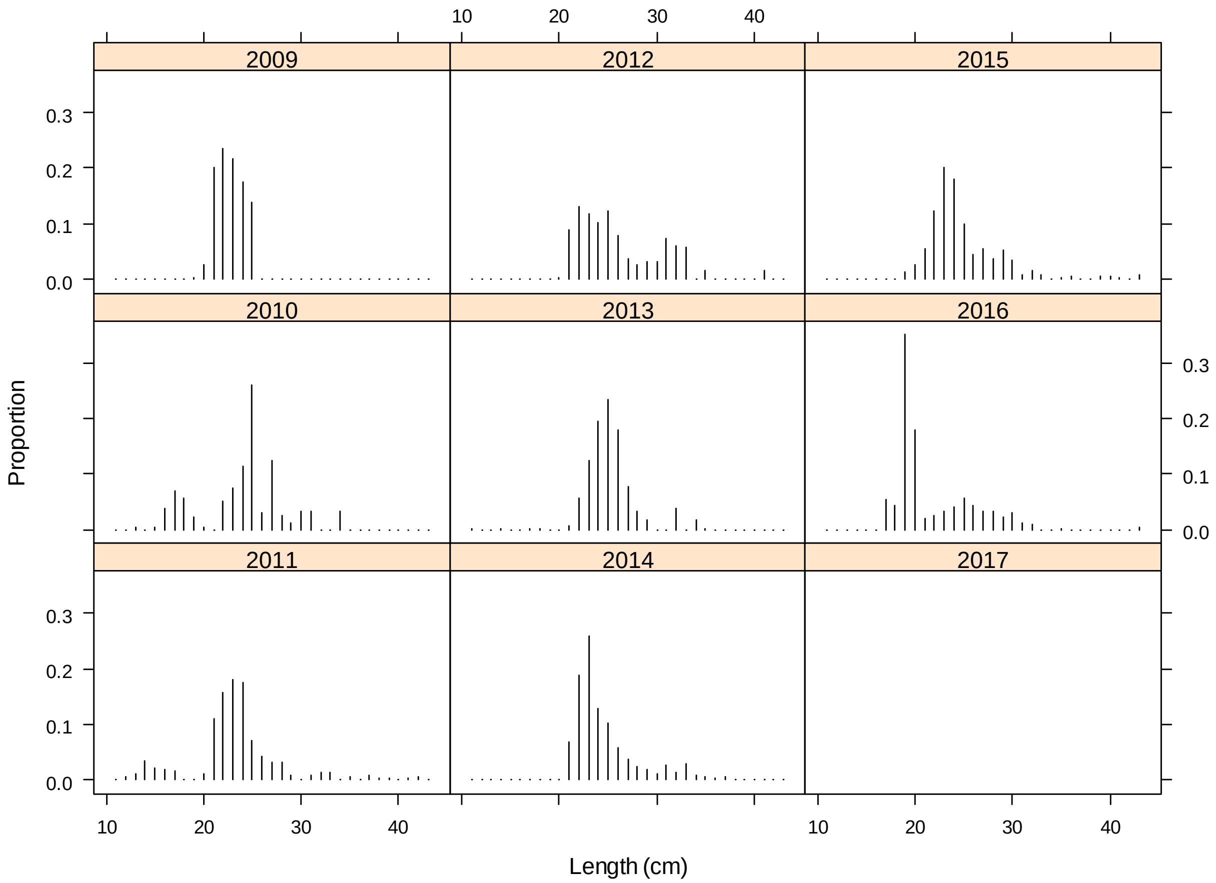


Figure 369. **Annual American shad length compositions from the NEFSC Bottom Trawl Survey (R/V Bigelow; Fall) 2009-2017. Length compositions from the 2017 fall bottom trawl survey are treated as missing because the full survey was not completed due to vessel mechanical issues.**

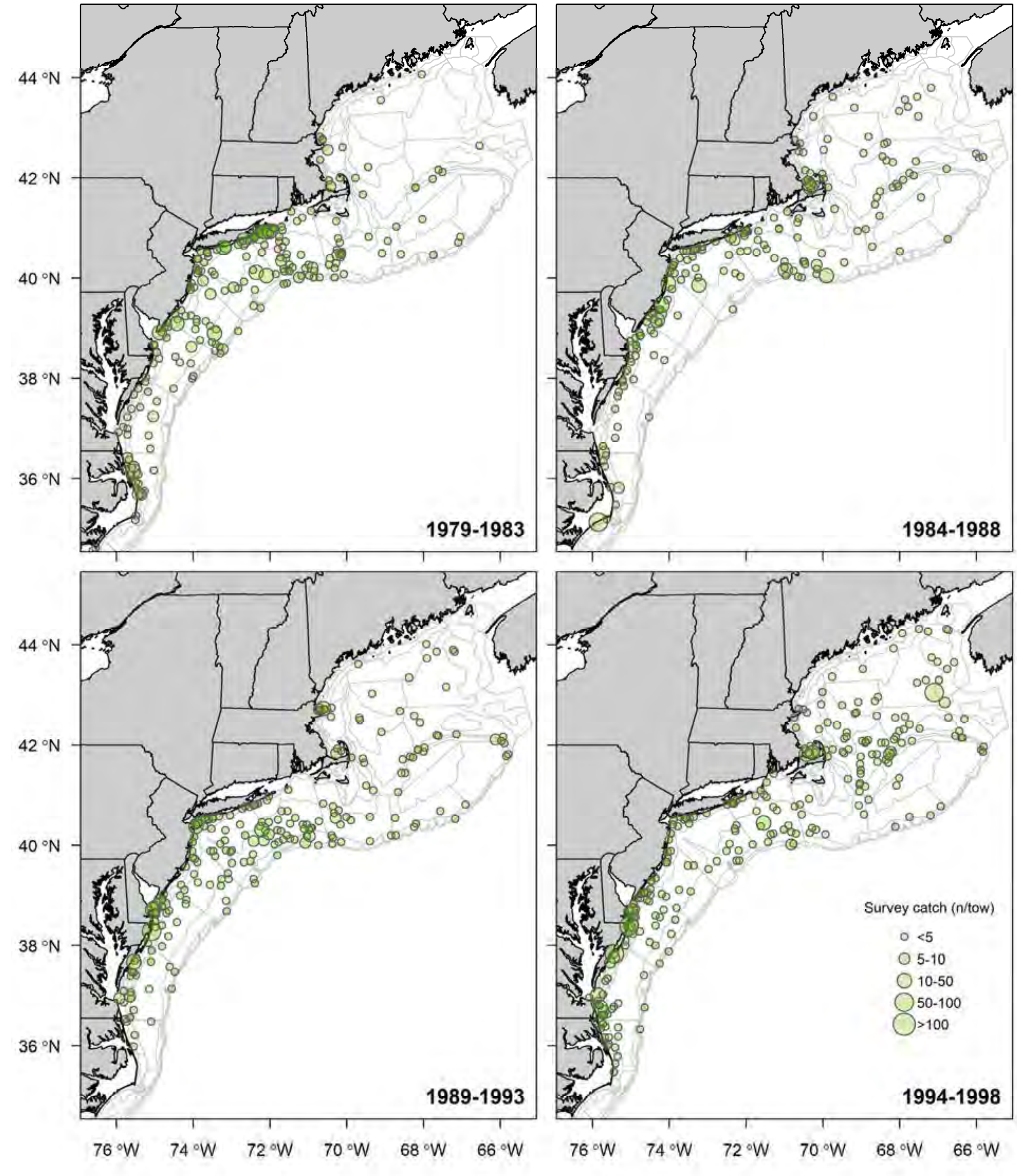


Figure 370. NEFSC Bottom Trawl Survey (Spring) catches (number/tow) of American shad from 1979-2017 by approximately 5-year intervals (*continued below*).

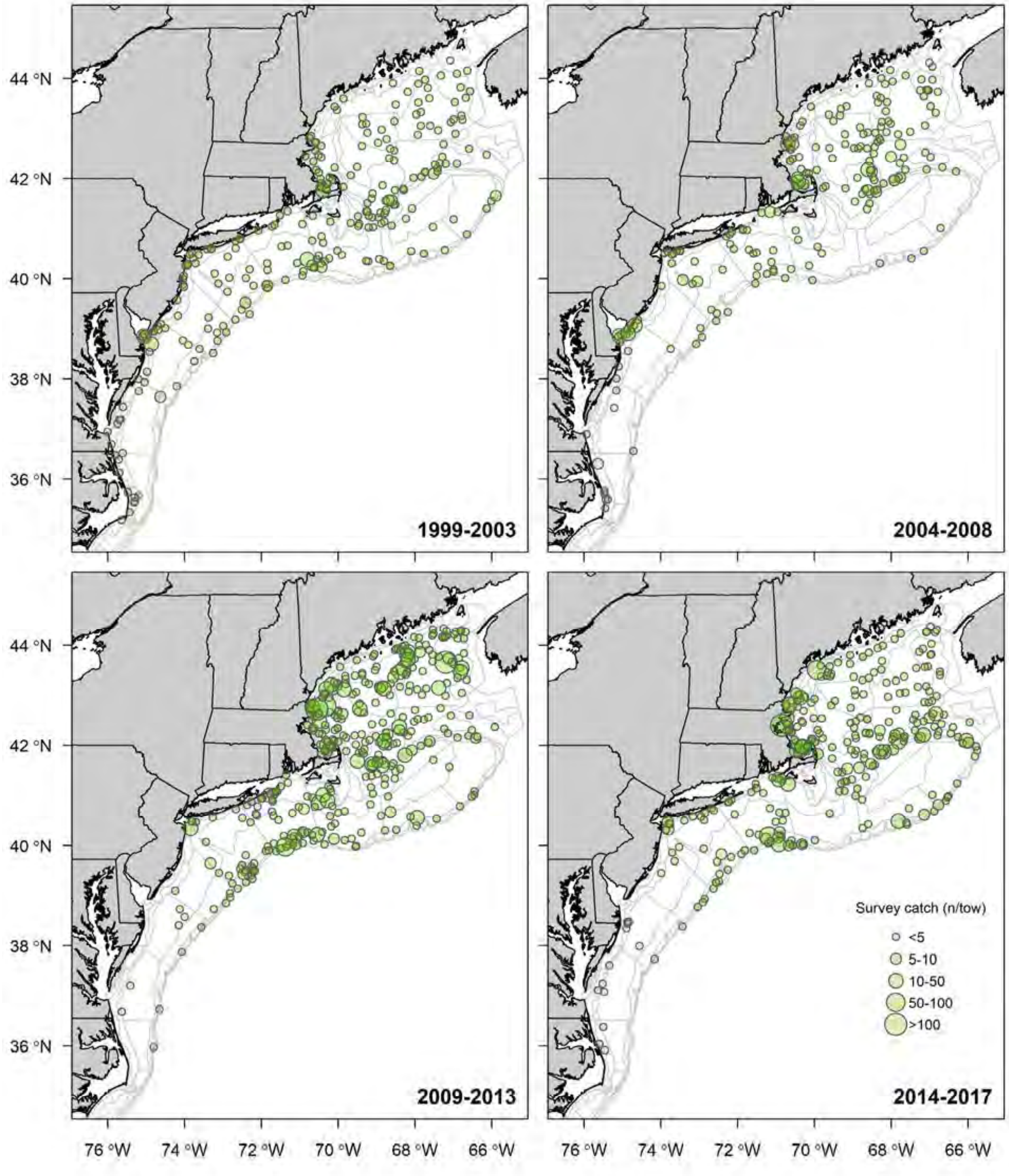


Figure 370. Continued.

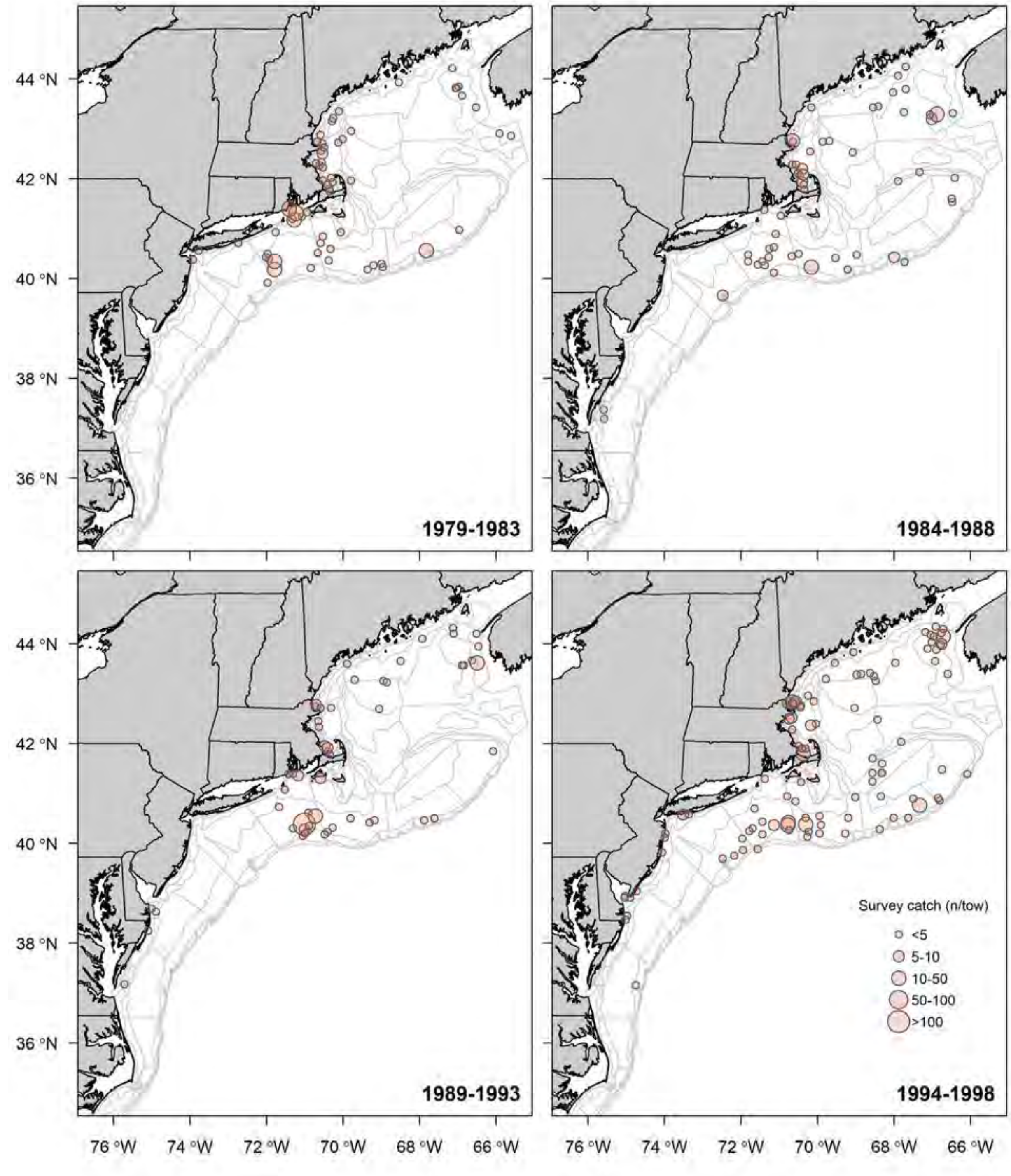


Figure 371. NEFSC Bottom Trawl Survey (Fall) catches (number/tow) of American shad from 1979-2017 by approximately 5-year intervals (*continued below*).

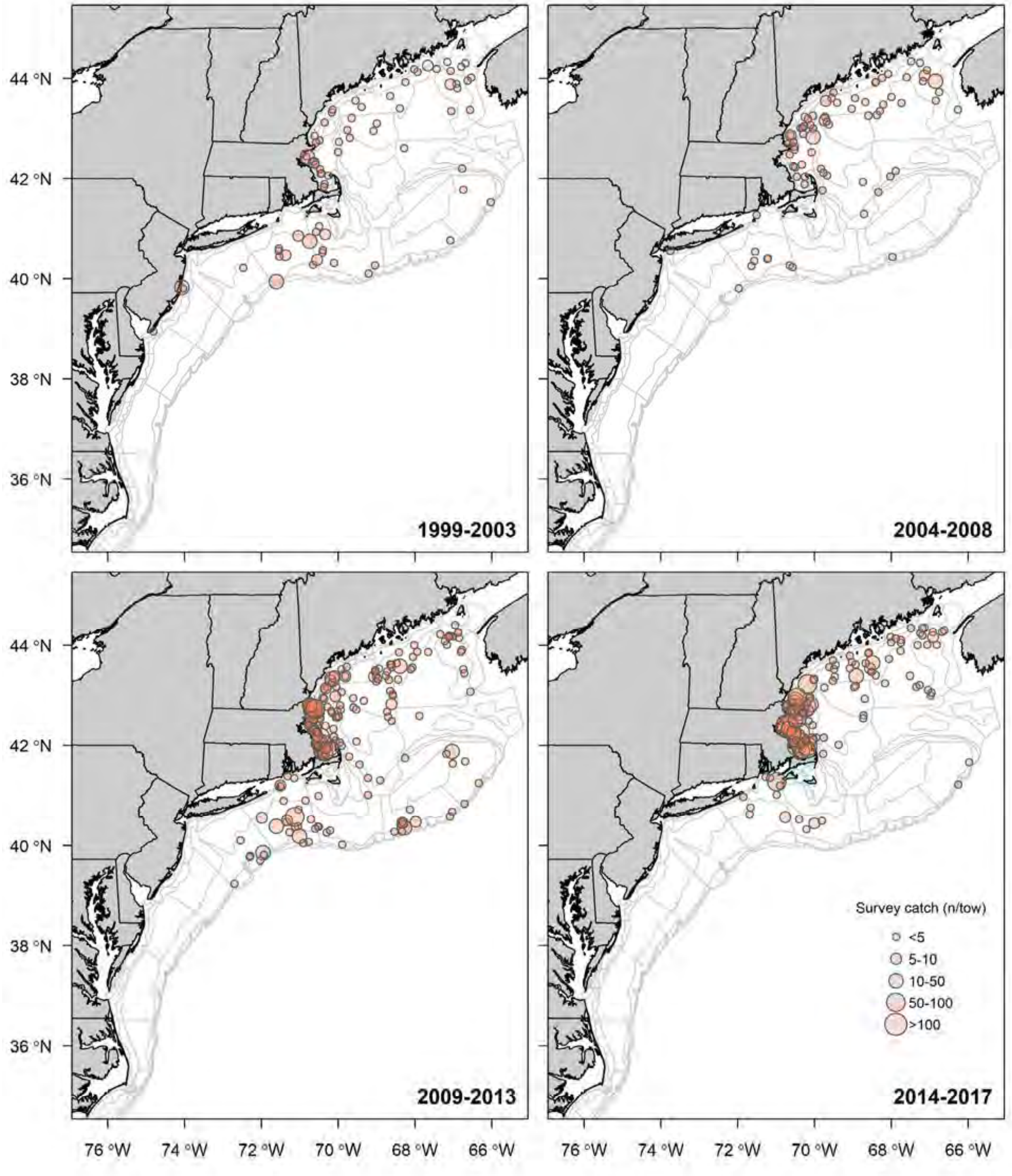


Figure 371. Continued.

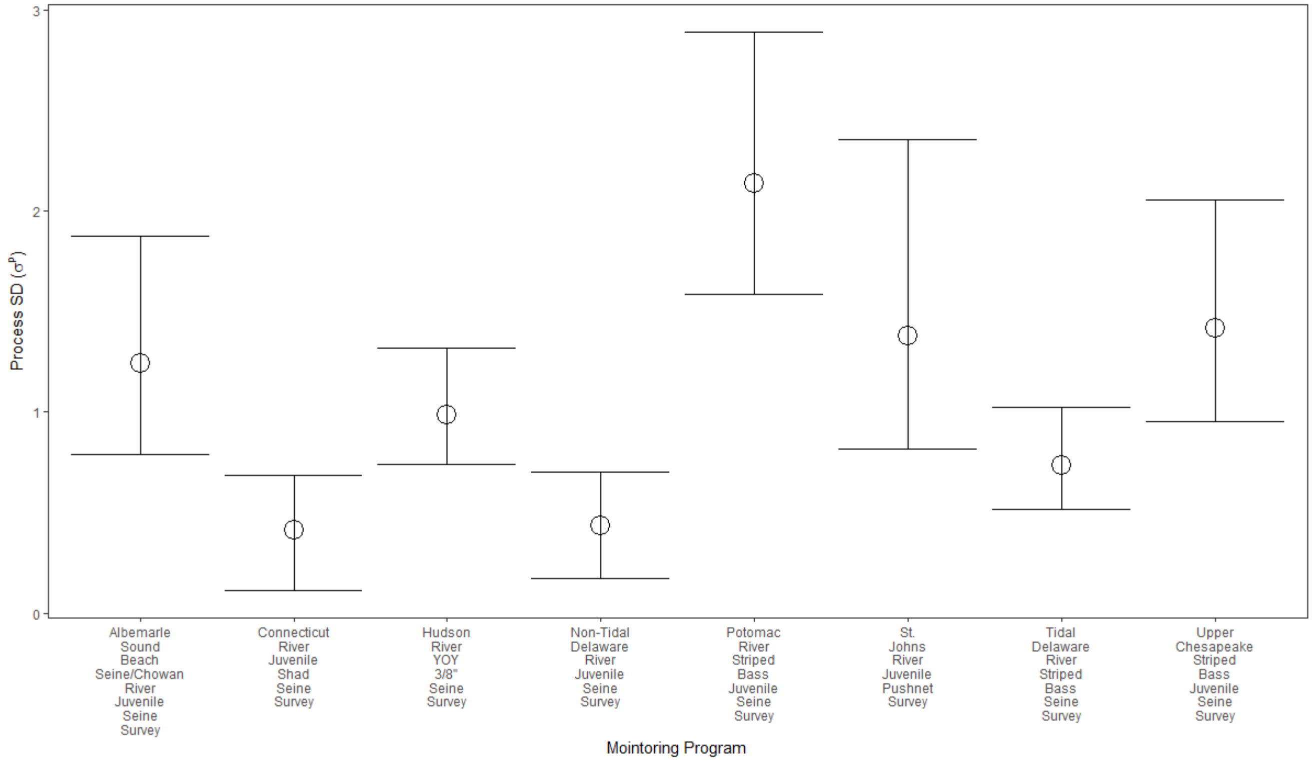


Figure 372. Survey-specific process error estimates for coastwide YOY surveys.

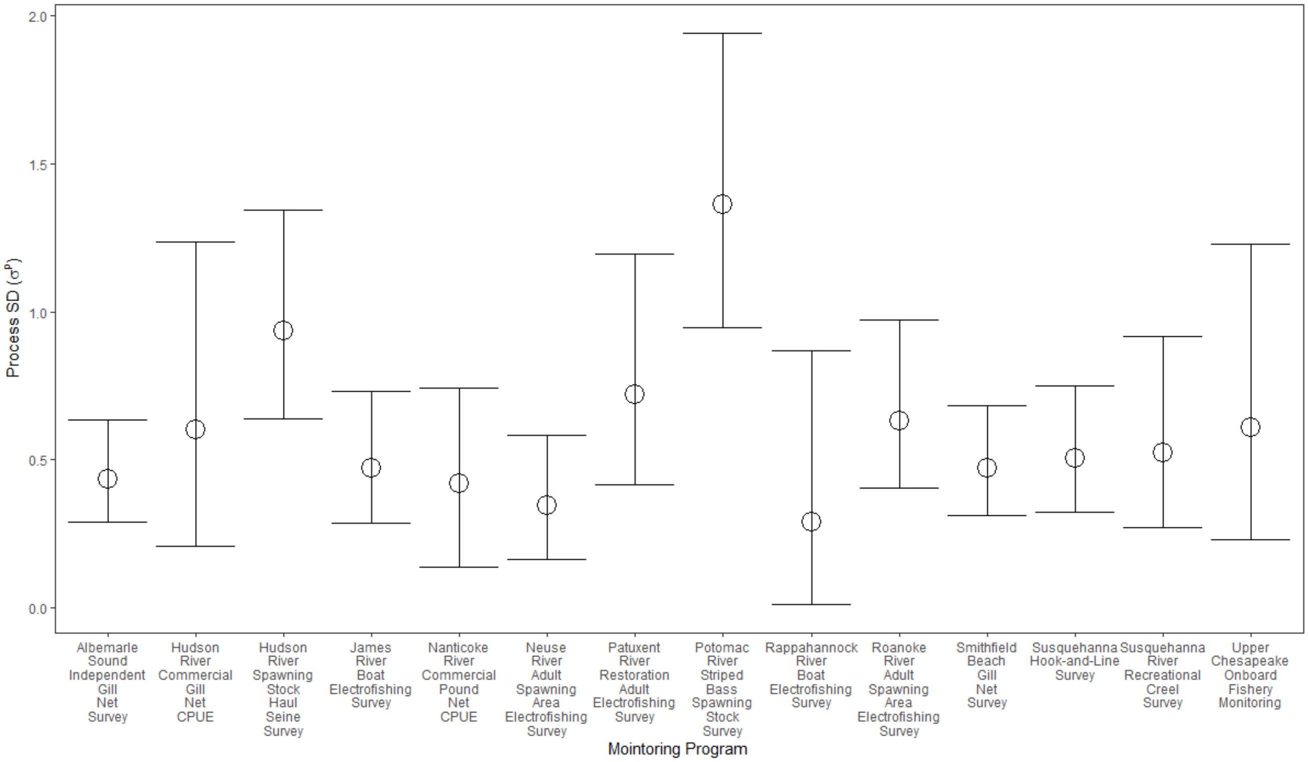


Figure 373. Survey-specific process error estimates for southern iteroparous spawning adult surveys (sex aggregate).

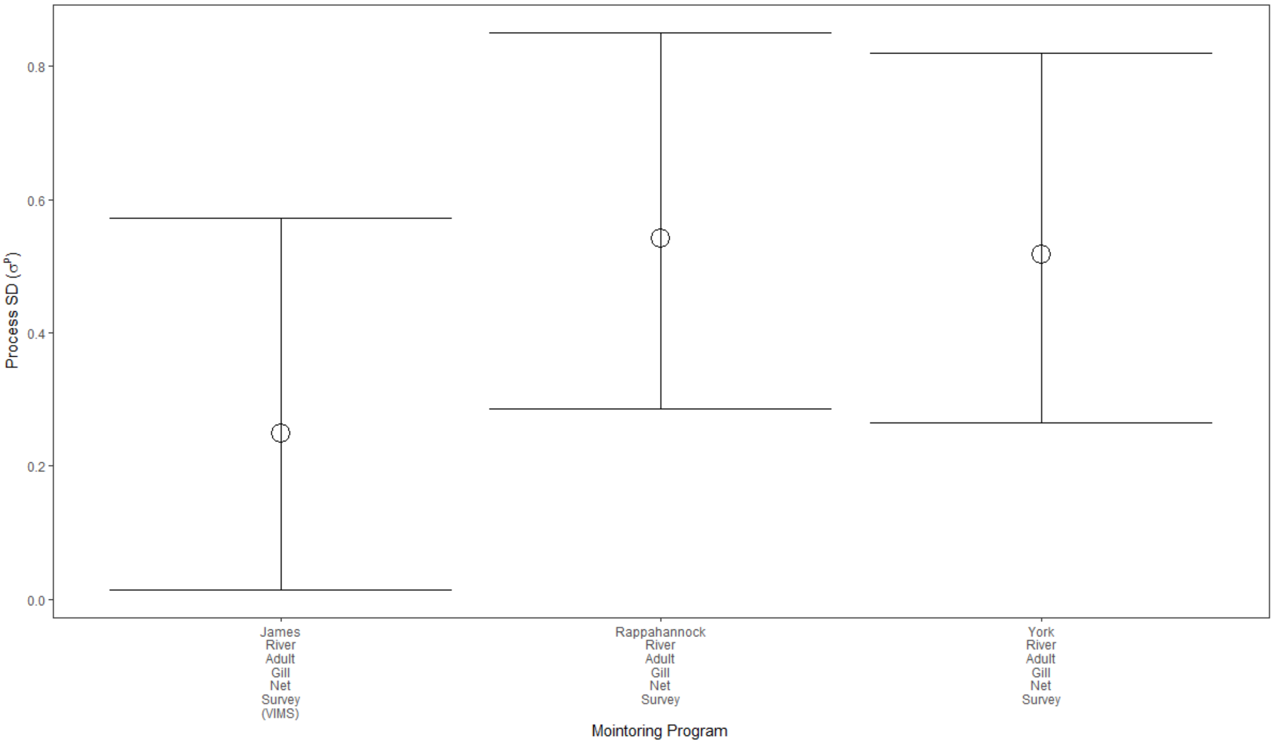


Figure 374. Survey-specific process error estimates for southern iteroparous female spawning adult surveys.

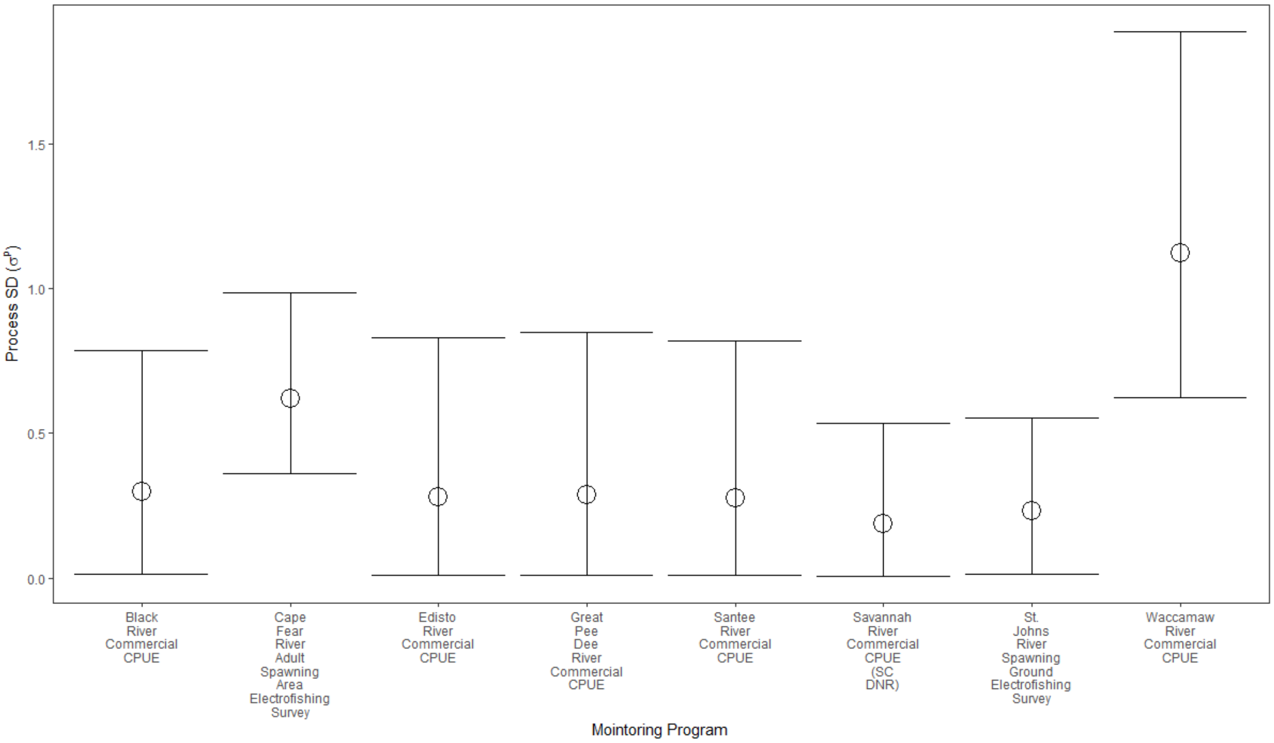


Figure 375. Survey-specific process error estimates for semelparous spawning adult surveys (sex aggregate).

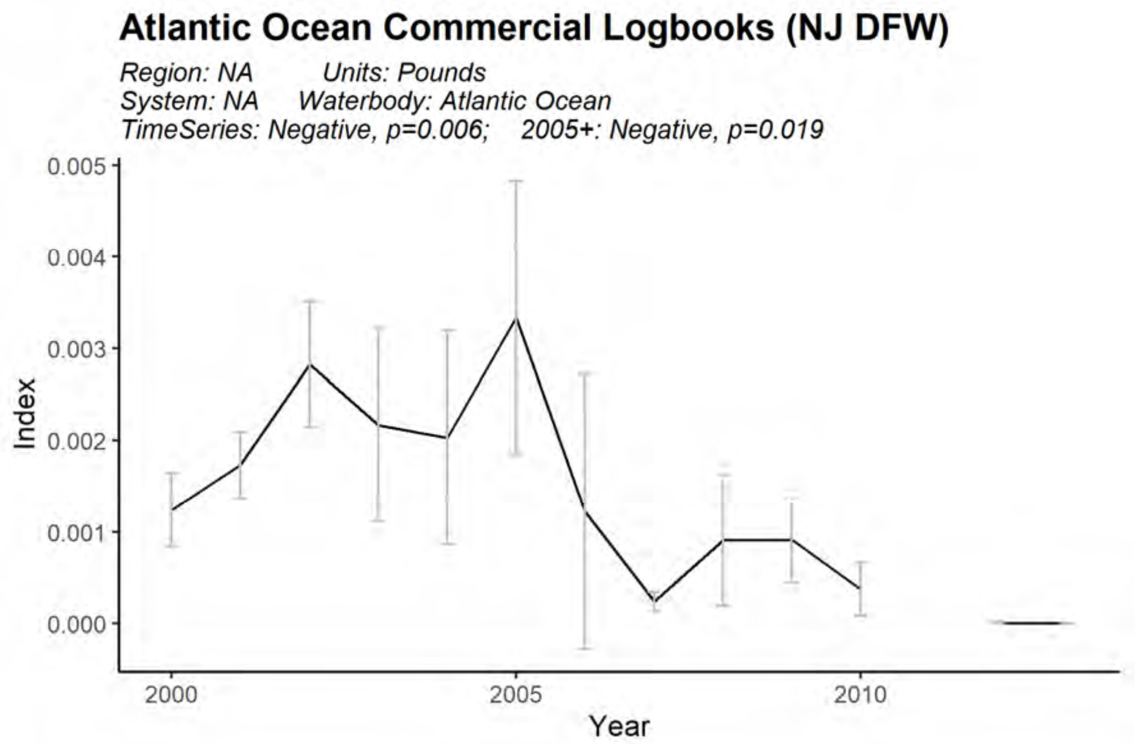


Figure 376. Abundance index from the Atlantic Ocean Commercial Logbooks (NJ DFW) and Mann-Kendall results.

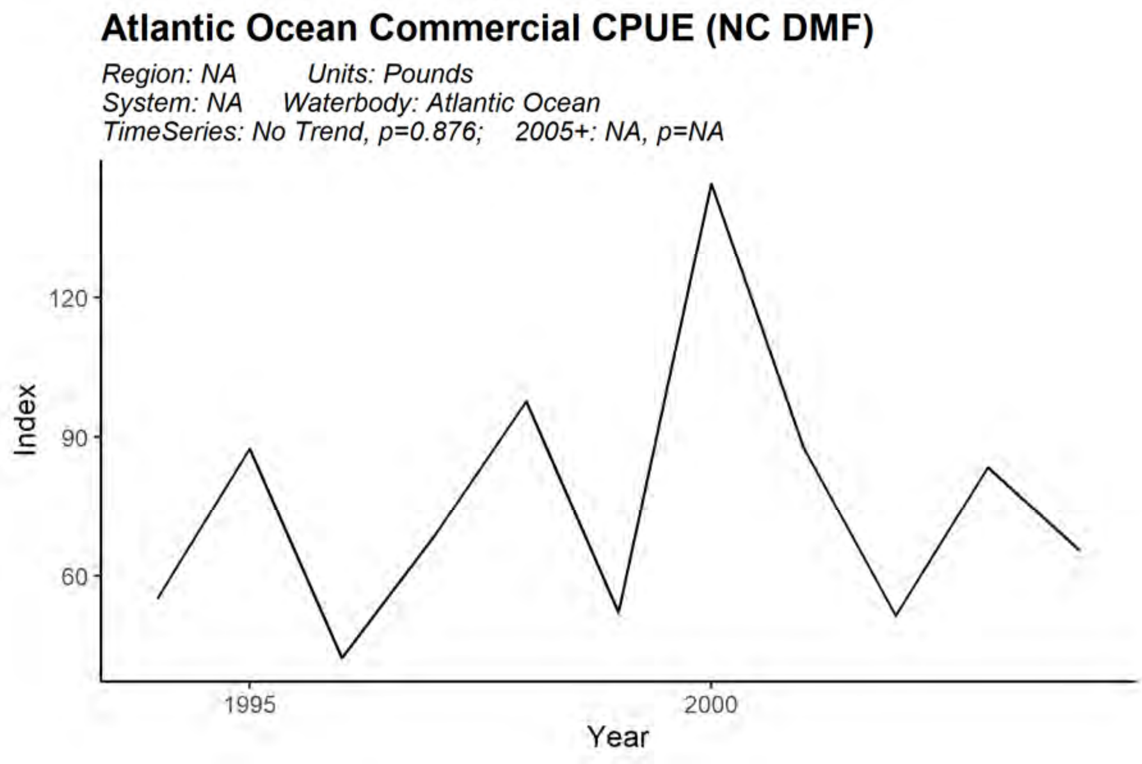


Figure 377. Abundance index from the Atlantic Ocean Commercial CPUE (NC DMF) and Mann-Kendall results.

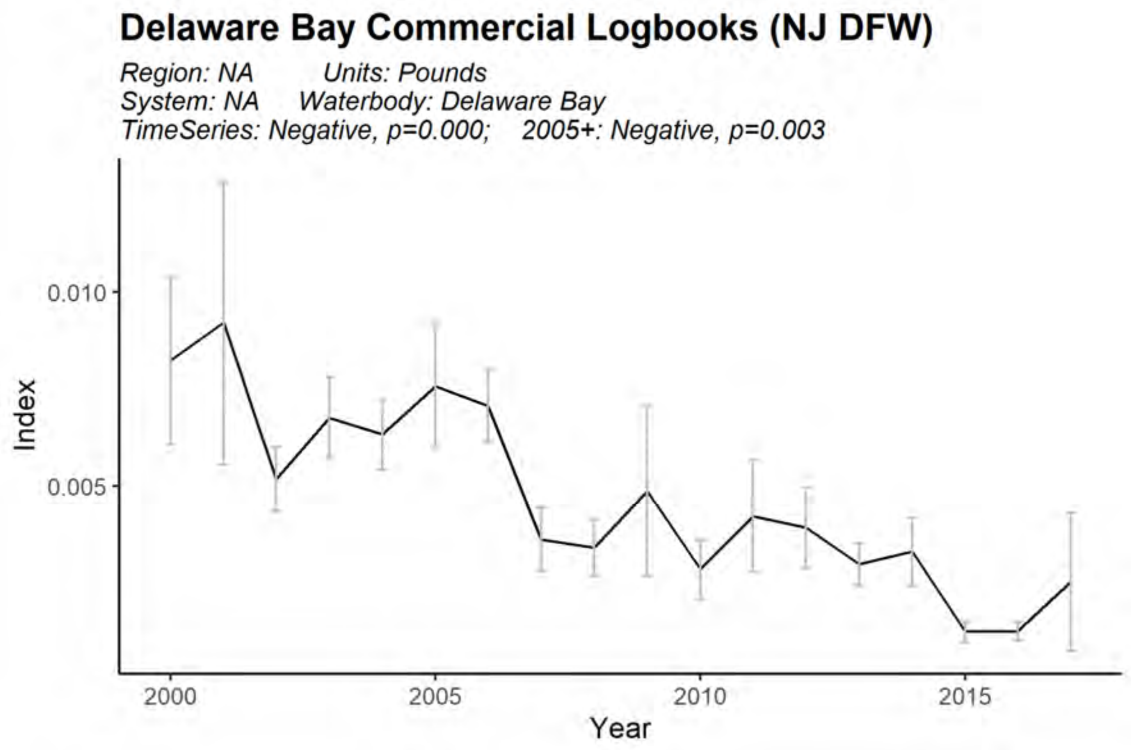


Figure 378. Abundance index from the Delaware Bay Commercial Logbooks (NJ DFW) and Mann-Kendall results.

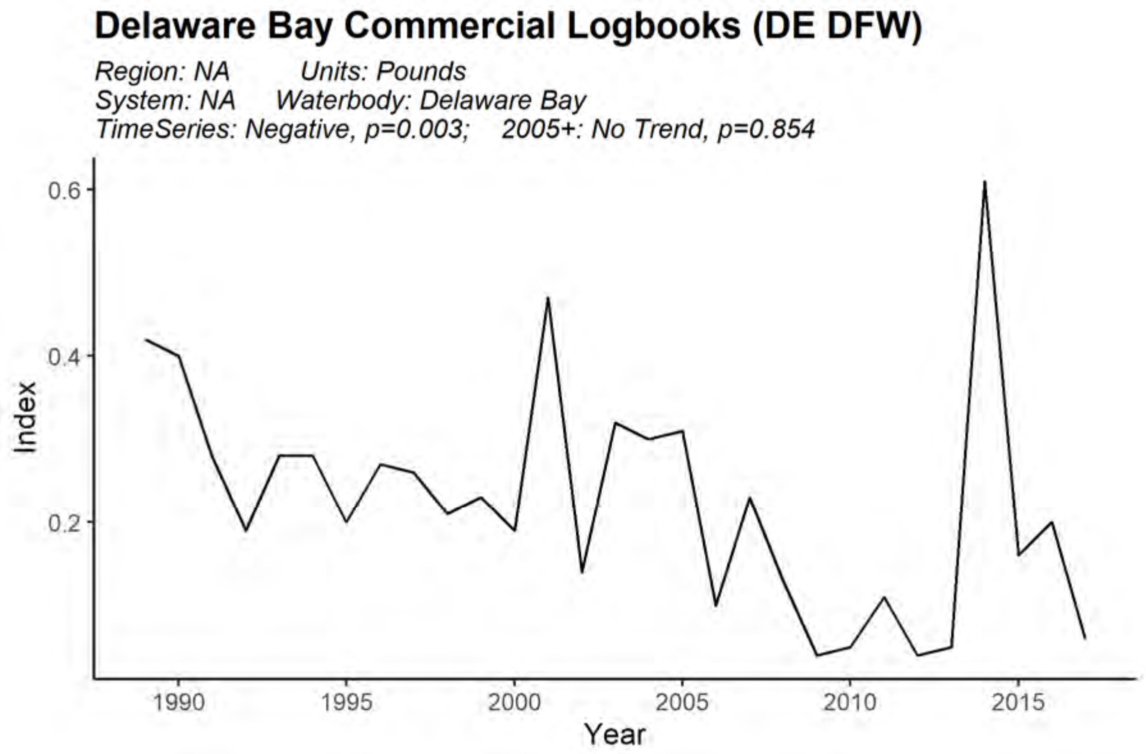


Figure 379. Abundance index from the Delaware Bay Commercial Logbooks (DE DFW) and Mann-Kendall results.

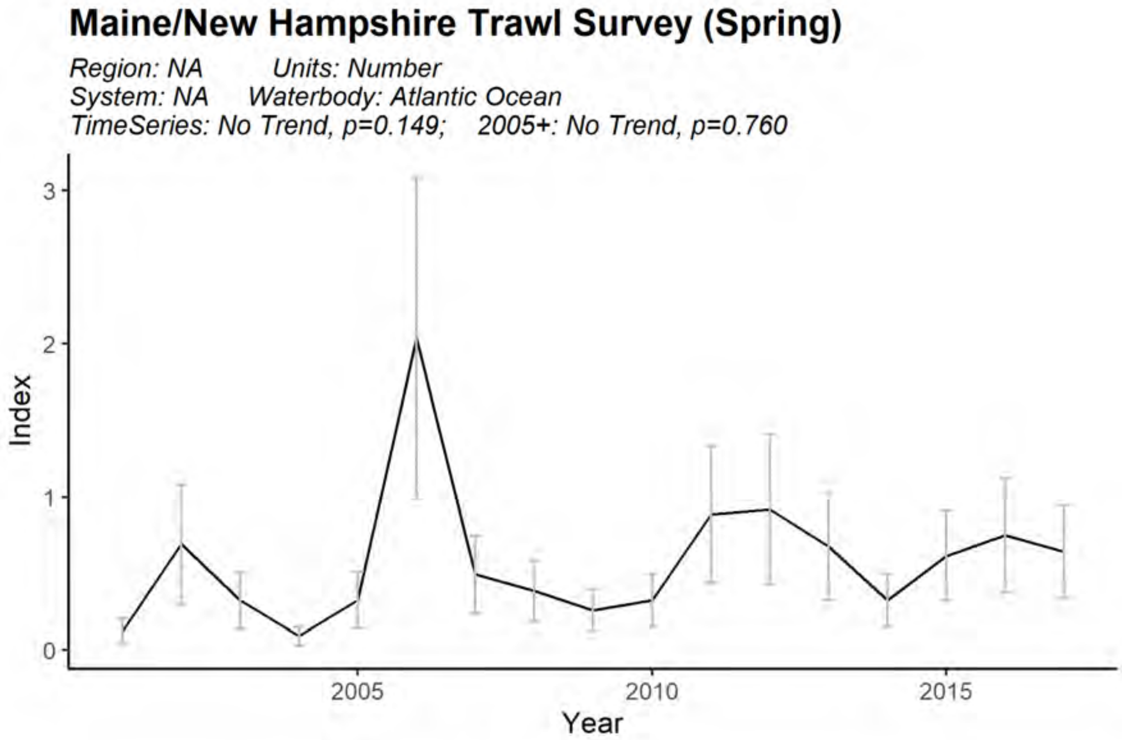


Figure 380. Abundance index from the Maine/New Hampshire Trawl Survey (Spring) and Mann-Kendall results.

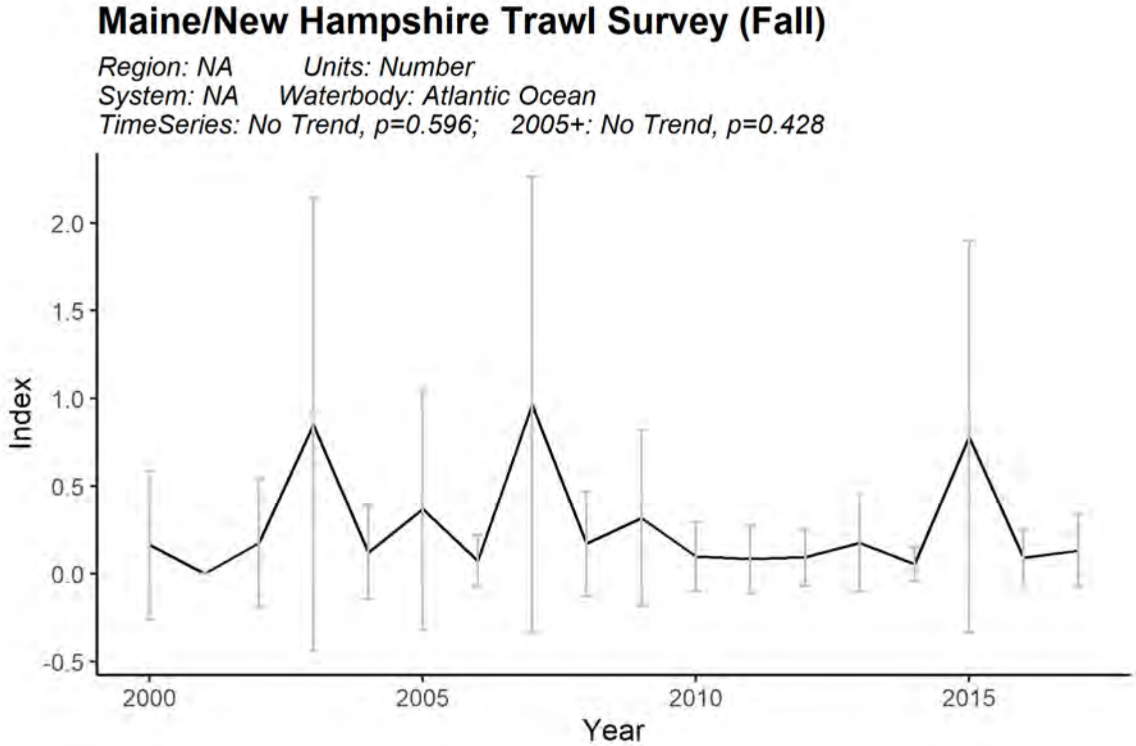


Figure 381. Abundance index from the Maine/New Hampshire Trawl Survey (Fall) and Mann-Kendall results.

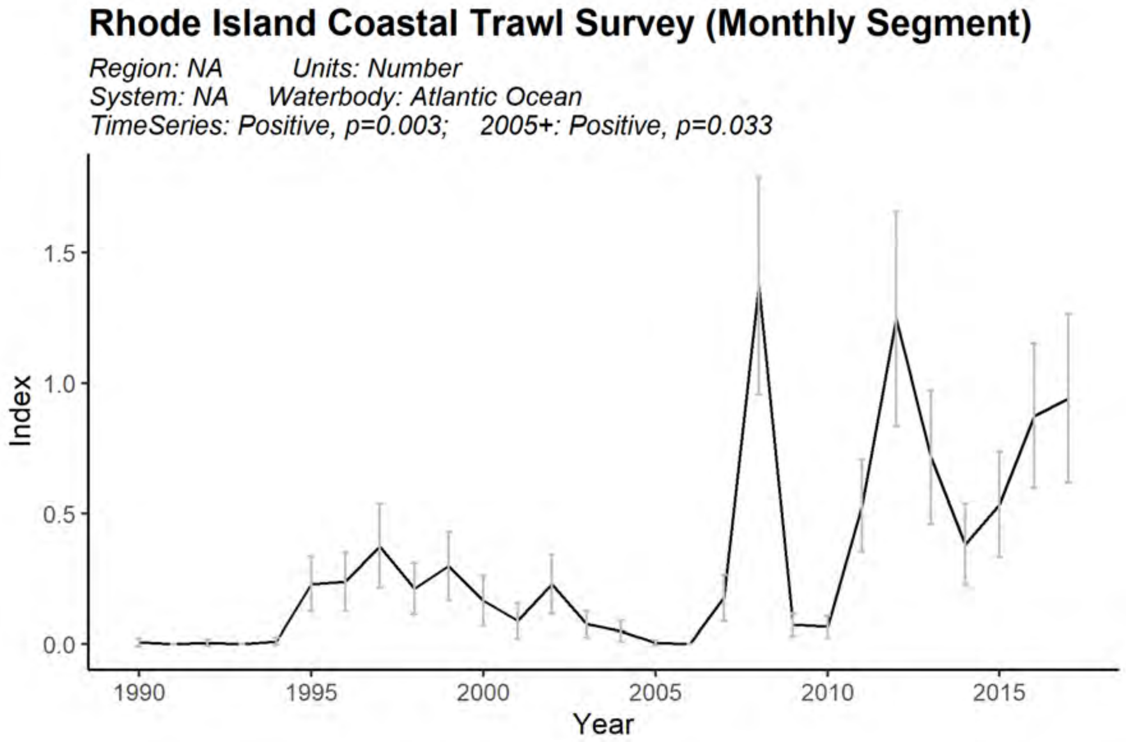


Figure 382. Abundance index from the Rhode Island Coastal Trawl Survey (Monthly Segment) and Mann-Kendall results.

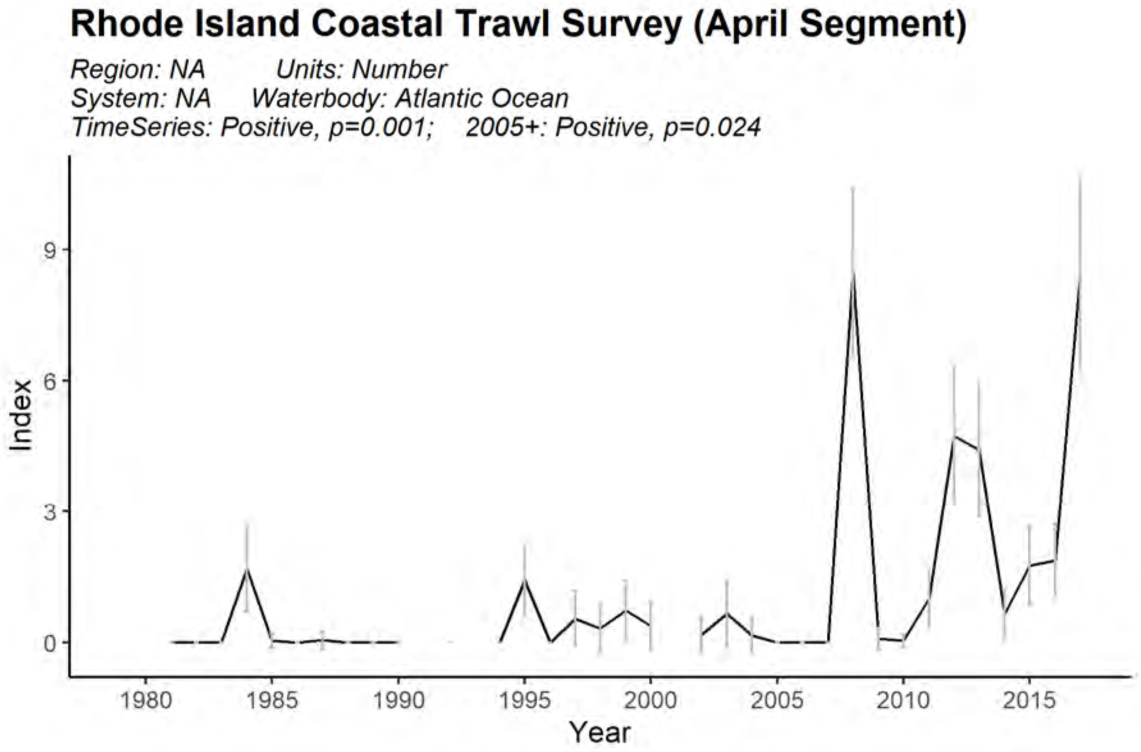


Figure 383. Abundance index from the Rhode Island Coastal Trawl Survey (April Segment) and Mann-Kendall results.

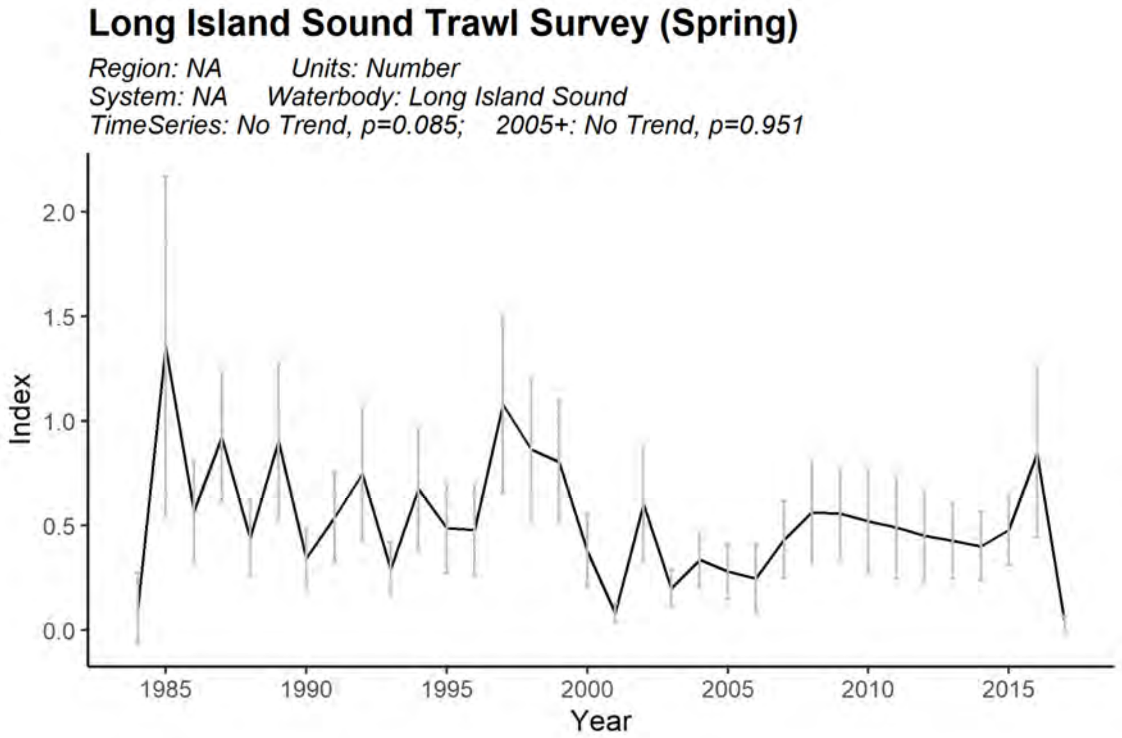


Figure 384. Abundance index from the Long Island Sound Trawl Survey (Spring) and Mann-Kendall results.

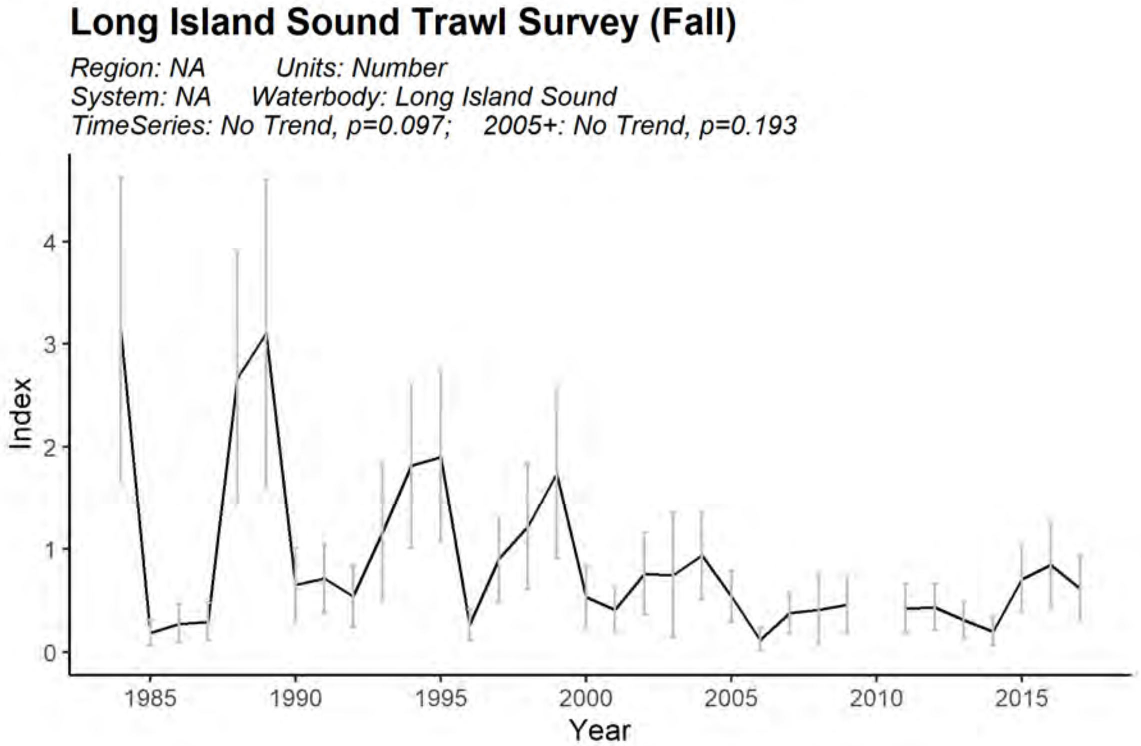


Figure 385. Abundance index from the Long Island Sound Trawl Survey (Fall) and Mann-Kendall results.

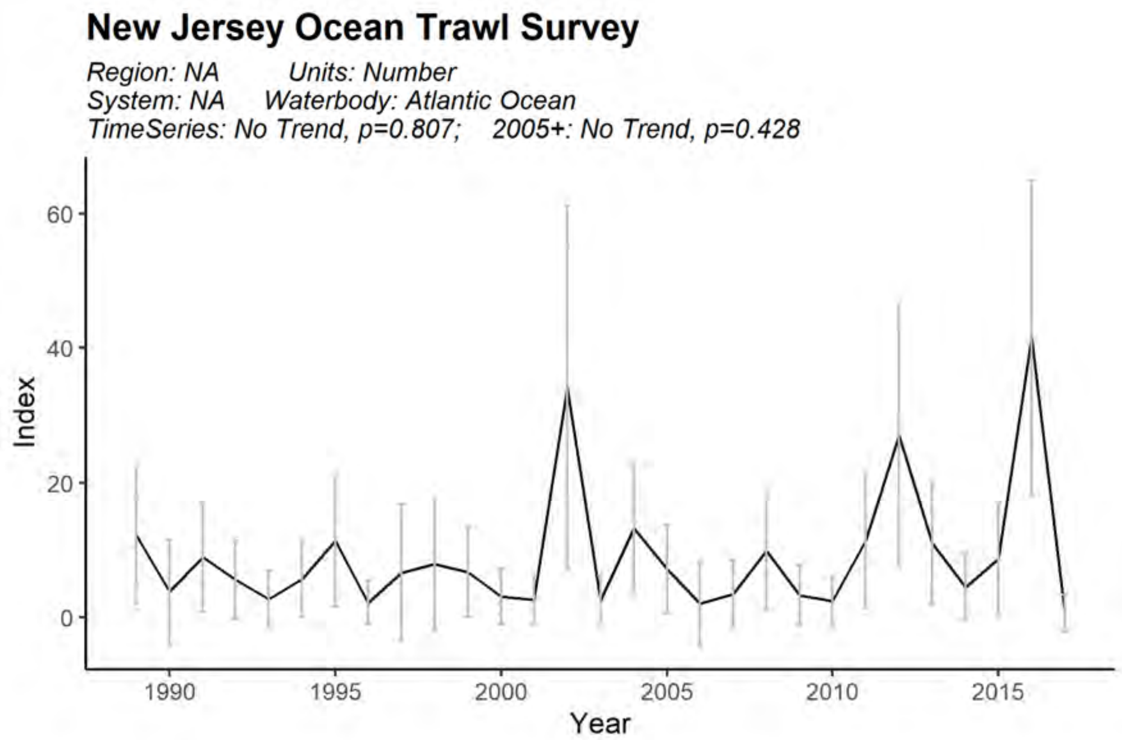


Figure 386. Abundance index from the New Jersey Ocean Trawl Survey and Mann-Kendall results.

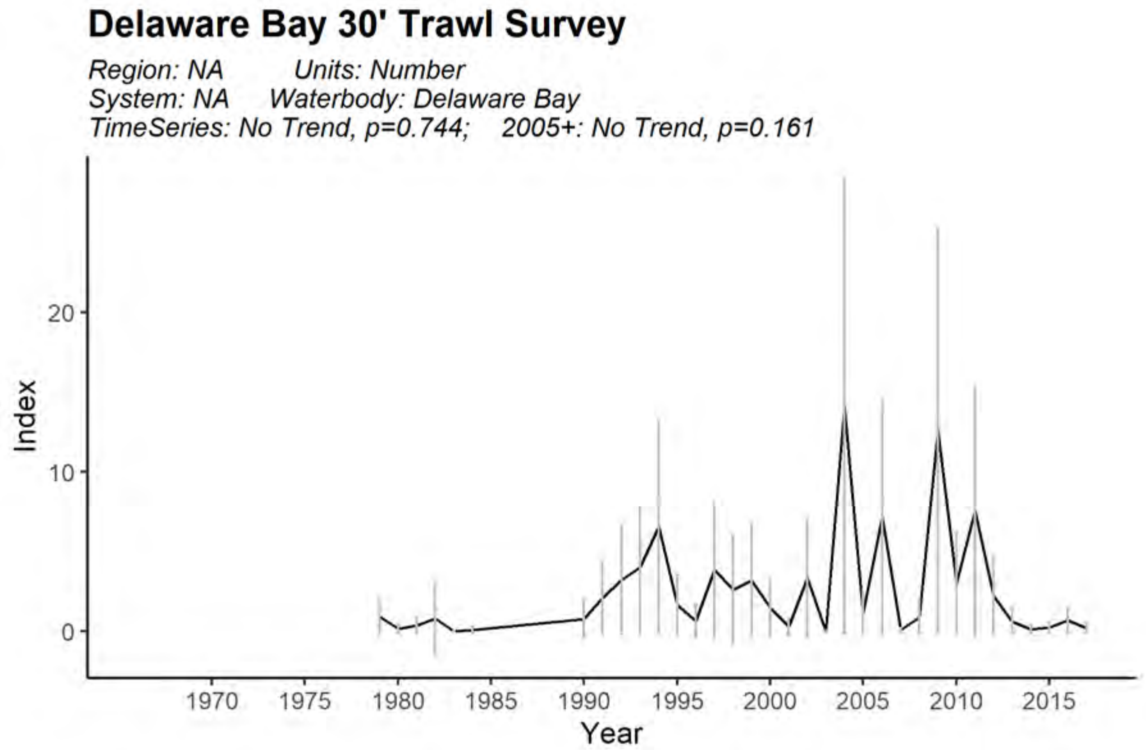


Figure 387. Abundance index from the Delaware Bay 30' Trawl Survey and Mann-Kendall results.

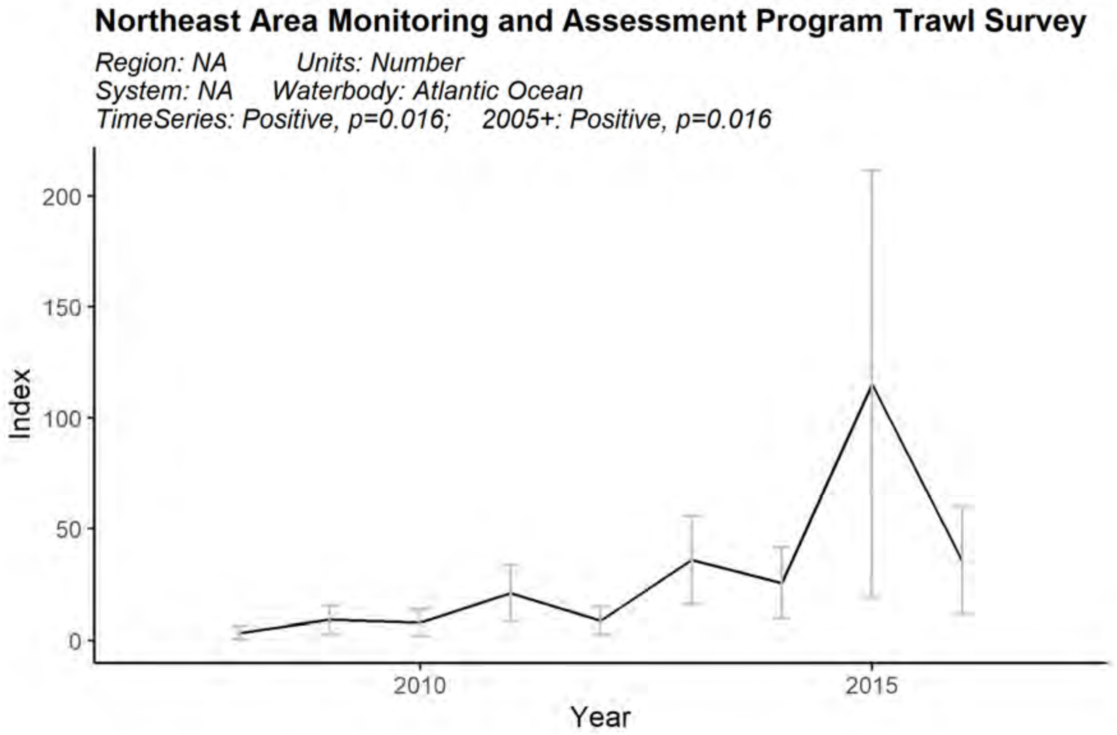


Figure 388. Abundance index from the Northeast Area Monitoring and Assessment Trawl Survey and Mann-Kendall results.

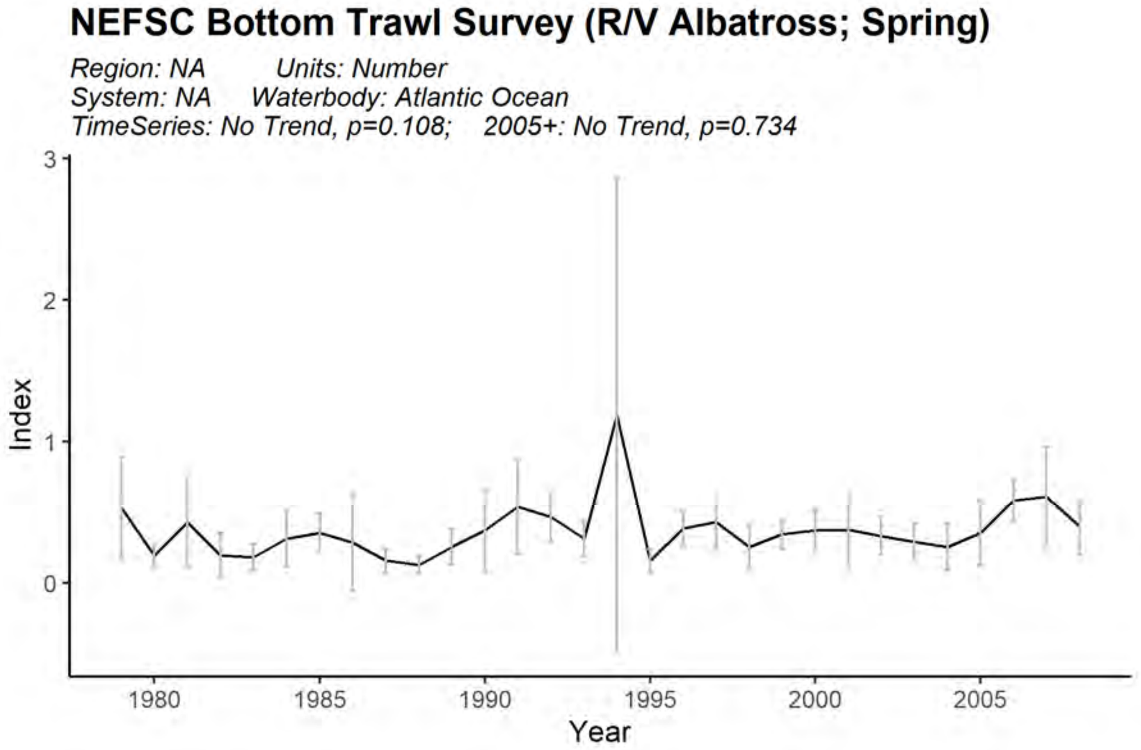


Figure 389. Abundance index (numbers) from the NEFSC Bottom Trawl Survey (R/V Albatross; Spring) and Mann-Kendall results.

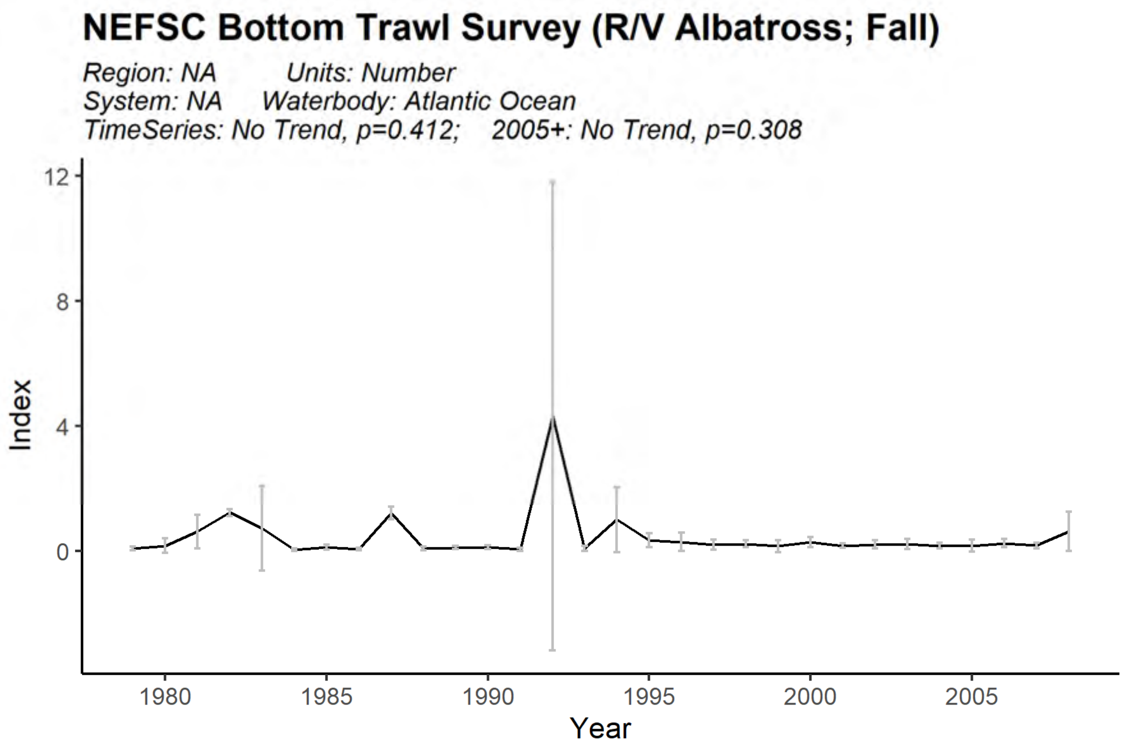


Figure 390. Abundance index (numbers) from the NEFSC Bottom Trawl Survey (R/V Albatross; Fall) and Mann-Kendall results.

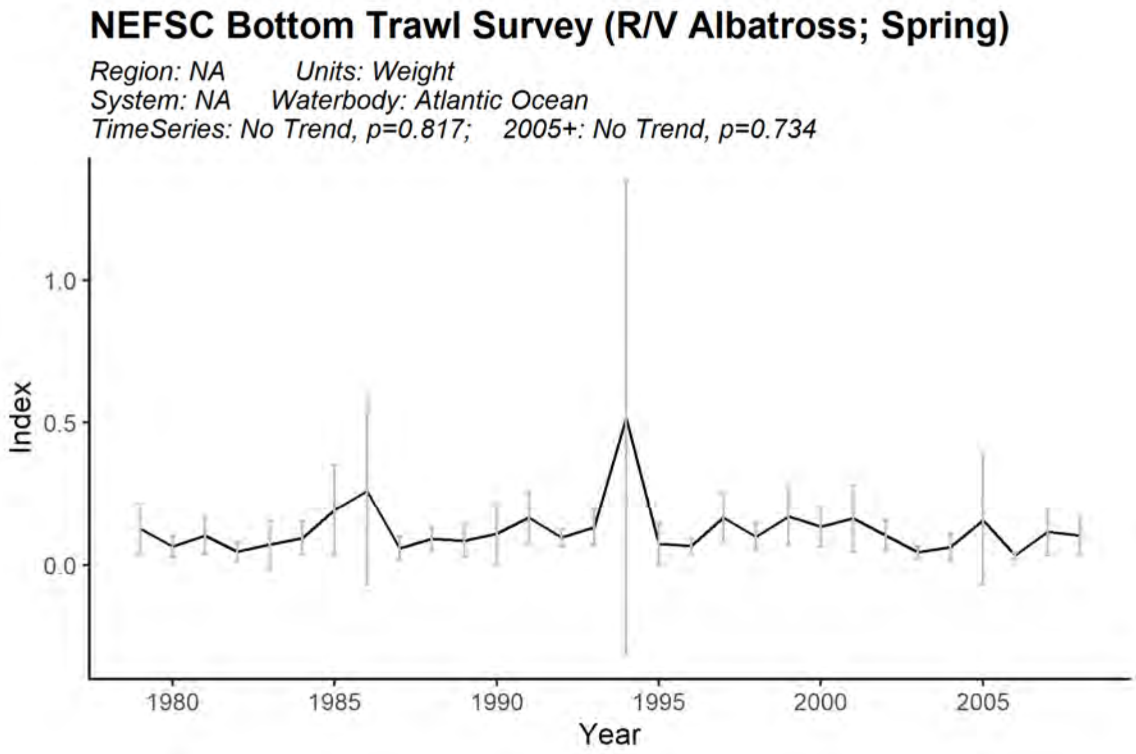


Figure 391. Abundance index (weight) from the NEFSC Bottom Trawl Survey (R/V Albatross; Spring) and Mann-Kendall results.

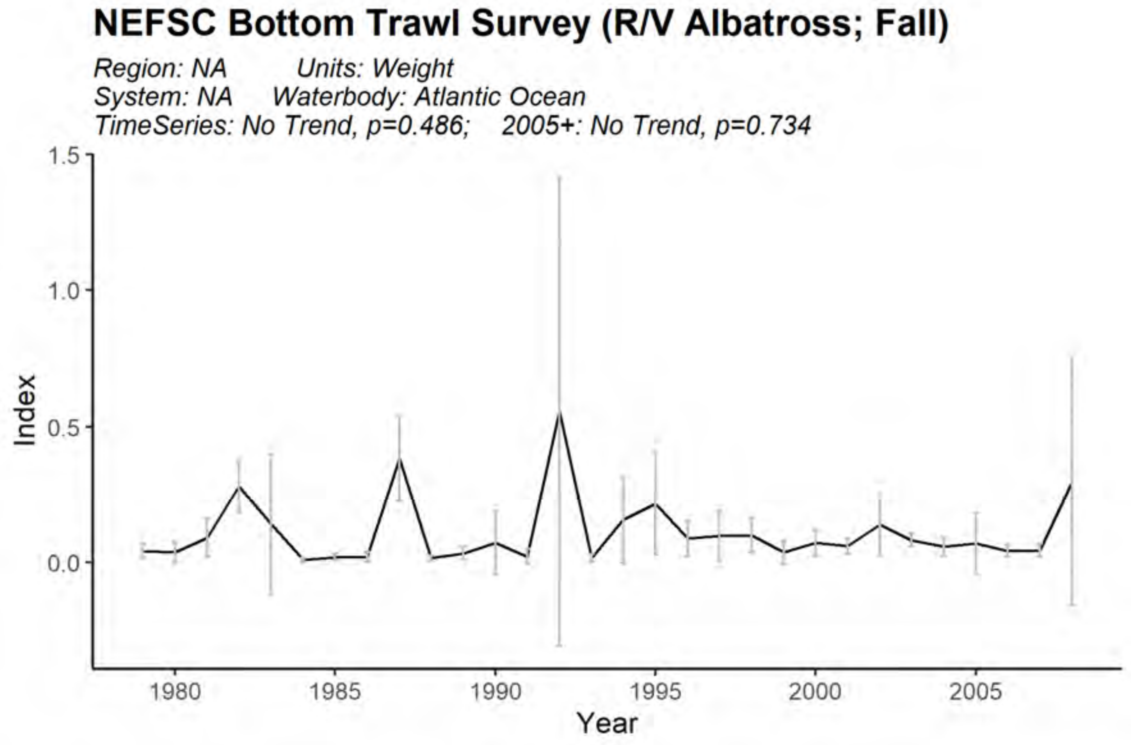


Figure 392. Abundance index (weight) from the NEFSC Bottom Trawl Survey (R/V Albatross; Fall) and Mann-Kendall results.

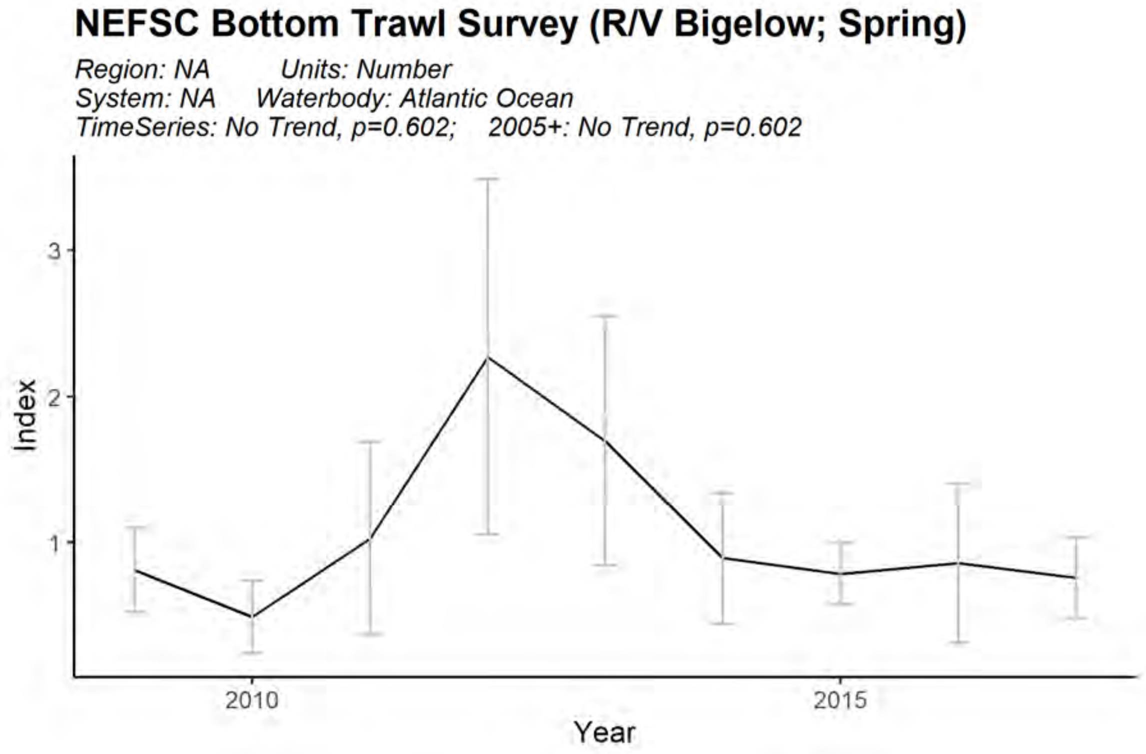


Figure 393. Abundance index (numbers) from the NEFSC Bottom Trawl Survey (R/V Bigelow; Spring) and Mann-Kendall results.

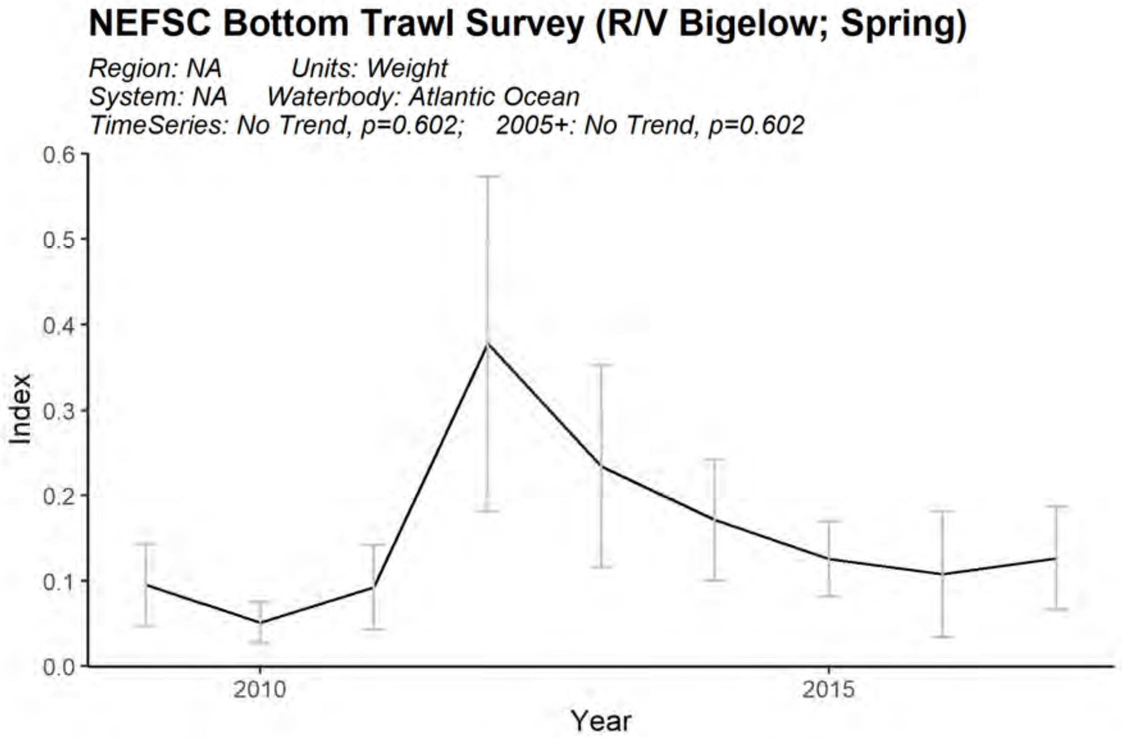


Figure 394. Abundance index (weight) from the NEFSC Bottom Trawl Survey (R/V Bigelow; Spring) and Mann-Kendall results.

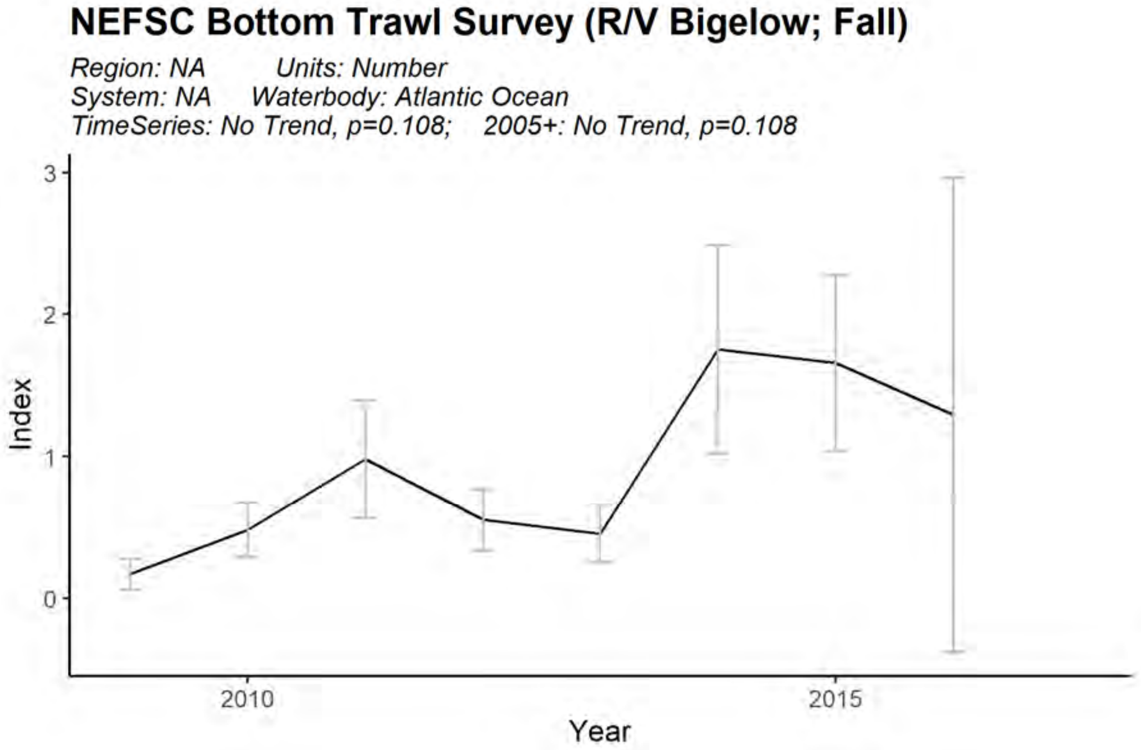


Figure 395. Abundance index (numbers) from the NEFSC Bottom Trawl Survey (R/V Bigelow; Fall) and Mann-Kendall results.

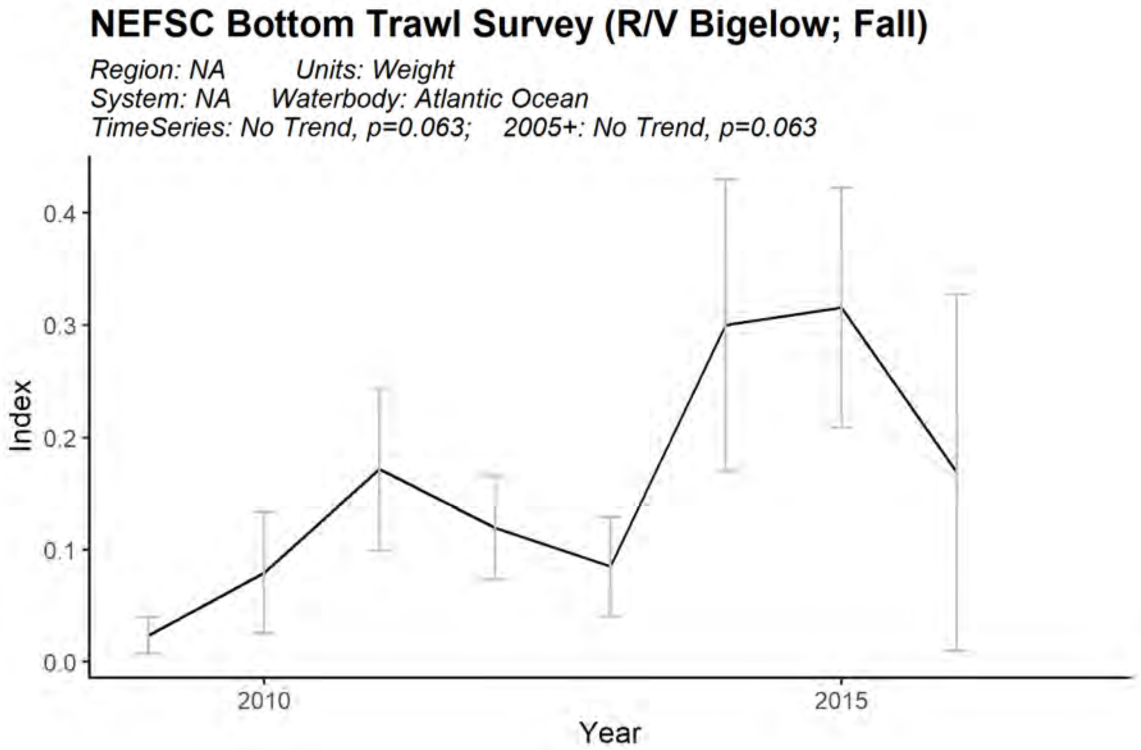


Figure 396. Abundance index (weight) from the NEFSC Bottom Trawl Survey (R/V Bigelow; Fall) and Mann-Kendall results.

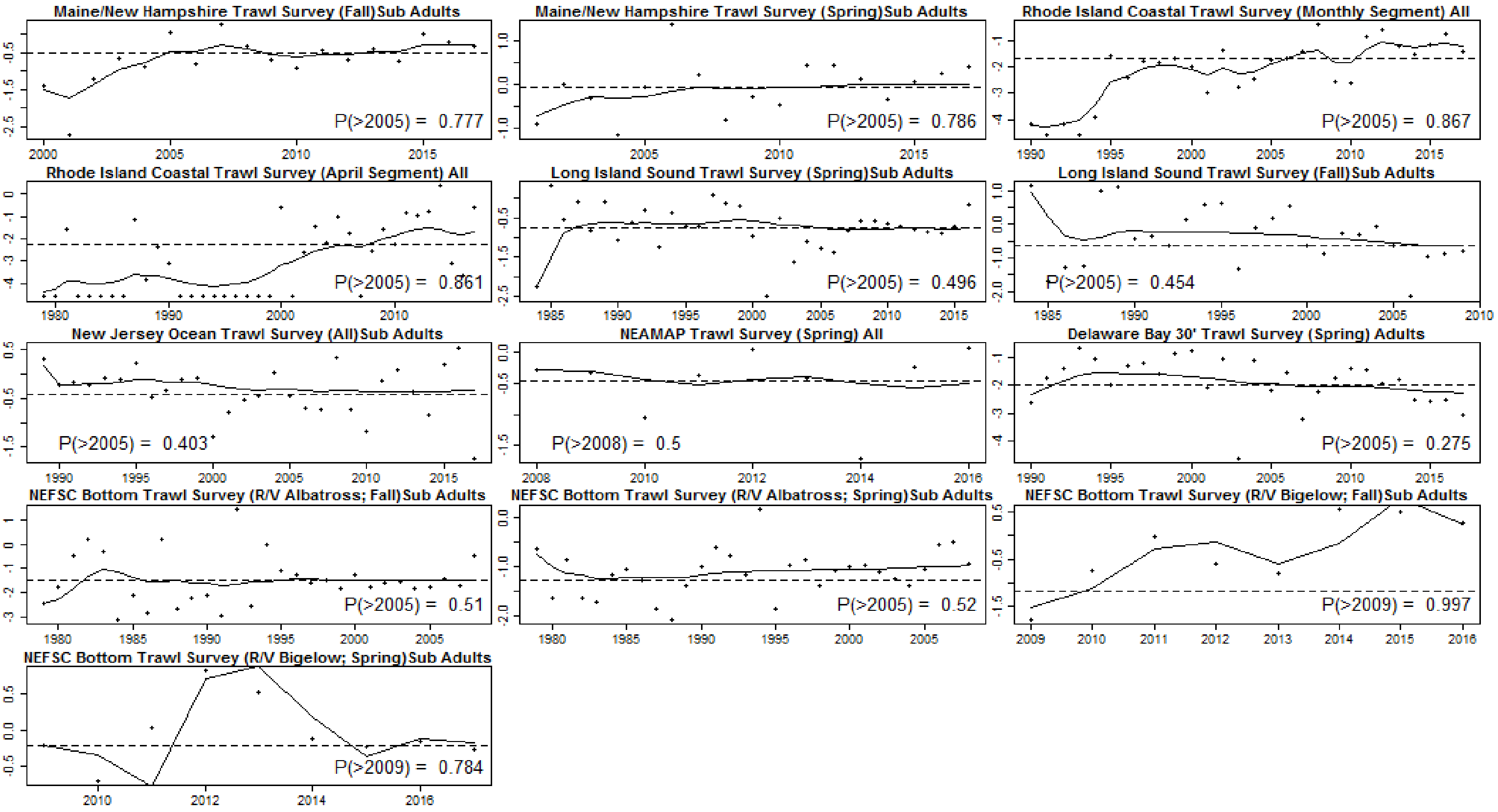


Figure 397. Autoregressive integrated moving average (ARIMA) model fits (solid lines) to log transformed American shad trawl survey indices (solid dots) from trawl surveys. The dotted horizontal lines correspond to the bootstrapped fitted 2005 index value. Text on the graphs represents the probability of the last year of the survey being greater than the 2005 index [P(>2005)], the season of the trawl survey, and the ages of American shad observed in the trawl survey. For surveys that started after 2005, terminal year is compared to first year of the survey.

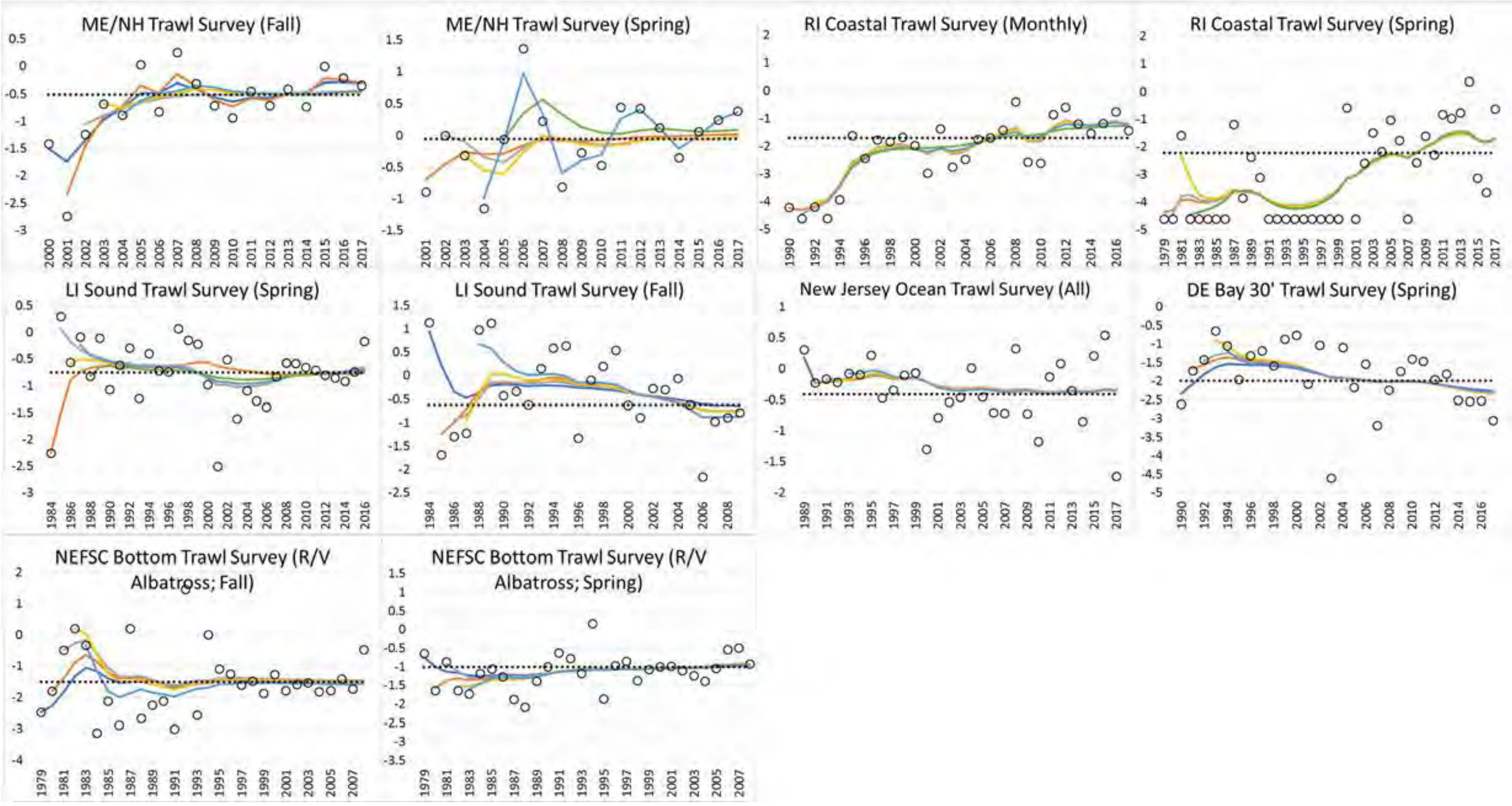


Figure 398. Results of retrospective sensitivity analysis where model runs were using entire time series followed by sequentially removing one year at a time for four years. Open circles are the natural log index values, solid lines are fitted index values and the dotted horizontal line is the bootstrapped fitted 2005 index value.

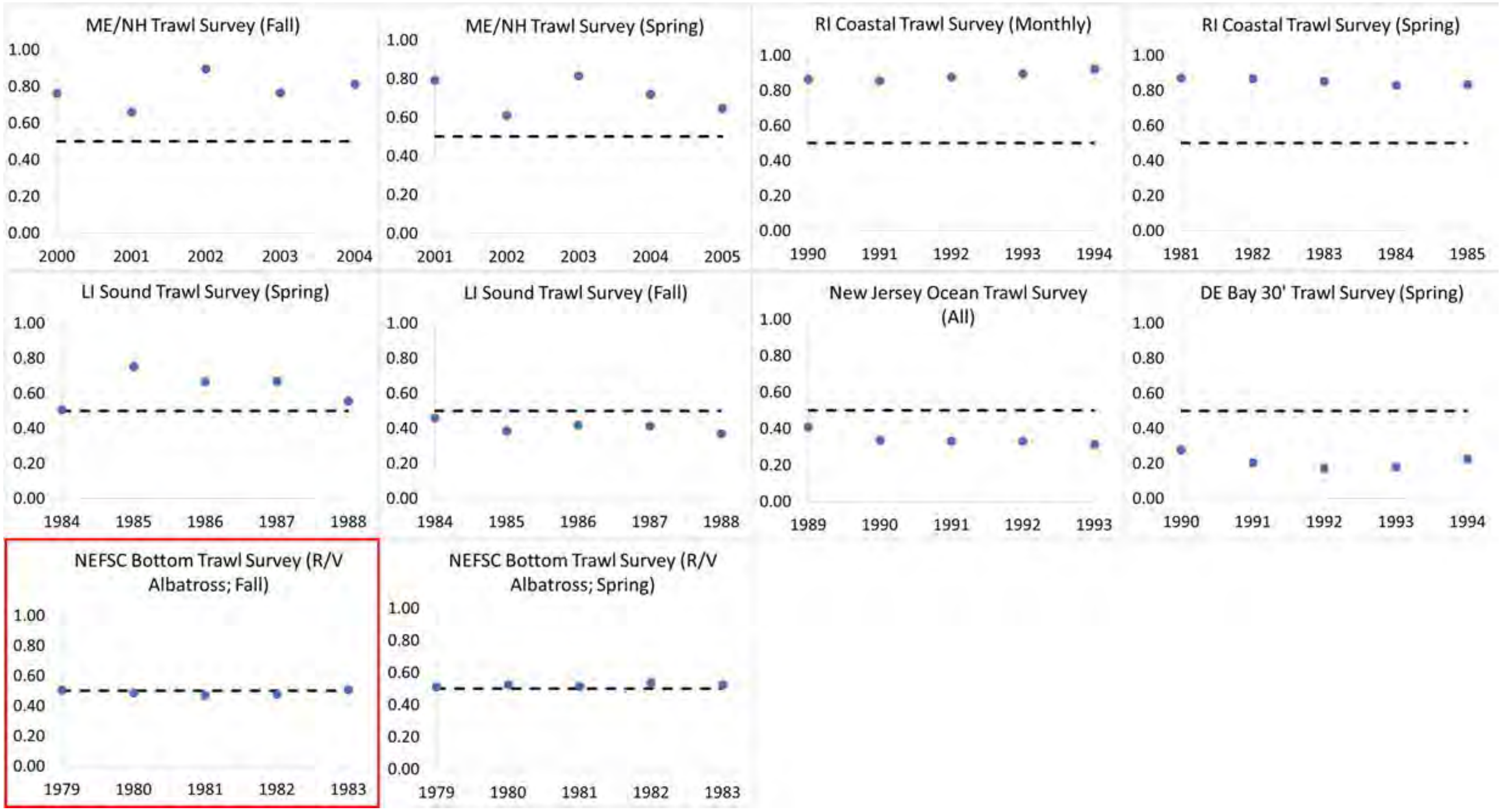


Figure 399. Probabilities that the terminal year of a given index is greater than the bootstrapped fitted 2005 index value. The dotted horizontal line is the probability = 0.50. A red box is drawn around indices where credibility of terminal year being above the 2005 index value of a given time series changes with survey start year. All terminal years = 2017 except: CT LIS spring = 2016, CT LIS fall = 2009, and NEFSC spring and fall = 2008.

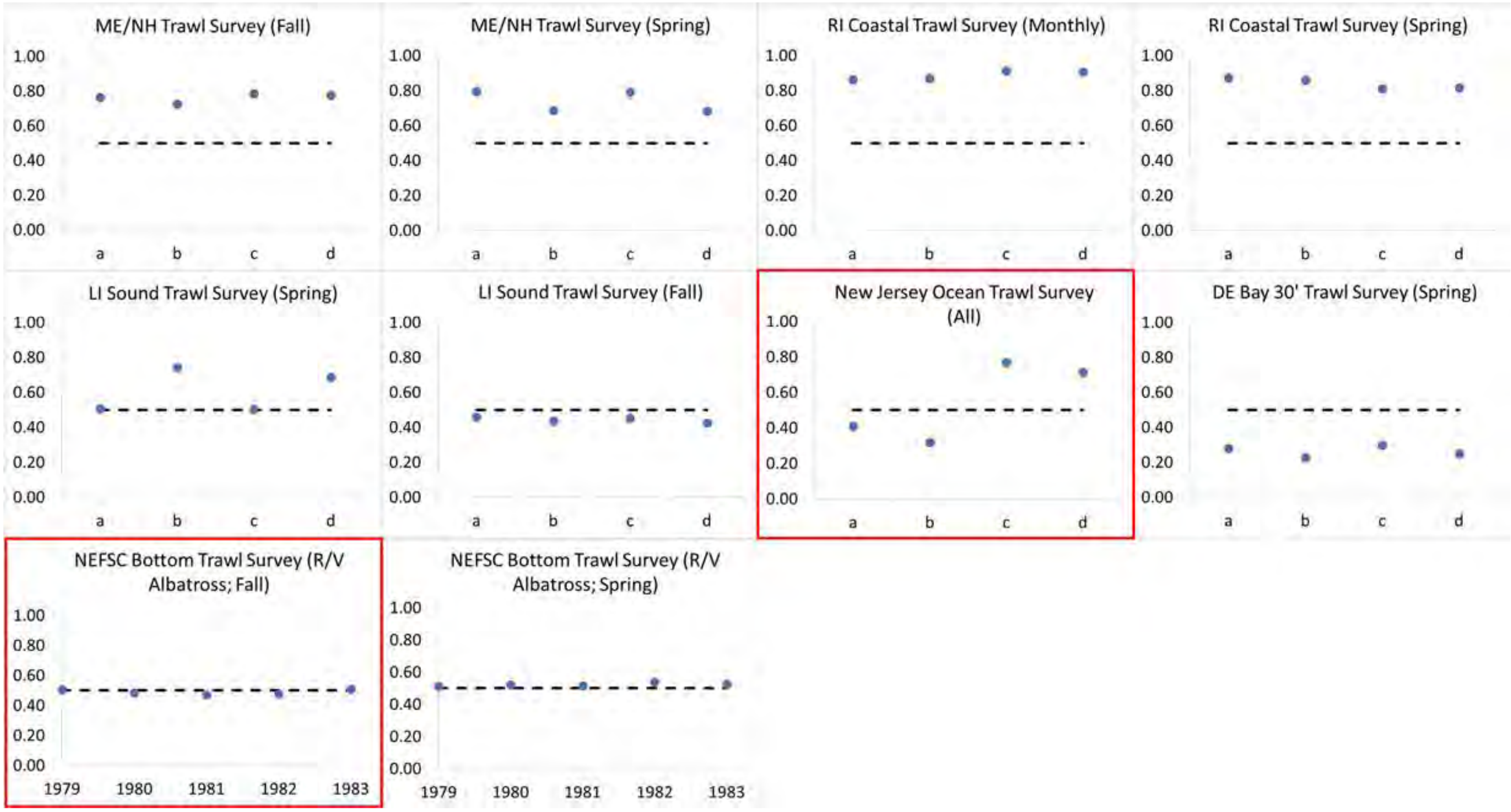


Figure 400. Probabilities that the terminal year of a given index is greater than the bootstrapped fitted 2005 index value when using a) original start year, b) start year=mean of first three years in time series, c) terminal year=mean of final three years in time series and d) both start and terminal year=three year means. The dotted horizontal line is the probability = 0.50. A red box is drawn around indices where credibility of terminal year being above the reference point of a given time series changes. All terminal years = 2017 except: CT LIS spring = 2016, CT LIS fall = 2009, and NEFSC spring and fall = 2008.

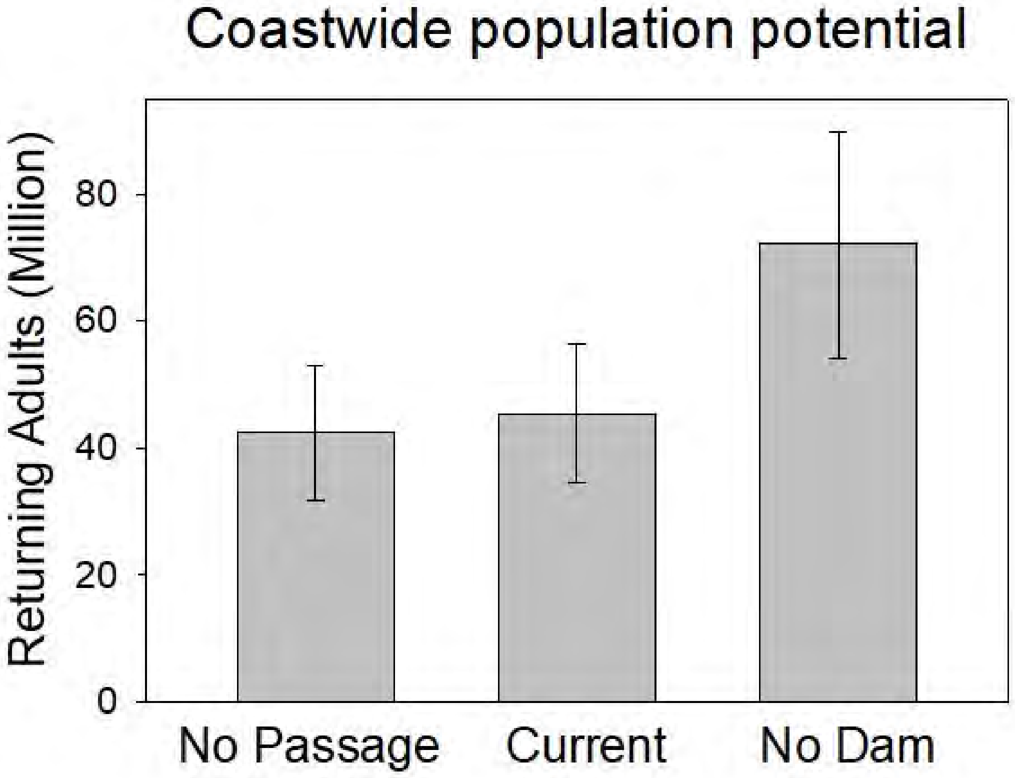


Figure 401. Anticipated abundance of spawning American shad under the no passage ("Dammed"), status quo ("Current"), and no dam ("Undammed") passage scenarios coast wide with 95% confidence intervals.

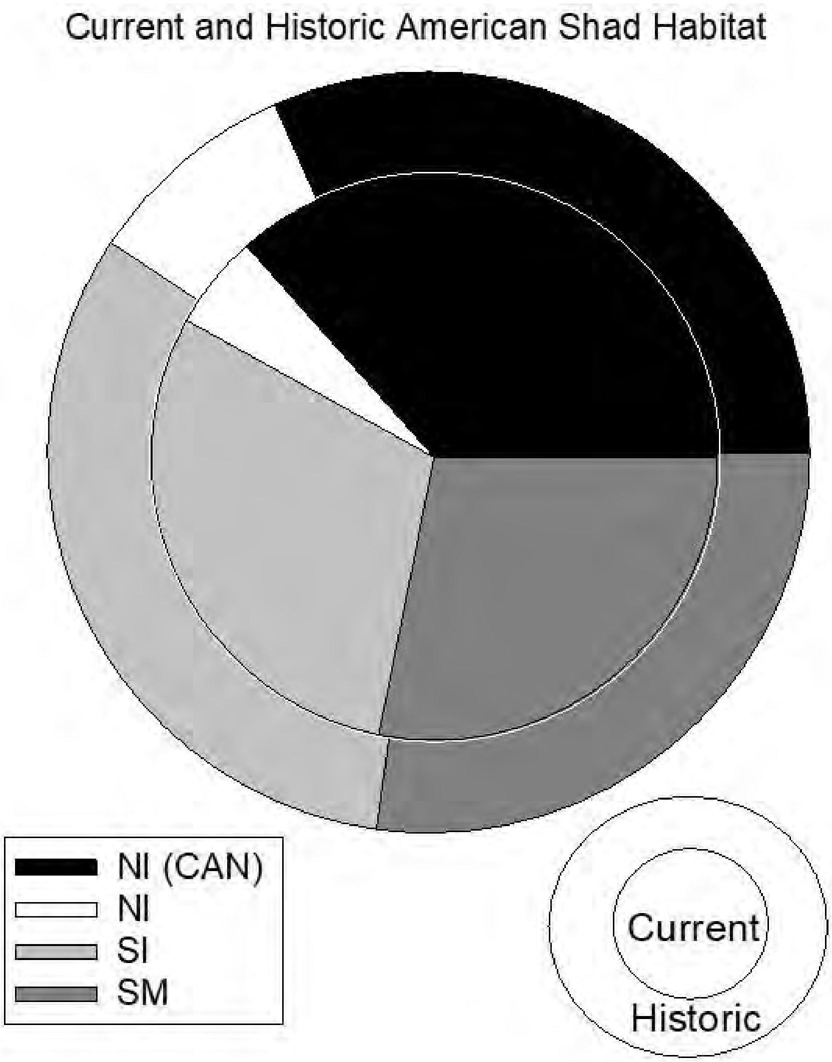


Figure 402. Graphic representation of both the historic (larger) and undammed (smaller) freshwater spawning habitat available to American shad throughout their native range. The size (area) of the circles is proportional to the area of historic (2740 km^2) and current unimpounded habitat (1636 km^2), indicating that American shad are impeded from reaching nearly 40% of their historic habitat.

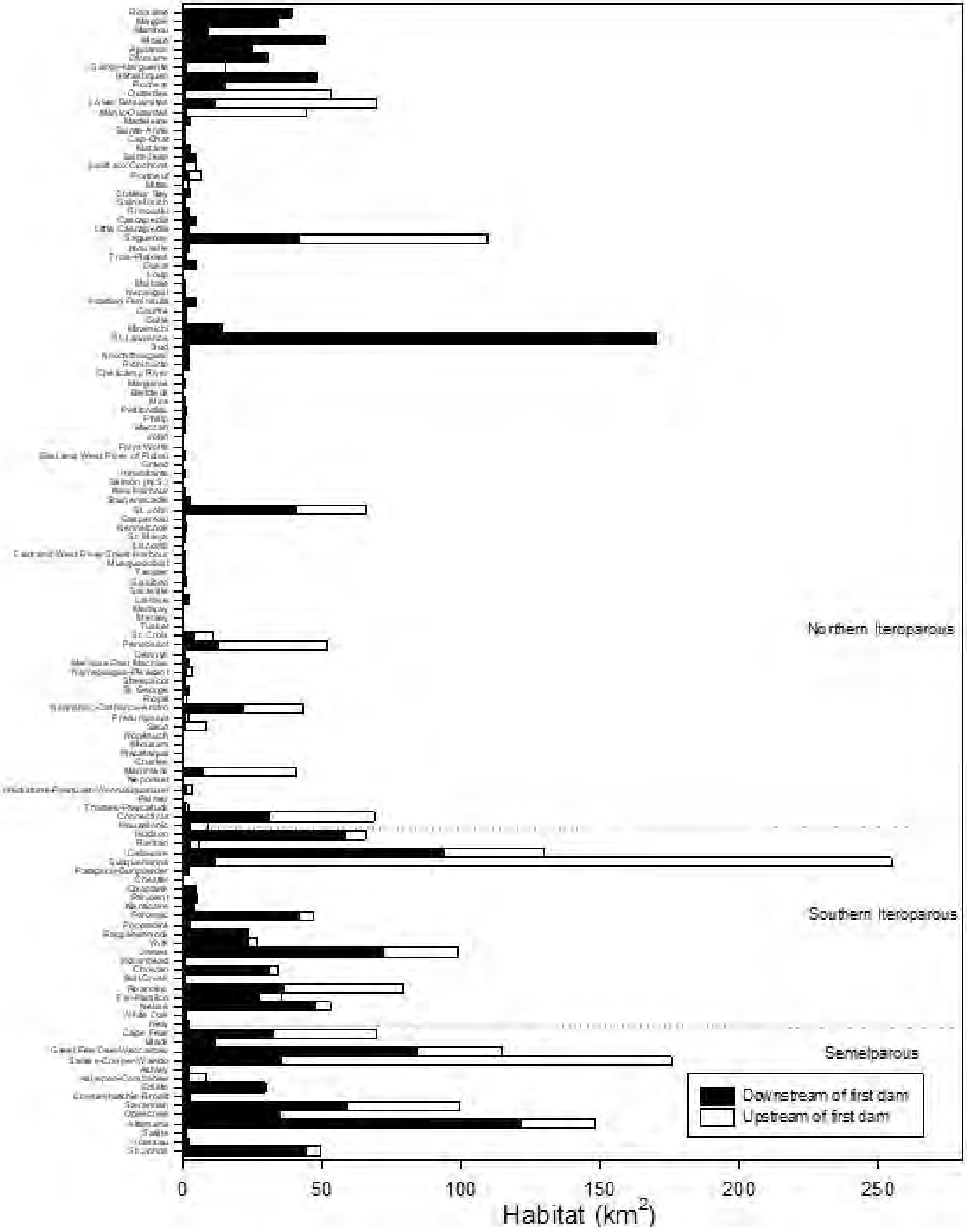


Figure 403. Total habitat available to American shad upstream and downstream of the first dam by river throughout their native range from Canada to Florida. Dotted lines indicate transitions between life-history regions. Rivers (y-axis) are ordered in descending latitude.

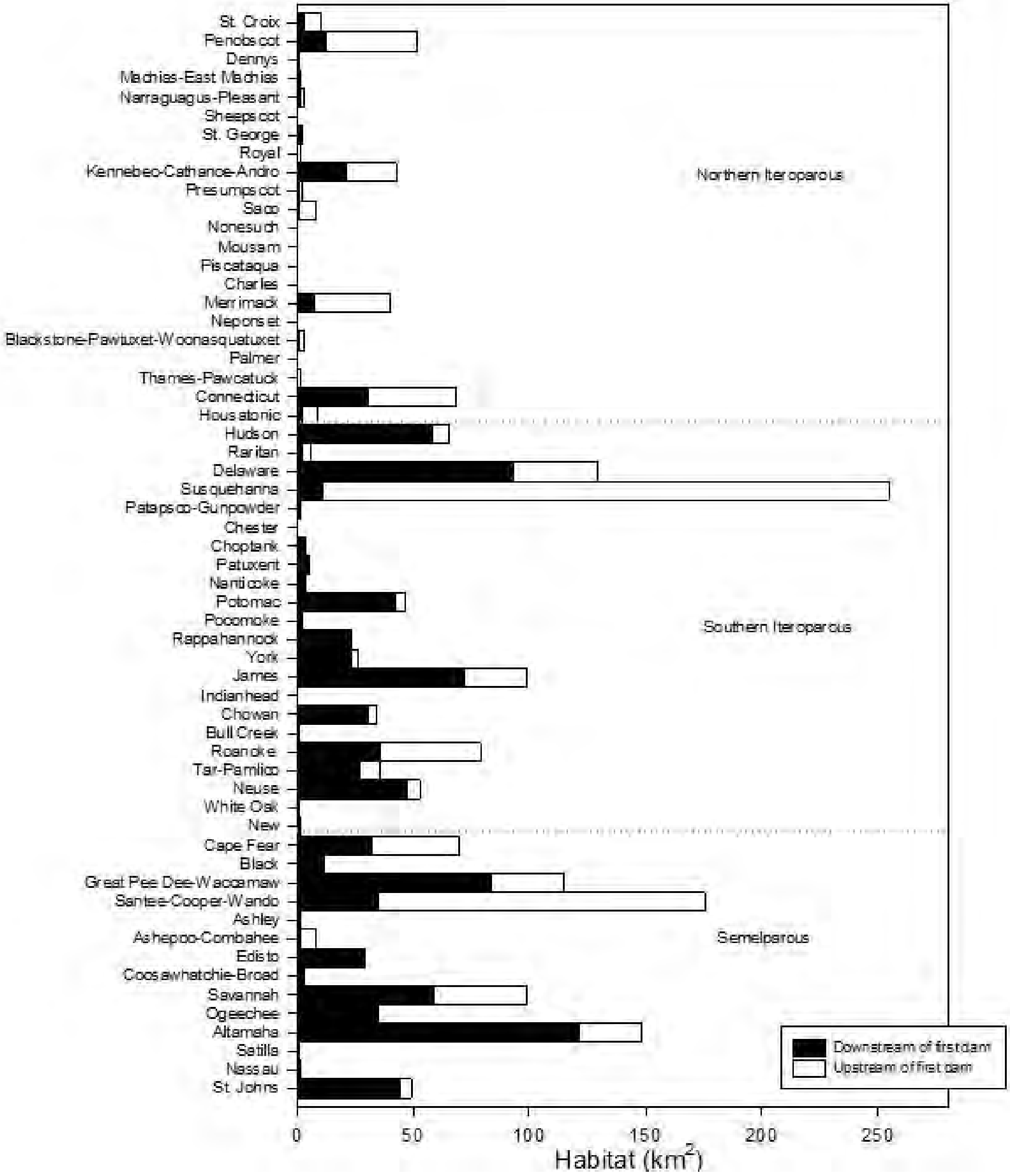


Figure 404. Total habitat available to American shad upstream and downstream of the first dam by river in the US. Symbols are as described in Figure 403.

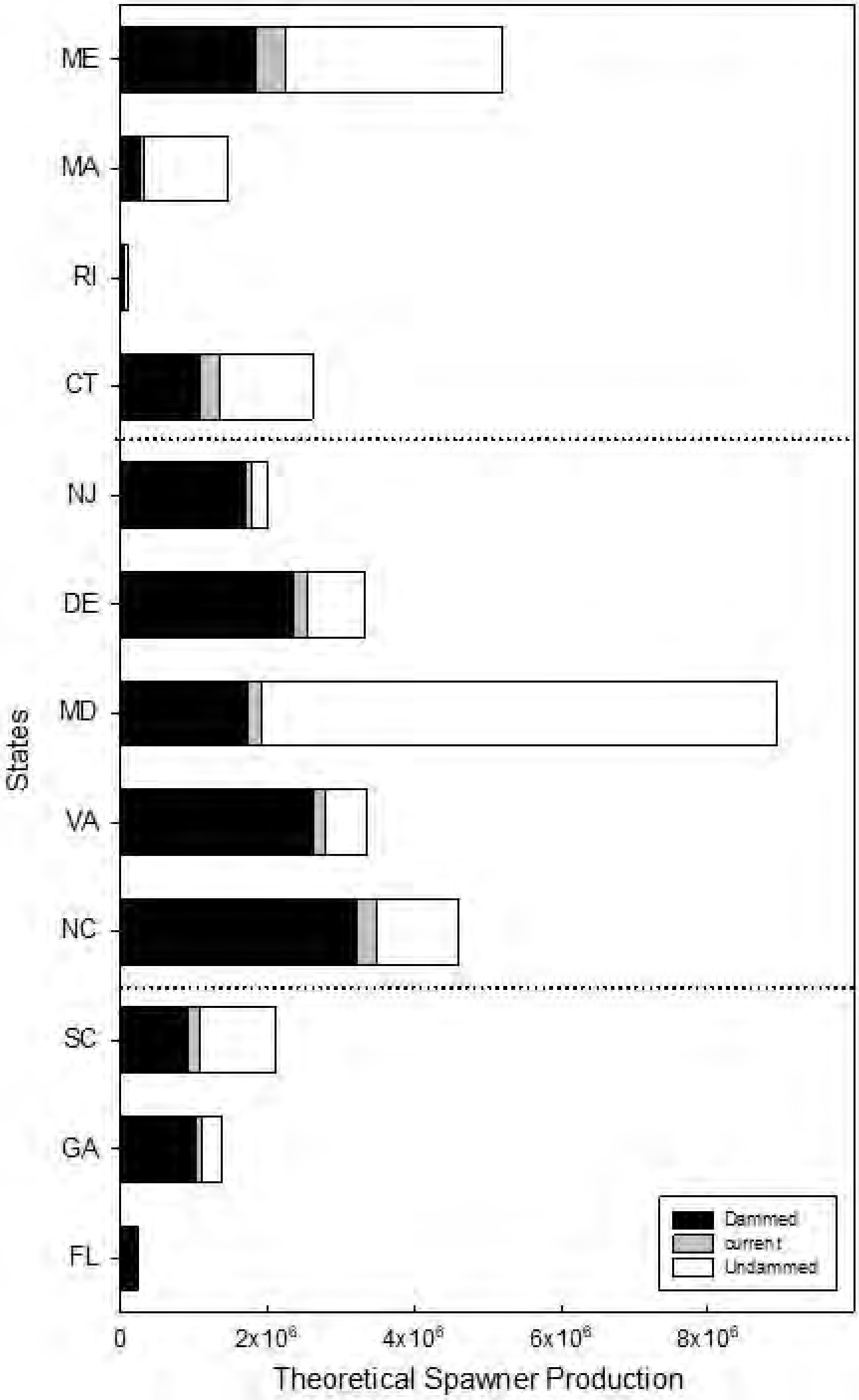


Figure 405. Abundance of American shad under the no passage ("Dammed"), status quo ("Current"), and no dam ("Undammed") passage scenarios by governing region at river outlet.

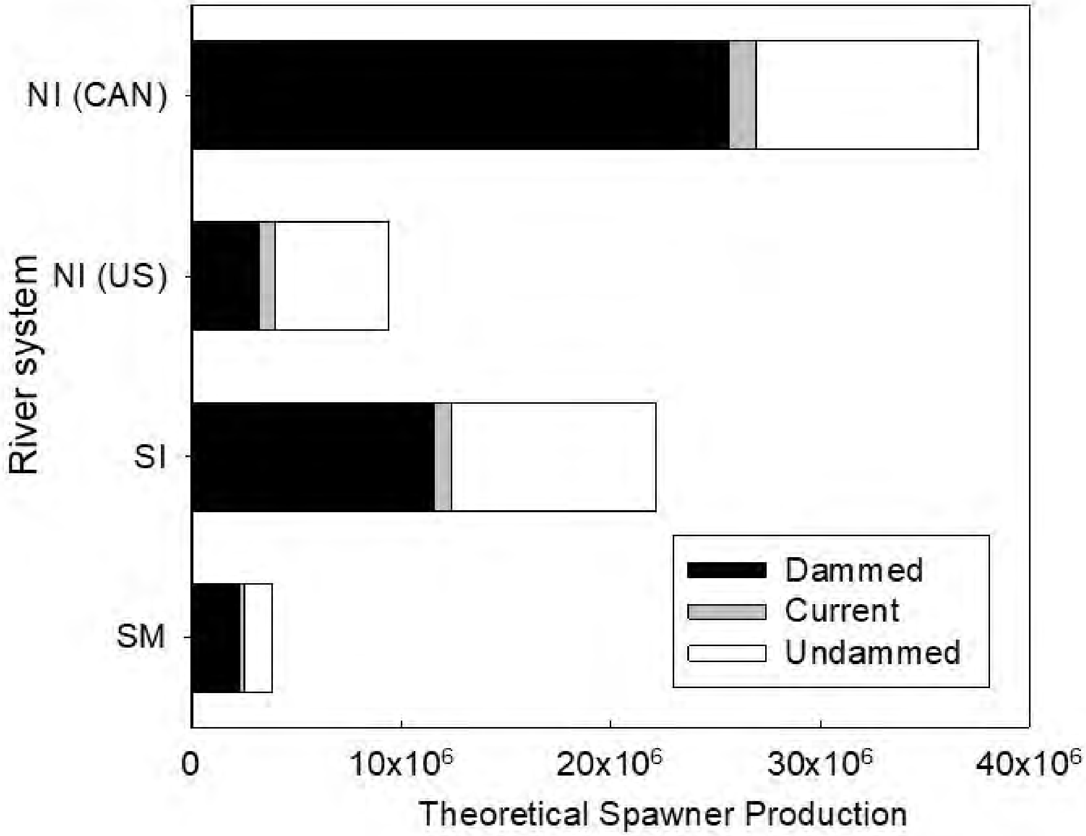


Figure 406. Anticipated abundance of spawning American shad under the no passage (“Dammed”), status quo (“Current”), and no dam (“Undammed”) passage scenarios by life-history regions in the USA and Canada.

9 ADDENDUM TO AMERICAN SHAD 2020 STOCK ASSESSMENT REPORT

During the Peer Review of the American shad stock assessment, the Peer Review Panel and Stock Assessment Subcommittee (SAS) discussed the analyses used to make stock status determinations. Additional analyses were conducted during the Peer Review and the Peer Review Panel asked that the SAS revisit stock status determinations for the systems affected by additional analyses and their recommendations to confirm final stock status determinations. This addendum provides details on the additional analyses conducted during the Peer Review, recommendations by the Peer Review Panel, and final stock status determinations for stocks where determinations changed from the initial stock assessment report. The stock status determinations that changed are described below with heading numbers that correspond to their heading numbers in the main stock assessment report.

The Peer Review Panel indicated concerns with the application and selection of some Delay-Difference models. Delay-Difference models were applied to the following semelparous systems during the assessment: Cape Fear, Winyah Bay, Santee-Cooper, ACE Basin, Savannah, and Altamaha* (*results not accepted by the SAS). The primary concern for application of Delay-Difference models to semelparous systems was the order of calculations for recruitment and mortality. A second concern was the use of a natural mortality value that was not reflective of the post-spawning mortality of semelparous stocks. The Peer Review Panel suggested running the model with a high natural mortality reflective of semelparous species (M = 10.0). This sensitivity analysis demonstrated that natural mortality of that magnitude does not produce realistic results (biomass = 8.2×10^{18} lbs of shad, average exploitation rate = 0.9, Addendum Figure 1) with the Delay-Difference model. Given the Peer Review Panel's concerns and the results of the additional analyses, the use of Delay-Difference models for semelparous systems is no longer supported by the SAS.

Application of Delay-Difference models to iteroparous systems was considered appropriate; however, the Peer Review Panel suggested several alterations to the selection and acceptance of model runs. The metric of sustainable mortality put forth in the stock assessment report was calculated as the average catch of the final 3-years divided by the Total Allowable Catch, bounded by the 25% and 75% quartiles. The Peer Review Panel suggested the use of exploitation rate (U) instead of catch, resulting in a relative harvest rate of U/U_{MSY}. The second suggestion was to investigate the influence of initial depletion on the models. The default value for initial depletion of the Delay Difference model is 1.0; however, that assumes an unfished population. The SAS concurred with the Peer Review Panel that since these systems have undergone fishing since before data collection began, exploration of initial depletion conditions was necessary. The third suggestion from the Peer Review Panel regarded the diagnostics for accepting model runs. A more rigorous approach to model acceptance was approved by the SAS beginning with selection of initial depletion condition by choosing the minimum negative log-likelihood value of model runs with initial depletion values at 1.0, 0.75, 0.5, and 0.25. This was followed by assessing the results for reasonable confidence intervals for U, biomass, and U/U_{MSY}. Four models of three iteroparous systems were analyzed under this approach: the Connecticut River (with two indices; Addendum Figure 2, Addendum Figure 3), the Neuse River

(Addendum Figure 4), and the Tar-Pamlico River (Addendum Figure 5). This approach resulted in the acceptance of the Connecticut River with fish lift index model and the Neuse River model, and the rejection of the Connecticut River with commercial CPUE index model and the Tar-Pamlico River model. The rejection of the Tar-Pamlico River model is consistent with the decision in the stock assessment report, hence no changes to stock status determination for this system. Both accepted models indicated sustainable adult mortality.

The Peer Review Panel noted concerns with using the Potomac statistical catch-at-age model as the primary analysis to estimate absolute scale of the stock and stock status due to high uncertainty in the upper bound of the mean recruitment parameter (R0) and the magnitude of the retrospective pattern observed. Instead, they recommended using the analysis to estimate trends in the stock and as a supporting analysis for mortality stock status determination. The SAS acknowledged the relatively high uncertainty in absolute stock scale in the stock assessment report and believe the analysis is informative of mortality status given the direction of the retrospective pattern (i.e., model tendency to underestimate mortality), the robustness of the model observed in sensitivity analysis, and the agreement with adult mortality status determination made with the total mortality estimators. Following the Peer Review, the SAS used the total mortality estimators to provide adult mortality status, which was supported by the findings of the statistical catch-at-age model and has not changed from the stock assessment report. Given the Peer Review Panel's concerns about the absolute stock scale estimation, the abundance status was changed to unknown as no other information was available to make this determination.

In the Connecticut system, multiple analyses were conducted to estimate adult mortality status. These analyses provided conflicting results for adult mortality status, with the accepted Delay-Difference model indicating sustainable adult mortality and the total mortality estimators indicating unsustainable adult mortality. Following review of the updated Delay-Difference model runs and further discussion with the SAS and Technical Committee, the total mortality estimators were selected as the preferred analysis to determine adult mortality status. The total mortality estimators are believed to more accurately reflect the total mortality being experienced by the stock, including non-fishing components of mortality (e.g., downstream passage mortality). Commercial fishing effort in the Connecticut has declined to relatively low levels due to attrition of the commercial fishing fleet and the commercial landings have become a less informative measure of mortality in addition to the assumed baseline constant natural mortality input in the Delay-Difference model.

3.4 Connecticut

3.4.7 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. Adult mortality status is unsustainable as the three-year average female total mortality in 2017 was 1.4, which is above the $Z_{40\%}$ threshold (1.00, Addendum Figure 6).

There were no trends detected in female mean length from two data sets (1995-2012, 1997-2017) nor in YOY abundance (1978-2017, 2005-2017).

3.10 Potomac

3.10.9 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. Adult mortality status is unsustainable as the three-year average female total mortality in 2017 was 1.1, which is above the $Z_{40\%}$ threshold (1.07, Addendum Figure 7).

There were conflicting trends in female mean length detected from two data sets, with a declining trend detected from the Broodstock Collections (2004-2017) and no trend in the Potomac River Striped Bass Spawning Stock Survey (2002-2017). There was a positive trend detected in YOY abundance since 1962, but no trend since 2005.

Abundance

Abundance status is unknown. There have been no trends in YOY abundance or adult abundance (2 data sets) since 2005.

3.16 Neuse

3.16.8 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. Adult mortality status is sustainable as the three-year average exploitation in 2017 was less than the Delay-Difference model U_{MSY} threshold (0.20, Addendum Figure 4).

There was a declining trend in female mean length from 1978-2017. There were no YOY recruitment data to compare to mean length trend analyses.

3.17 Cape Fear

3.17.9 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. The adult mortality status is also unknown, as the Delay-Difference model experienced diagnostics problems and could not be used for status determination.

There was a declining trend detected in female mean length from a long-term data set (1984-2017), but no trend from an additional shorter-term data set (2001-2017) detected. There were no YOY recruitment data to compare to mean length trend analyses.

3.18 Winyah Bay

3.18.9 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. The adult mortality status is also unknown, as the Delay-Difference models experienced diagnostics problems and could not be used for status determination.

There was a declining trend detected in female mean length from 1981-2015, but no YOY recruitment data to compare to mean length trend analyses.

3.19 Santee Cooper

3.19.9 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. The adult mortality status is also unknown, as the Delay-Difference models experienced diagnostics problems and could not be used for status determination.

There were inconsistent trends detected in female length from four data sets of varying time series (1979-2017, 2000-2014, 2000-2017, 2006-2017). There were no YOY recruitment data to compare to mean length trend analyses.

3.20 ACE Basin

3.20.9 Stock Status and Conclusions

Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. The adult mortality status is also unknown, as the Delay-Difference model experienced diagnostics problems and could not be used for status determination.

There were no mean length data available for trend analyses.

3.21 Savannah

3.21.9 Stock Status and Conclusions

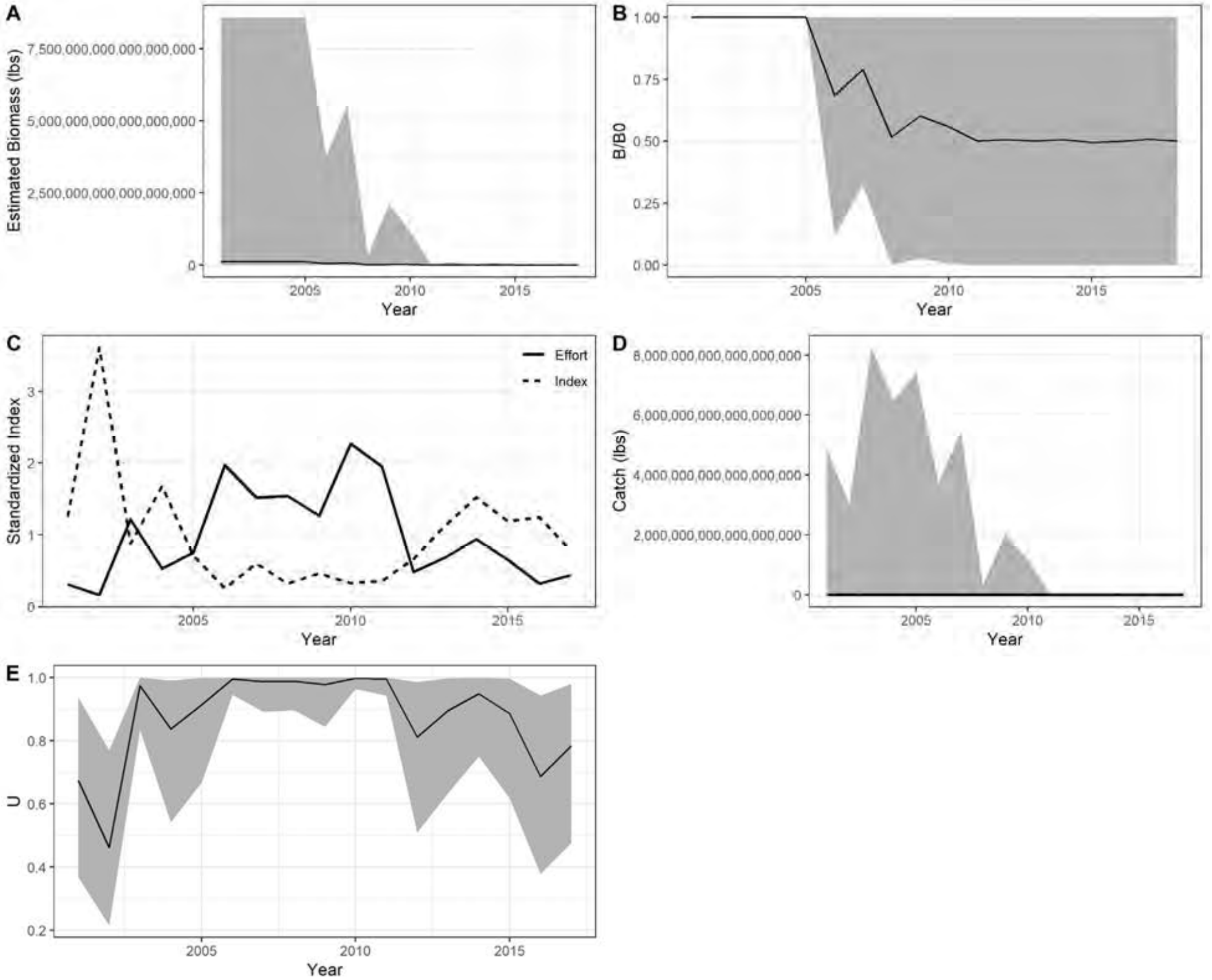
Mortality

Juvenile mortality status is unknown due to lack of data to make this determination. The adult mortality status is also unknown, as the Delay-Difference model experienced diagnostics problems and could not be used for status determination.

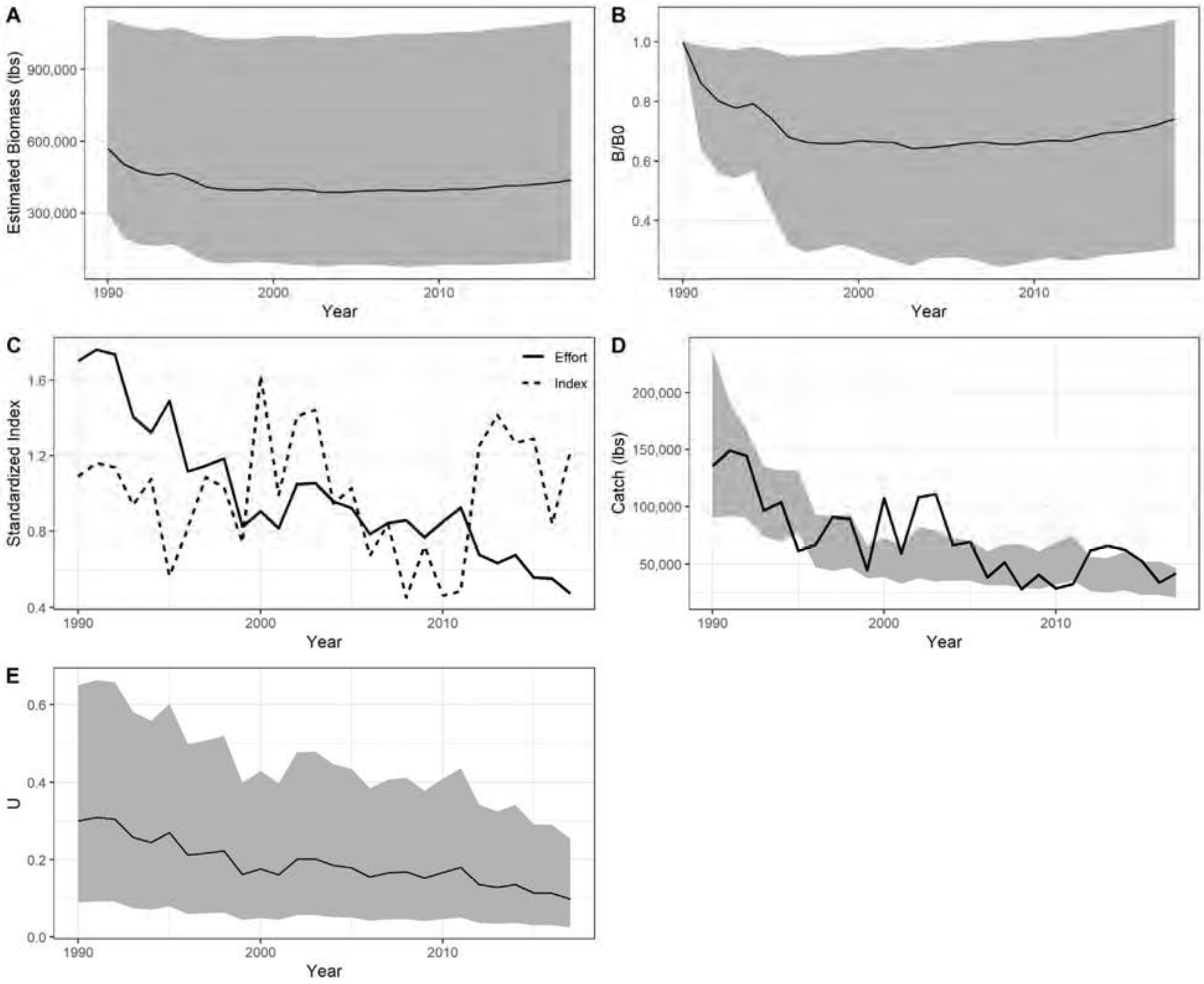
There were no mean length data available for trend analyses.

‘

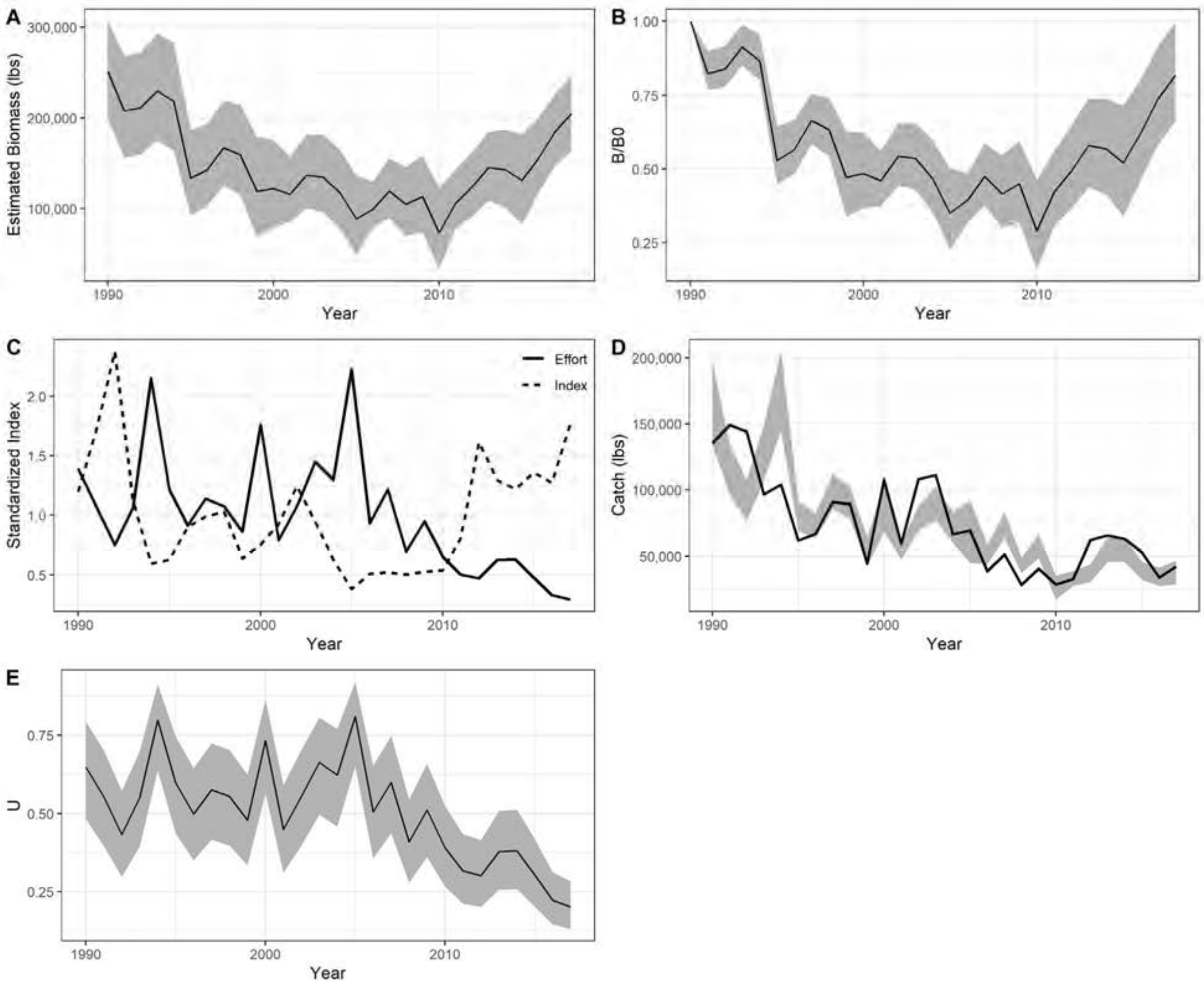
ADDENDUM FIGURES



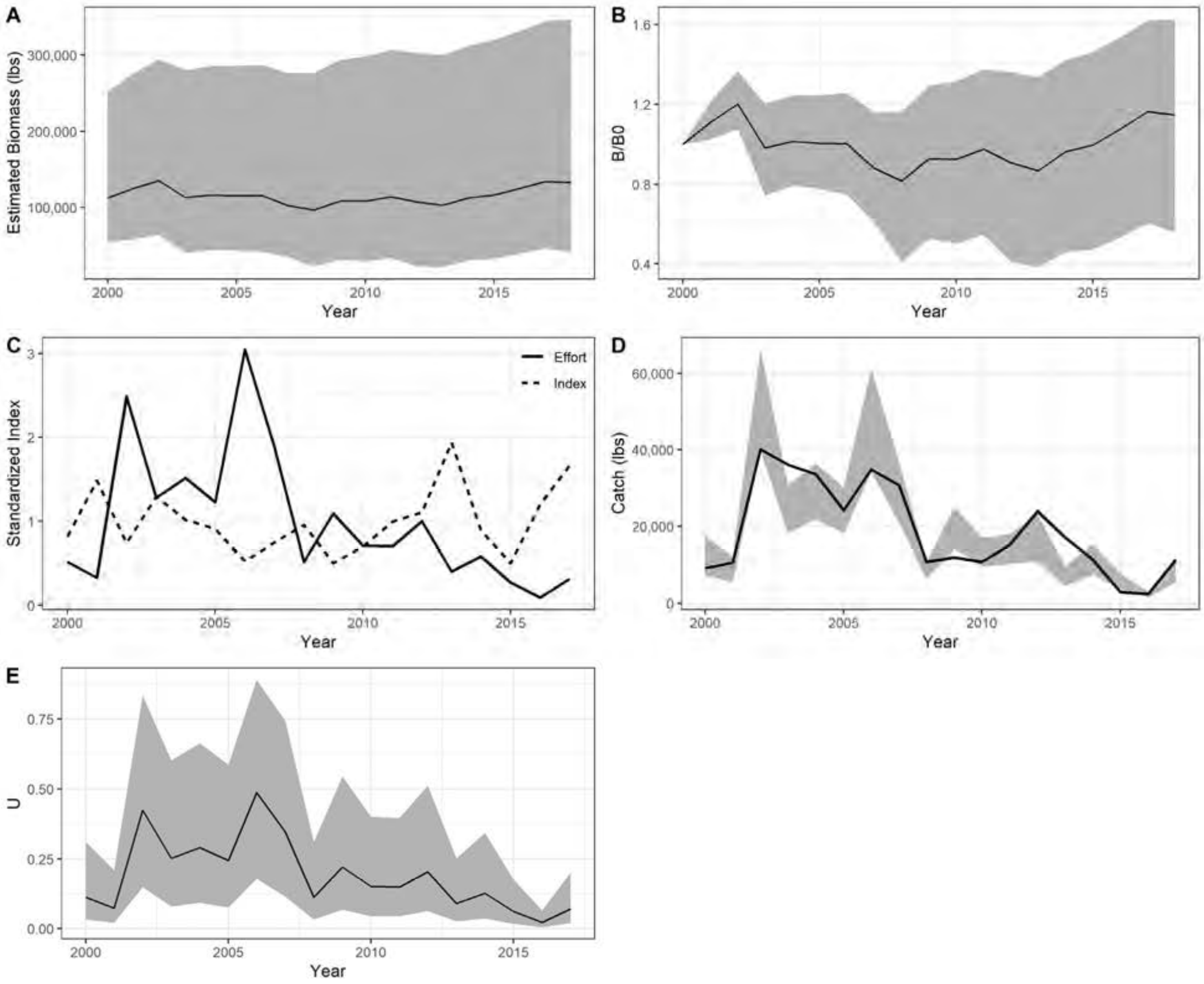
Addendum Figure 1. Output of Delay-Difference model for the Cape Fear River American shad population with natural mortality (M) of 10.0. A. Estimated biomass of the population over the time series. The black line represents the median biomass over 100 simulations. B. Relative biomass (ratio of annual biomass to initial biomass). The black line represents the median relative biomass over 100 simulations. C. Standardized index and fishery effort over the time series. D. Total catch over the time series. The black line represents the observed, historical catch. The gray area represents estimated catch over 100 simulations. E. Exploitation rate (U) over the time series. The black line represents the median exploitation rate. The gray area represents exploitation rates over 100 simulations.



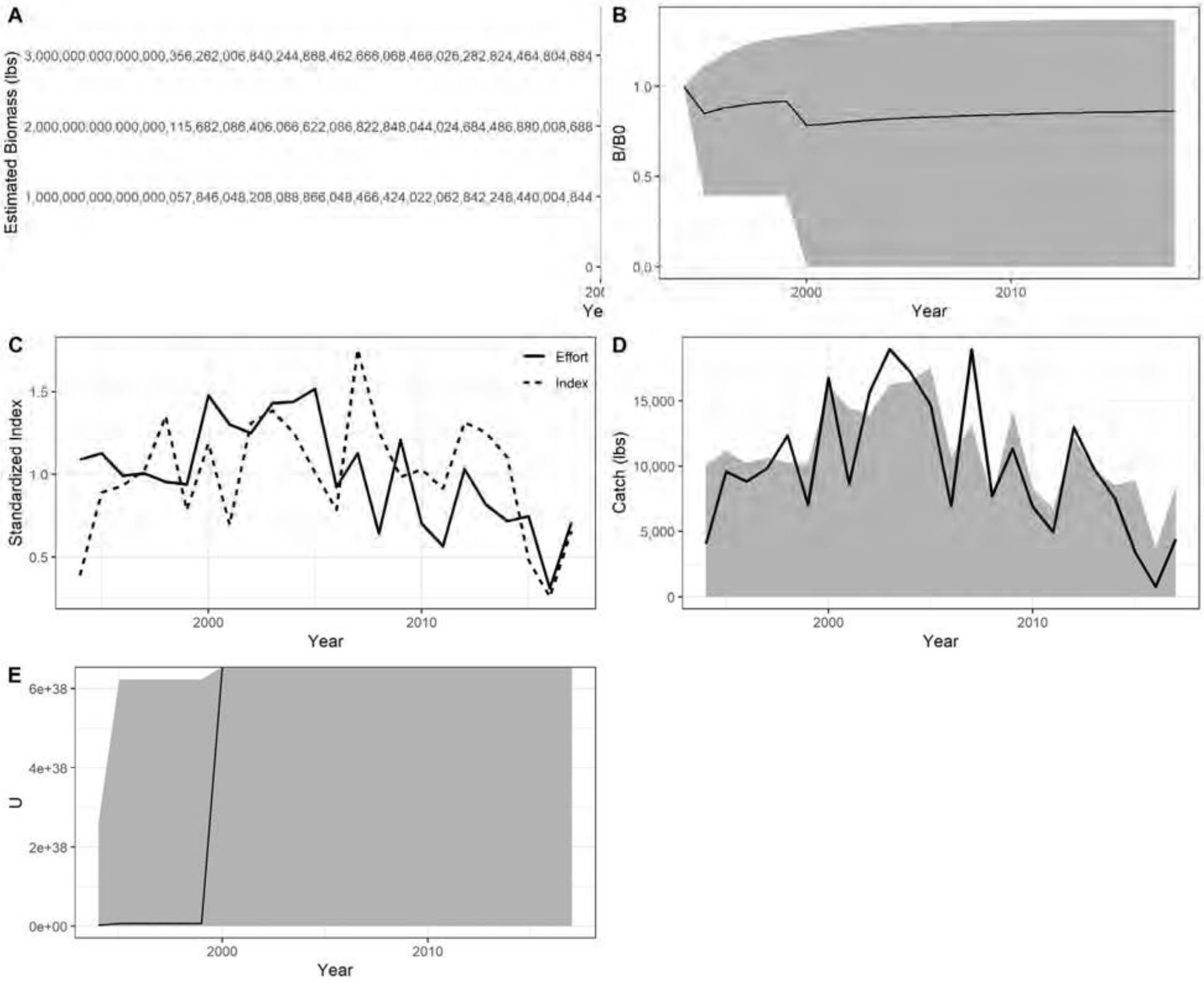
Addendum Figure 2. Output of Delay-Difference model for the Connecticut River American shad population with commercial CPUE index. Initial depletion value of 0.75 was selected by minimizing negative log-likelihood values. A. Estimated biomass of the population over the time series. The black line represents the median biomass over 100 simulations. B. Relative biomass (ratio of annual biomass to initial biomass). The black line represents the median relative biomass over 100 simulations. C. Standardized index and fishery effort over the time series. D. Total catch over the time series. The black line represents the observed, historical catch. The gray area represents estimated catch over 100 simulations. E. Exploitation rate (U) over the time series. The black line represents the median exploitation rate. The gray area represents exploitation rates over 100 simulations.



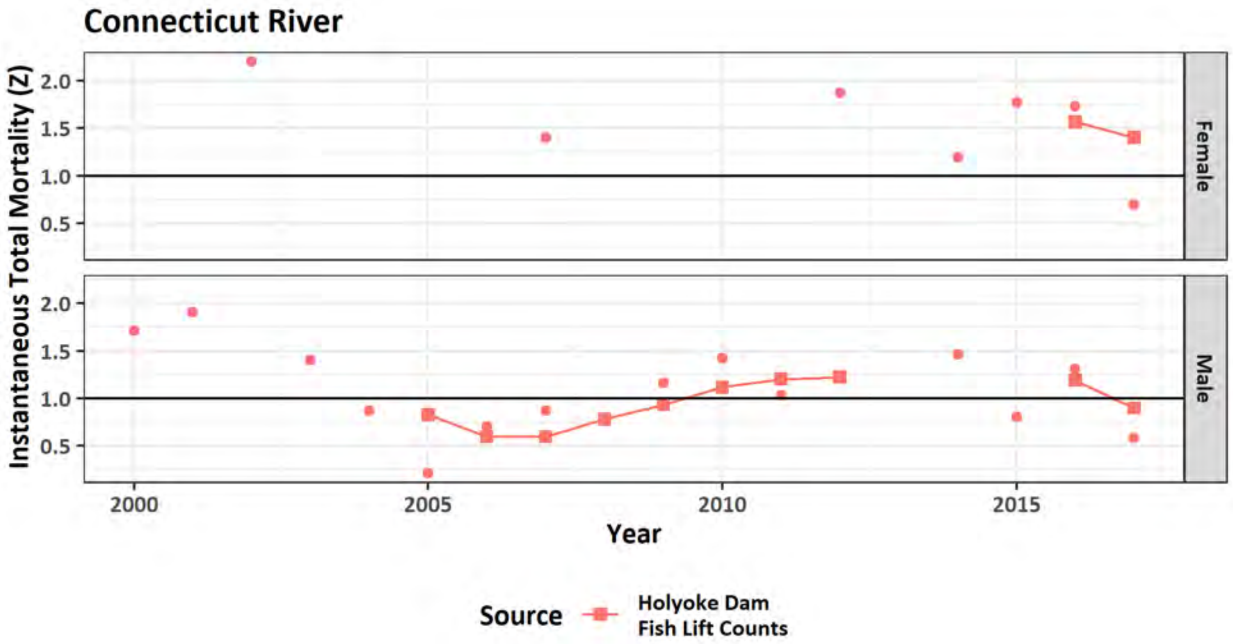
Addendum Figure 3. Output of Delay-Difference model for the Connecticut River American shad population with Holyoke fish lift index. Initial depletion value of 0.5 was selected by minimizing negative log-likelihood values. A. Estimated biomass of the population over the time series. The black line represents the median biomass over 100 simulations. B. Relative biomass (ratio of annual biomass to initial biomass). The black line represents the median relative biomass over 100 simulations. C. Standardized index and fishery effort over the time series. D. Total catch over the time series. The black line represents the observed, historical catch. The gray area represents estimated catch over 100 simulations. E. Exploitation rate (U) over the time series. The black line represents the median exploitation rate. The gray area represents exploitation rates over 100 simulations.



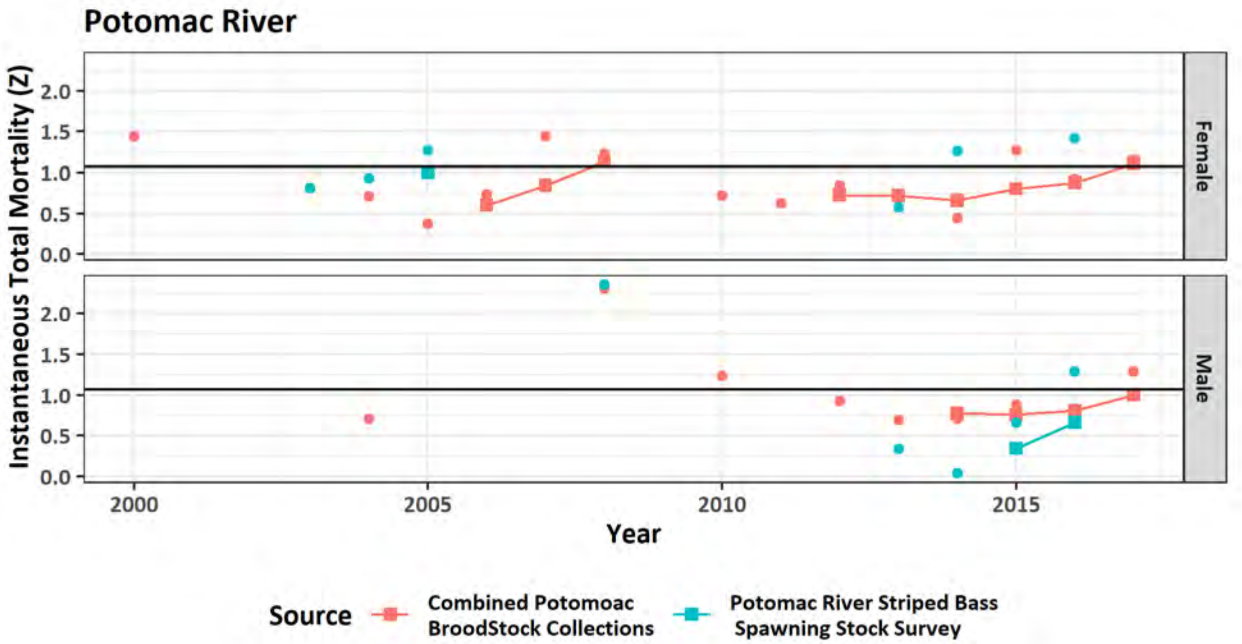
Addendum Figure 4. Output of Delay-Difference model for the Neuse River American shad population. Initial depletion value of 0.5 was selected by minimizing negative log-likelihood values. A. Estimated biomass of the population over the time series. The black line represents the median biomass over 100 simulations. B. Relative biomass (ratio of annual biomass to initial biomass). The black line represents the median relative biomass over 100 simulations. C. Standardized index and fishery effort over the time series. D. Total catch over the time series. The black line represents the observed, historical catch. The gray area represents estimated catch over 100 simulations. E. Exploitation rate (U) over the time series. The black line represents the median exploitation rate. The gray area represents exploitation rates over 100 simulations.



Addendum Figure 5. Output of Delay-Difference model for the Tar-Pamlico River American shad population. Initial depletion value of 0.75 was selected by minimizing negative log-likelihood values. A. Estimated biomass of the population over the time series. The black line represents the median biomass over 100 simulations. B. Relative biomass (ratio of annual biomass to initial biomass). The black line represents the median relative biomass over 100 simulations. C. Standardized index and fishery effort over the time series. D. Total catch over the time series. The black line represents the observed, historical catch. The gray area represents estimated catch over 100 simulations. E. Exploitation rate (U) over the time series. The black line represents the median exploitation rate. The gray area represents exploitation rates over 100 simulations.



Addendum Figure 6. Three year average *Z* estimates via weighted linear regression by sex and monitoring program for the Connecticut River System based on scale-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual Z estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).



Addendum Figure 7. Three year average Z estimates via weighted linear regression by sex and monitoring program for the Potomac River System based on scale-derived ages, synthetic cohorts, annual age compositions. Full recruitment to the gear is defined as age where peak-#s-at-age are found. In each panel are provided the annual Z estimates (colored dots (●)) for each methodology, the 3-year rolling average (colored lines and solid squares (■)) for periods with a minimum of three consecutive years with estimates, and region specific $Z_{40\%}$ reference points (solid, horizontal, black line).