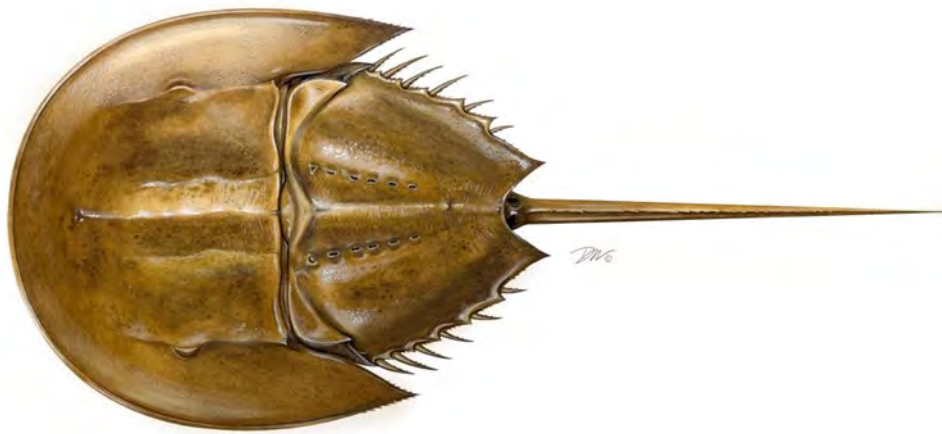


Atlantic States Marine Fisheries Commission

2021 Revision to the Adaptive Resource Management Framework and Peer Review Report



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by the Horseshoe Crab Management Board
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Sustainable and Cooperative Management of Atlantic Coastal Fisheries

ACKNOWLEDGEMENTS

The Atlantic States Marine Fisheries Commission thanks all the individuals who contributed to the development of the Adaptive Resource Management Revision.

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PREFACE

The 2021 Adaptive Resource Management Revisions and Peer Review Report is divided into three sections:

Section A – 2021 Horseshoe Crab Adaptive Resource Management Revision Peer Review Report

PDF pages 1-31

This section provides a summary of the Adaptive Resource Management Revision results supported by the Peer Review Panel. The Terms of Reference Report provides a detailed evaluation of how each Term of Reference was addressed by the Adaptive Resource Management Subcommittee and provides recommendations from the Panel for further improvement of the model in the future.

Section B – Supplemental Report to the 2021 Revision to the Adaptive Resource Management Framework

PDF pages 32-69

This section describes additional information and analysis requested by the Peer Review Panel during the Peer Review Workshop. This report, a supplement to the full Adaptive Resource Management Revision report, describes the changes requested by the Panel and the revised base run.

Section C - Revision to the Framework for Adaptive Management of Horseshoe Crab Harvest in the Delaware Bay Inclusive of Red Knot Conservation

PDF pages 70-317

This section is the Adaptive Resource Management Revision report that describes the background information, data used, and analysis for the assessment submitted to the Peer Review Panel. This report begins with a Term of Reference Report which describes how the Adaptive Resource Management Subcommittee addressed each Term of Reference followed by the more detailed assessment report.

Atlantic States Marine Fisheries Commission

2021 Horseshoe Crab Adaptive Resource Management Revision Peer Review Report

Conducted on
November 16-18, 2021
via webinar

Prepared by the
ASMFC Adaptive Resource Management Revision Peer Review Panel

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Introduction

An independent peer review of the Revision to the Framework for Adaptive Management (ARM) of Horseshoe Crab (HSC; *Limulus polyphemus*) Harvest in the Delaware Bay Inclusive of Red Knot (REKN) Conservation was conducted from November 16-18, 2021. The Review Panel (Panel) comprised Dr. Yong Chen (Stony Brook University, Chair), Dr. Kelly Robinson (Michigan State University), Dr. Erica Nol (Trent University), and Dr. Justin Bopp (Michigan State University). The Panel was assisted by the Atlantic States Marine Fisheries Commission's (ASMFC) Director of Fisheries Science, Patrick Campfield. Supporting information for the ARM assessment was presented by the Adaptive Resource Management Subcommittee Working Group (WG): Dr. John Sweka (Chair, USFWS), Dr. James Lyons (Vice Chair, USGS), Dr. Kristen Anstead (ASMFC), Dr. Bryan Nuse (University of Georgia), and Dr. Anna Tucker (USGS).

The ARM report and supporting appendices were made available to the Panel approximately three weeks prior to the review. The Panel met on November 10, 2021, for introductions, to seek clarifications on materials within the ARM, and highlight areas of the assessment the Panel would like to focus on during the review meeting. The discussions throughout the full review were collegial, and the Panel sincerely appreciates the rapid turnaround of analyses by the WG to address requests from the Panel. The Panel was able to conduct a thorough review of the HSC ARM Revision and thanks the WG and the Science Director for their diligence, patience, and assistance throughout the review.

The purpose of the 2021 ARM Review is to evaluate the work conducted by the WG in relation to the Terms of Reference (TOR). The ARM Revision provided several significant modifications since the original ARM Framework was established in 2009. Notable modifications included projecting sex-specific HSC abundance with a Catch Multiple Survey Analysis (CMSA), modelling red knot population dynamics with an integrated population model (IPM), and changing the reward function and shifting to Approximate Dynamic Programming (ADP) in the ARM model to allow for the evaluation of continuous harvest of both male and female HSC.

The Panel concludes the WG completed their TORs, revised the ARM thoughtfully, and results derived from the ARM Revision are suitable for management advice. The Panel summarizes their findings with respect to the TORs for the review and makes recommendations for further improvement of the ARM and its parameterization for management advice.

Terms of Reference for the Adaptive Resource Management Revision Peer Review

1. Evaluate the adequacy of the proposed models for estimating horseshoe crab population dynamics and projections for use in the ARM Framework, including the definition of Delaware Bay crabs.

The Panel concludes the proposed CMSA model and projection model are appropriate for the ARM Framework. The estimated stock dynamics are suitable for use in the ARM Framework for Delaware Bay Horseshoe Crabs (DB HSC). The Panel considers the CMSA-estimated DB HSC stock dynamics to be robust and appropriate for use in the ARM. The Panel has concerns and

questions about the recruitment parameterization in the projection model and definition of DB HSC.

The current weighting of surveys is based on the CVs estimated for the design-based abundance indices. A survey abundance index with a higher CV is considered less precise and is given less weight in the CMSA modeling. The Virginia Tech (VT) Trawl Survey abundance index tends to have similar or higher CVs in some years compared with the other two survey programs, implying the VT Survey index might be considered similar to or less reliable and important in the CMSA model. This may contradict the fact that the VT Survey program is specifically designed for monitoring the DB HSC stock and should be considered more important in estimating HSC stock parameters. The Panel supports the ARM WG decision to remove the weighting scheme based on the inverse Conn variances (Conn 2009) because this weighting scheme may double-count the survey CVs. During the review, the Panel suggested the WG use the survey area coverages to weight the survey programs in the CMSA. A sensitivity analysis was conducted during the review. The estimated stock abundances for both adult females and males are similar to the base case where the three survey programs were given the same weights. The Panel requested the WG evaluate the relationship between abundance indices of the three survey programs for primiparous and multiparous females and males. There were moderate to strong correlations between the different survey indices. The correlations may explain the robustness of the CMSA estimates with respect to different weighting schemes and support the use of equal survey weightings. The Panel concludes the equal weighting of the three survey programs in the CMSA is adequate as long as the three survey abundance indices are moderately correlated. The Panel recommends the sensitivity analysis results be included in Tables 18 and 19 of the ARM Revision Report.

The Panel recommends a habitat suitability index (HSI) model and species distribution model be developed to evaluate spatio-temporal distribution of the suitable habitat and abundance for DB HSC. If the WG plans to further explore different weighting schemes for survey programs in the CMSA, the spatio-temporal coverage of suitable habitats and abundance distribution by a survey program may be more appropriate for use as survey weights. However, if high correlations between survey programs' results persist over time, the resultant CMSA estimates are likely to be robust to different weighting schemes.

The Panel recommends more background be included in the report regarding the methodology and spatial sampling extent used to genetically delineate Delaware Bay-origin crabs. During the review, the Panel did not have access to the most recent HSC genetic structure report conducted by Dr. Eric Hallerman at Virginia Tech. For example, it was unclear which genetic markers (i.e., microsatellite, Single Nucleotide Polymorphisms, or haplotypes) and statistical approaches were used. During the review, the Panel requested a sensitivity analysis be conducted on the proportion of Delaware Bay-origin horseshoe crabs in Virginia and Maryland in the CMSA. The panel appreciated the Delaware Bay-origin sensitivity analysis in the CMSA in Virginia and Maryland conducted during the review workshop and recommend the sensitivity analysis be included in Tables 18-19 of the ARM Revision Report. Additional detail regarding the definition of DB HSC would be beneficial because it was ambiguous as to whether or not

spawning horseshoe crabs that immigrated into Delaware Bay from other regions were designated as Delaware Bay-origin HSC. The Panel agrees with the WG that further efforts should be pursued for classifying the proportion of DB HSC, especially within the New York region given its poor stock status.

The Panel also recommends that greater emphasis be placed on genetic sampling across multiple HSC populations within Long Island's South Shore to ameliorate the proportion of Delaware Bay-origin crabs within the New York area. Recent mark-recapture data indicates there is net movement (16% net annual migration rate) of adult HSC from the Sandy Hook, New Jersey, and Jamaica Bay, New York, region into the eastern adjacent South Shore estuaries of Long Island (Bopp et al. 2019; Bopp et al., *in prep*). Coupling this knowledge of movement with genetics in the New York area could bolster the understanding of metapopulation connectivity among and within stock units (Delaware Bay region vs. New York region). The Panel encourages the WG's research recommendation of exploring the migratory patterns of Delaware Bay-origin crabs, particularly in the New York area.

In addition to different weighting schemes, other major sources of uncertainty in the CMSA include missing years of 2012-2015 data from the VT survey, uncertain VT survey efficiency, possible uncertainty in total removal estimates (most likely under-estimates), the short time period of data, possible temporal changes in life history parameters, and lack of understanding of juvenile and sub-adult life history. The WG conducted a simulation study to evaluate the performance of the CMSA and developed a series of sensitivity analysis runs to evaluate the robustness of the modeling results with respect to select sources of uncertainty. The WG conducted additional analyses during the review to evaluate the sensitivity of the CMSA regarding increased discard mortality. Based on these analyses, the Panel concludes the proposed CMSA can provide robust estimates of DB HSC stock dynamics, and the estimates for the base case scenario are suitable for use in the ARM Framework. The Panel recommends the sensitivity analysis results be included in Tables 18 and 19 of the ARM Revision Report.

The Panel noted the estimated primiparous and multiparous HSC abundances have large uncertainties for 2012-2015 when the VT data are not available. In particular, the primiparous estimates for these years are not reliable, potentially introducing large uncertainties (and biases) in the projection model and ARM. The Panel agrees that such uncertainty will be reduced when more years of survey catch data become available in future.

The Panel noted the Delaware survey follows a fixed station survey design and the current abundance index was derived as if the survey followed a stratified random survey design. This is inappropriate. The Panel suggests the WG apply GLM or GAM to develop a model-based abundance index and relevant CV estimate for the Delaware survey program for use in the CMSA. The current design-based abundance index for the Delaware survey used in the CMSA is inappropriate.

The previous projection model included too many life history processes and was difficult to parameterize. The life history stages prior to maturation incorporated in the previous projection model are not monitored and cannot be measured directly. The previous projection

model also cannot incorporate the stock assessment model results directly and has to use HSC life history parameters outside the DB areas, potentially making the stock assessment estimates and projections incomparable. The current CMSA-based simulation model uses the CMSA results for the DB HSC directly and addresses this problem. The Panel concludes the proposed simulation model improves the stock projection compared to the previous simulation model and the current projection model is adequate in projecting the DB HSC stock dynamics for use in the ARM. However, the Panel has concerns about using the time period (i.e., 2013-2019) with high recruitment in the current report and recommends the full time series of recruitment estimates (i.e., 2003-2019) or recruitments in years when the VT HSC Survey data are available be used in the simulation model to project future DB HSC stock dynamics for use in the ARM Framework. The Panel made this recommendation because the HSC is a long-lived animal with a complex life history, subject to low fishing mortality, and environmental factors may be more important in regulating HSC recruitment dynamics. Given the uncertainty in future environments as a result of climate change, it is better to encompass greater variability in recruitment for future projections used in the ARM Framework.

The Panel commends the use of primiparous data to estimate recruitment of newly mature male and female HSCs within the DB system. Identifying primiparous individual crabs is challenging, especially for females, where egg presence needs to be confirmed. With that being said, it appears there is substantial overlap in prosoma width among immature sub-adult crabs and primiparous crabs (Fig. 4, Hallerman and Jiao 2020). The Panel appreciates the use of a prosomal width cutoff of 180mm to delineate immature vs. mature crabs. However, the Panel suggests the size cutoff be re-evaluated for female horseshoe crabs in future assessments given Hallerman and Jiao's (2020) conclusion, "...some error is associated with distinguishing newly mature from immature females.", and there was considerable overlap of immature female sizes with newly mature and mature females. For instance, the newly mature size ranges overlapped completely with immature female horseshoe crabs in some years (Fig. 4 from Hallerman and Jiao 2020). While the Panel understands that data from immature crabs is not incorporated into the CMSA or the revised ARM Framework, the size cutoff is important for estimating the proportion of immature vs. mature crabs in the discard estimates. Therefore, the Panel recommends the WG further explores the proportion of mature female HSC based on egg presence/absence at various size ranges above the 180mm threshold to better understand size-at-maturity for females. The Panel also recommends periodically re-evaluating because climate change and harvesting may exert different selection pressures on HSC for earlier reproduction.

2. Evaluate the proposed changes to the red knot population dynamics model and model weights.

The Panel commended the ARM WG for developing the Integrated Population Model (IPM) that consists of three submodels: mark-resight model, matrix population model, and state-space model for count data. The models use the data collected in the monitoring program in the DB region and quantify the relationships between key red knot (REKN) life history, population dynamics parameters, HSC abundance, and REKN breeding ground snow cover conditions.

There is good empirical data to suggest snow cover can impact shorebird reproductive success. Adding snow cover to the models appears appropriate.

The Panel concludes the proposed IPM for REKN is a significant improvement over the previous model for elucidating the relationship between horseshoe crab abundance and red knot survival. The Panel appreciated that numerous inputs of potential uncertainty were incorporated into the IPM, and hence the ARM. Thus, the analyses are appropriate for use in the ARM Framework. While the multi-stage modeling framework was illuminating, and calculated transition probabilities into mass classes that would meet the thresholds for REKN migration, there was model instability and counterintuitive results, while incorporating recent data (post-2009). Additionally, the multi-state model's instability addressed the need to potentially reassess the 180g cutoff weight. During the review, the WG stated that multiple weight thresholds have been previously assessed in the multi-state framework. The WG mentioned they will be evaluating survival across multiple weight classes within a mark-recapture framework. The Panel encourages this endeavor, as it could provide greater insight into the probability of gaining weight and improve the understanding between REKN survival and weight gain. The Panel encourages the WG to continue exploring the multi-state model that can provide useful information for corroboration purposes with IPM moving forward. Additionally, it is recommended that the WG determine whether recent changes in phenology or persistence patterns of REKN in Delaware Bay have a role in the previous model's poor performance.

The IPM uses REKN annual counts from aerial surveys as one of the model inputs. To standardize annual counts due to yearly differences in survey timing and coverage, corrections to the counts were applied that incorporated both the proportion of the total stopover area surveyed from the air, or ground in the case where ground surveys were used as counts, and the time within the migratory phenology when the survey took place. During the two COVID years (2020 and 2021), counts have been low or very low. During the Review Workshop the WG suggested the low counts may have occurred due to differences in observers, differences in numbers of observers, or differences in coverage. As count data are quickly conveyed to stakeholders, the low counts cause significant concern in the broader conservation community. Thus, the Panel urged the WG to incorporate soon the low counts from the last two years into the full IPM model, to reparameterize the models and hence the utility functions used to determine HSC harvests.

The Panel found it interesting that, although counts were low in 2020 and 2021, the passage population was relatively stable. This was reassuring. However, as stated by a minority opinion, persistence times have been lower in recent years. This suggests that use of Delaware Bay by REKN is more transient than it has been in the past. While the Panel acknowledges the stated goal of the DB-HSC-REKN system has been to stabilize the endangered red knot population, lower persistence suggests potential uncoupling of the relationship between HSC and REKN.

The REKN survival estimates from the IPM were nearly 4% points higher than those reported in a previous, but contemporary, analysis (Tucker et al. 2021) that used a portion of the same

data, with birds observed only on the Delaware beaches and not New Jersey beaches. Both analyses show significant and positive effects of HSC abundances on REKN survival, a result that confirms the results from an earlier paper (McGowan et al. 2011). REKN adult survival from the mark-recapture model of the IPM (without the influence of recruitment) provides estimates that are even higher (94% versus 93%, Table 5 below) than what is reported in the full IPM. Thus, there are three potential contemporary measurements of adult REKN survival (two of which have non-overlapping credible confidence intervals, Table 5) and across the three estimates, there is a range of 12%. This degree of uncertainty should be modeled to determine the impact on lambda for this population, as adult survival, in long-lived species, is the most important life history characteristic that underlies population trajectories. The Panel suggests the WG consider conducting an analysis of the expected value of perfect information (EVPI) to determine the effects of this uncertainty on the decision (see TOR 3 below).

While the majority opinion argued they had investigated the effects of climate change on REKN populations, the Panel argued they investigated one aspect of climate change - snow coverage during 15-30 June in the presumed breeding area. While snow depth was shown to positively impact REKN survival in McGowan et al. (2011), snow coverage, as measured in the ARM Revision, was a non-significant predictor in the IPM. The Panel's view is that climate change can also impact phenology (Smith et al. 2010), and phenology is often a better predictor of breeding productivity than adult survival (Weiser et al., 2018, McGuire et al. 2020). There are other potential effects of climate change on REKN, including, for example, excessive drying effects that can influence survival at any stage of the annual cycle. While the Panel appreciates that one aspect of the potential effects of climate change was incorporated into the IPM, this was done because snow coverage had significant impacts in earlier data series. The Panel urges the WG to not overstate their investigation of general climate change effects and continue to consider how climate change might affect REKN throughout their life history in potentially unexpected ways.

With respect to model weights used in the original ARM Framework, the previous mark-recapture model and competing hypotheses / models allowed for applying weights to hypotheses describing effects of HSC on REKN survival and weight gain. However, these model weights were not updated. The new IPM framework provides a very clear means to update uncertain parameter estimates through learning as more data are collected, rather than relying on competing model weights. The Panel believes the ability to update parameter estimates (e.g., survival and recruitment) as more data are collected should lead to more frequent updates, making the best use of the ARM Framework. The Panel suggests the WG strive to update the parameters frequently, particularly in the short term, to reduce uncertainty in the model and the decisions for HSC harvest.

During the review, the Panel asked if tag loss was an issue. The WG stated tag loss is likely minimal. The current mark-recapture models (multi-state open robust design) include multiple resightings of individuals within and across secondary sampling periods within each year. This bolsters the argument that tag loss is relatively not concerning as it applies to calculating

apparent survival. The Panel commends the WG for the thorough formulation of the mark-recapture model while minimizing violations of model assumptions.

3. Evaluate the adequacy of the fishery-dependent, fishery-independent, and life history data used in the ARM Framework revisions for both horseshoe crabs and red knots, including the use of biomedical data.

The Panel evaluated the fishery-dependent, fishery-independent, and life history data used in the revised ARM Framework and concluded overall they are adequate for use in the ARM Framework.

The Panel recommends the WG continue to evaluate the relationships among the inter-annual variability in timing of the surveys and environmental variables, such as temperature, photoperiod, and salinity, to determine how environmental parameters may influence catchability, and subsequently, influence abundance indices. The Panel recommends the evaluation because a recent acoustic telemetry study demonstrated the timing of horseshoe crab migration between the continental shelf and local estuaries is strongly influenced by the photoperiod and temperature (Bopp et al. 2021). Additionally, the 2020 Virginia Tech Trawl Survey Report indicated catch may be related to the sampling date and temperature (Hallerman and Jiao 2020). Given this information, the Panel recommends the continued evaluation of how the timing of sampling and environmental covariates for all trawl surveys may affect horseshoe crab catch from fisheries-independent data sources through modeling frameworks, such as generalized linear models (GLMs) or generalized additive models (GAMs). The Panel encourages the WG's research recommendation of continued evaluation of potential factors that may be influencing HSC catchability in the VT Survey and other trawl surveys (New Jersey and Delaware).

The Delaware trawl survey has a fixed-station design. The current use of a design-based abundance index is inappropriate for this program. A model-based abundance index needs to be developed for use in the CMSA.

The previous HSC stock assessment and projection models have to rely on some life history parameters from the literature and/or other areas outside of Delaware Bay. The current HSC models remove the need to borrow information from areas outside of Delaware Bay. Use of the local life history information directly from DB improves the stock assessment and projection, making them more reliable and relevant to the DB HSC.

The Panel agreed with an improved new natural mortality estimate (i.e., from 0.27 to now 0.30). The Panel noted both population and operational sex ratios continue to be skewed towards males over time even though it is a male-only fishery and sex ratio is considered 1:1 for juveniles. This may imply possible differences in natural mortality between females and males. The Panel recommends examining individual stations data in the VT survey to examine the spatio-temporal distribution of M:F ratios. The Panel also recommends examining New Jersey survey stations and Delaware survey (fixed) stations sex ratios to evaluate possible shifts of crabs from the New Jersey side of the Bay to the Delaware side. The Panel recommends

evaluating possible differences in natural mortality for primiparous and multiparous HSC between females and males.

The Panel asked if there are different habitat usage between females and males, and the WG suggests generally no differences, although males tend to arrive earlier and stay longer than females on spawning beaches.

During the review the Panel asked the WG to conduct a correlation analysis to evaluate relationships between abundance indices derived from different surveys. Moderately strong correlations were found between survey programs, which explains why the CSMA estimates are robust to different weighting schemes for the three programs.

The WG provided information about the proportion of positive tows for the three survey programs. The plots show no obvious temporal patterns, suggesting no large shifts in the spatial distribution of the DB-origin HSC over the study time. This suggests the current survey coverage and design may be adequate.

The Panel commends the WG on the efforts to identify variables influencing HSC fishery discards and develop models to yield the HSC discard estimates. The Panel considers the discard estimates used in the current assessment to be greatly improved from previous assessments.

The Panel evaluated the revised HSC-REKN ARM Decision Model, including the estimation and projections models for both HSC and red knots, harvest functions and reward function, and its parameterization and optimization. The Panel concludes the revised ARM Framework is suitable for use in making HSC management recommendations.

The original ARM Framework for HSC-REKN (2009) was based on an objective statement that included objectives related to HSC harvest and maintaining adequate stopover habitat for shorebirds. The Panel commends the WG on updating the objective statement to reflect concerns specifically related to ensuring that HSC management does not affect the recovery of the REKN population. This provides specific guidance for building the utility and reward functions and also maintains an explicit link to the modeling efforts conducted for both species.

In the ARM Revision, the WG decided to abandon the use of the Adaptive Stochastic Dynamic Programming (ASDP) software because it was antiquated and constrained the use of an HSC projection model that mirrors the CSMA assessment model. The Panel agrees the ASDP software should no longer be used because of these concerns. As a replacement, the WG is now using Approximate Dynamic Programming (ADP), coded in R software. ADP appears to be an excellent choice. The method does not constrain the optimization to competing REKN models, and it allows the user to create a projection model for HSC that makes use of the same framework as the assessment model, accounting for the time lag between birth and recruitment to the spawning population. Importantly, this new approach to optimization allows for the evaluation of a continuous range of harvest recommendations for both male and female HSC, much preferred to the five previous harvest packages from the original ARM. During the

review, the WG elaborated on the choice of ADP and described the conversations that were held with an expert in optimization methods. The Panel believes the change from ASDP to ADP will provide the WG with more flexibility in optimization and evaluation of the effects of uncertainty in demographic parameters for both species.

The results of sensitivity analyses provided in the ARM Revision Report, as well as additional analyses conducted during the review workshop, suggest that decisions for HSC harvest management are affected by uncertainties in demographics of both species. As described above, the projection of HSC abundance into the future appears to be affected a great deal by the value and associated uncertainty around the recruitment parameter. In addition, uncertainty exists in the estimates of survival and recruitment for REKN, as well as the effects of HSC abundance on these parameters. The Panel therefore suggests the WG explore the use of expected value of perfect information (EVPI) to evaluate the implications of uncertainties on decisions for HSC harvest, especially as it pertains to REKN survival and recruitment. The Panel and WG discussed potential methods for applying EVPI to continuous parameters, such as breaking the distribution up into ranges representing “high” and “low” values, similar to a multi-model approach. Ultimately, the Panel’s concern relates to ensuring that harvest decisions for HSC truly account for uncertainties in the input parameters for the projection models. The Panel recommends exploration of EVPI as a long term task for WG consideration.

In addition to sensitivity and EVPI analyses, the Panel suggests the new reward and utility functions be fully considered in terms of the values they represent. The Walsh minority report suggested the new utility function for REKN does not reflect the values of the original stakeholder group from the 2009 ARM process, arguing the new utility function will allow for the immediate resumption of harvest of female HSC. In the original ARM Framework, REKN concerns were incorporated as a constraint within the utility function for harvest of female HSC, effectively setting harvest to zero if the REKN population was predicted to be less than 81,900 or HSC abundance was less than 11.2 million. This has led to no harvest of female HSC since implementation of the Framework. There are two components to the new reward and utility functions that are different and lead to increased harvest of female HSC. First, the new reward function includes an explicit utility function for REKN (u_r). The utility function remains at zero until REKN abundance reaches 90% of the threshold value established for REKN. At this point, the utility score increases linearly until it reaches one when REKN abundance reaches the threshold value. The Panel agrees with the WG that the knife-edge effect of the constraint from the prior version of the ARM was not preferable, and including the new utility function that allows for an increase in female HSC harvest with an increase in REKN abundance makes more sense. The Panel believes the change is helpful and the new utility function for REKN does not in itself lead to the immediate resumption of female HSC harvest, as suggested in the minority report.

The second component that differs from the original ARM Framework is the reward function, which now leads to immediate resumption of female HSC harvest. The new reward function includes a combined utility for male and female HSC harvest (similar to the original reward function), as well as a utility for REKN abundance, and leads to greater rewards when HSC

harvest and REKN abundance are both high. However, this new reward function also allows for female harvest even when the REKN utility is zero. Because the changes would lead to harvest of female HSC, which has been restricted since the implementation of the original ARM Framework, the Panel cautions the WG to fully consider if the new reward function truly represents the values articulated by stakeholders in the 2009 ARM Framework. The previous reward function was a knife-edge function, and effectively acted as a harvest control rule. Therefore, the Panel believes a change in the reward function to allow for gradual increases in female harvest is likely preferable. Furthermore, the Panel recognizes the form of the reward and utility functions are value judgements, and for this ARM revision the WG was not able to convene a group of stakeholders that would represent all interests (e.g., HSC harvesters, biomedical industry, conservationists, etc.). Therefore, the Panel believes the aforementioned EVPI analyses will allow the WG to more fully consider the implications of the changes and weigh the opinions of stakeholders of different interests. Overall, the Panel does not disagree with the WG's approach to revising the functions, as long as they truly reflect the objectives related to HSC harvest and REKN recovery and the risk associated with HSC harvest.

The Panel recommends the WG strive to update the assessment models for both species on an annual basis in the near term, particularly in light of the low REKN counts during the recent COVID years, with updates carried through the decision model. Given the sensitivity of the projection models for both species to estimates of sex-specific recruitment, frequent updates will allow for immediate incorporation of new data that likely can reduce uncertainty around the estimates. In addition, the Panel recommends updating the optimization model every 5 to 10 years after the initial short term updates.

The Panel agrees with the WG that egg survey measures conducted on the New Jersey shoreline of DB may not accurately capture the number of available eggs for REKN because of high-quality habitat loss confounding egg-density comparisons (WG rebuttal to Niles comment #4; Botton et al. 2021). The Panel also agrees with the WG that quality of spawning beaches changes over time due natural processes (i.e., longshore drift, erosion, sand migration) and hence, may potentially result in low interannual site fidelity and/or shifting distributions of spawning horseshoe crabs. In a previous study, interannual site fidelity was low, as most crabs did not return to their original tagging beach within Pleasant Bay, Massachusetts, but most crabs returned within 2.5 km of their original release location in subsequent years (James-Pirri 2010).

Another complication of relating HSC egg densities to HSC abundance is due to differences in temporal sampling that may not completely capture peak egg densities as discussed by the WG in rebuttal to Niles comment #4. Given these nuances and implications, the Panel understands the challenge of incorporating egg data into the IPM framework. However, the Panel recommends additional work examining the temporal and spatial link between egg densities and REKN (survival and abundance). HSC egg density should be explored further with existing and future data given these linkages are strong and HSC egg availability directly impacts REKN population dynamics (Michael-Haramis et al. 2007; Takahashi et al. 2021). The Panel recommends that interannual site fidelity of tagged horseshoe crabs be evaluated in both the

Delaware and New Jersey shorelines in the long-term. Understanding interannual site fidelity could facilitate the identification of high-quality spawning habitats (James-Pirri 2005) and in turn, can prioritize spawning beaches to sample on an annual basis for egg surveys despite ongoing habitat loss. Furthermore, the Panel acknowledges that changing beach characteristics can affect where HSC spawning occurs (Jackson et al 2005; Smith et al. 2011) and therefore, may affect the distribution of egg densities. However, the Panel is not aware of the impact of beach migration on the spatial distribution of HSC eggs. The WG mentioned this in its rebuttal to Niles comment #4 as a potential challenge of adequately accounting for spatial variability in egg densities. The Panel recommends the relationship between beach migration and the spatial distribution of HSC egg densities be evaluated in the long-term.

4. Develop recommendations for improving assessment methodology and data collection.

Short term

- The ARM Revision is greatly improved, including: refinement of the objective statement, the new DB HSC stock assessment and projection models, and the new REKN IPM model, that allows for easier and more frequent updating. The Panel recommends the WG regularly update the assessment and projection models to further reduce uncertainties with additional data and information. The Panel recommends the ARM data be updated sooner than later (3 years or less) as new data become available, notably when the Delaware and New Jersey trawl surveys collect new stage data to improve the estimation of HSC recruitment dynamics. The Panel also recommends the ARM Framework be revisited every 5-10 years for possible revision to account for dynamic changes in the ecosystem.
- The Panel recommends the full time series of recruitment estimates (i.e., 2003-2019) or recruitment estimates in years when the VT HSC survey data are available be used in the simulation model to project future DB HSC stock dynamics for use in the ARM Framework. The Panel suggests the WG re-run the model and incorporate the new results in the ARM Revision report.
- The Panel highlights the importance of the VT HSC survey for monitoring the population dynamics of the DB HSC stock and for providing reliable estimates of recruitment for projections in the ARM Framework. The Panel recommends continuing funding the VT HSC survey. However, with more data available, the Panel encourages a simulation study be done to evaluate the performance of current survey design in capturing the DB HSC stock dynamics. A simulation could also potentially identify a more cost-effective survey program to ensure the quality of the survey abundance indices.
- The Panel considers it is necessary to develop a model-based abundance index for the DB Trawl survey because it follows a fixed station design. A design-based abundance index is inappropriate.
- The Panel recommends the WG expand on the HSC spawning survey methodology and briefly explain how percent female spawning was estimated in the main text of the revised ARM report to provide readers with greater transparency and clarity. The Panel knows the estimation of the proportion of spawning female HSCs was obtained through

indices of spawning abundance from HSC spawning surveys, but little information is presented on how these data were obtained. The Panel also desires clarification on differences in the duration cutoffs and methodologies between the revised ARM Framework and Tucker et al. (2019) for defining the proportion of female HSCs available to REKN. The revised ARM Framework estimates the proportion of available spawning HSCs based on cumulative spawning density by the end of May divided by the total female density for that given year. Whereas, Tucker et al. (2019) defined HSC egg availability to shorebirds as the proportion of total spawning activity that occurred by the 95% arrival cutoff date for each species (HSC and REKN) in each year. The Panel also recommends that data for the proportion of HSC availability and REKN cumulative arrival be presented in either a table or figure from 2003-2019 (i.e., Figure 2 from Tucker et al. 2019) in the revised ARM report to provide context of interannual differences in REKN arrival and HSC spawning availability.

- The new utility and harvest functions are a representation of values, and the Panel understands that convening a group of stakeholders for this revision was not possible. Therefore, the Panel recommends the WG fully consider whether the new utility and harvest functions represent stakeholder values as articulated in 2009.

Long term

- The ARM Framework tends to be most sensitive to recruitment dynamics for both species. Although the recruitment dynamics are currently quantified with large uncertainty because of the short time period and missing years of data, the interannual variability in recruitment will be better understood when more data become available. The Panel encourages the WG to regularly update the model runs and new information when it becomes available to continue improving the estimates of recruitment dynamics for both species in the ARM Framework.
- Continue monitoring natural mortality from tagging data within the Delaware Bay region. The Panel appreciates and commends the WG for updating the natural mortality estimate for adult horseshoe crabs. However, it is unlikely that natural mortality is constant across all age stages post-maturation. The WG should consider recording post-maturation age group data based on carapace wear, epibionts, and mating scar criteria defined by Botton et al. (2021) in order to estimate age group-specific mortality estimates. Preliminary mark-recapture results from Cormack-Jolly-Seber and multi-state models indicate the oldest age group has 25% lower average survival compared to the youngest adult age group in Massachusetts (Bopp et al., in prep). In the more immediate future, exploring differences in natural mortality among primiparous and multiparous crabs would be beneficial for obtaining age-group specific mortality estimates that could be incorporated into the CMSA model to obtain more accurate abundance estimates.
- Conduct habitat suitability index modeling for primiparous and multiparous HSC for both males and females to examine spatio-temporal variability in suitable habitat
- Conduct species distribution modeling to examine spatio-temporal changes in distributions of primiparous and multiparous female and male HSC.

- The Panel agrees the amount of suitable spawning habitat should be quantified and monitored over time. The Panel encourages the monitoring of available fringe marsh habitat, in addition to spawning habitats, throughout DB. Over the past two decades, there is increasing evidence that juvenile horseshoe crabs heavily depend on salt marsh food webs for nutritional needs (Carmichael et al. 2004; Bopp et al., in prep) and often occupy salt marsh fringe habitats adjacent to spawning beaches (Bopp, personal communication). Therefore, changes in the availability of salt marsh fringe habitat in the future may affect HSC recruitment dynamics, especially with sea-level rise impacts associated with climate change.
- The Panel suggests the WG consider future HSC spawning habitat availability, its temporal dynamics, and how it may be associated with SLR and effects on recruitment.
- Evaluate phenology of horseshoe crab migration into Delaware Bay with more contemporary tools, such as satellite tags or acoustic telemetry. Understanding migration timing could improve understanding of temporal implications of trawl survey timing and HSC abundance index inference, as well as the timing of HSC spawning migrations relative to REKN arrival. Acoustic receiver arrays are currently operational within Delaware Bay (Delaware F&W; David Secor, UMCES; Secor et al. 2020).
- The Panel recommends the WG further explore the proportion of mature female HSCs based on egg presence/absence at various size ranges above the 180mm threshold to better understand size-at-maturity for females. The Panel also recommends periodic evaluation because climate change and harvesting may exert different selection pressures on HSC for earlier reproduction.
- The Panel recommends that the WG explore the use of expected value of perfect information (EVPI) to evaluate the effects of uncertainties in REKN and HSC dynamics on harvest decisions.

Data collection

- Develop a survey targeting older juvenile horseshoe crabs within the subtidal zone to enhance the understanding of HSC recruitment. The population dynamics and habitat use of juveniles (age 5-9) remains elusive within the literature, with the exception of the population in Pleasant Bay, MA.
- Expand horseshoe crab tagging efforts throughout the US East Coast, particularly in North Carolina, to ameliorate movement and population exchange patterns adjacent to DB. North Carolina has the lowest tagging effort (by tagged individuals and resighting effort) out of any U.S. state on the East Coast. There is limited information regarding the migratory exchange between North Carolina and Delaware Bay that is also the boundary between stock units (ASMFC 2019). A greater understanding of movement to/from North Carolina would be useful to understand the origin of Delaware Bay crabs.
- The Panel encourages the WG to continue exploring the apparent lack of relationship between HSC egg densities measured by beach surveys and REKN survival. In a recent study by Takahashi et al. (2021), a positive correlation between number of foraging shorebirds (including red knot) and HSC eggs were found in the Cape Romain-Santee Delta Region, South Carolina. The authors found 95% of the samples tested had DNA

from HSC eggs in a molecular analysis of shorebird fecal samples. Similar work can be done for the DB area to evaluate the spatio-temporal overlap between HSC and REKN, and analyze fecal samples. In New Jersey, there is also ongoing work evaluating the spatial (cross-shore and along-shore) and temporal patterns in shorebird distribution in relation to horseshoe crab eggs (Daphne Munroe, Rutgers, <https://njseagrant.org/research/research-projects/>). The Panel recommends the WG evaluate the results and methodologies of this project to determine if the sampling design could be feasible for a large-scale implementation of HSC egg sampling throughout DB.

5. If a minority report has been submitted, review minority opinion(s) and associated analyses. If possible, make recommendations on current or future use of alternative approaches presented in minority report(s).

The Panel evaluated two minority opinions.

Niles minority opinion

Niles argued egg densities in New Jersey have not increased over the past two decades and currently remain below historic abundances. The WG majority stated incorporating egg densities would be inappropriate at this time given the difficulty of addressing spatial and temporal variability of eggs and inconsistent methodologies between the New Jersey and Delaware egg density surveys. Additionally, the WG majority stated the New Jersey shoreline areas sampled in egg surveys have experienced habitat loss since the 1980s and may not be representative of available habitat elsewhere in the Delaware Bay. The Panel agrees with the WG majority that the lack of interannual site fidelity at spawning beaches (James-Pirri 2005) and shifts in habitat use based on geomorphology makes comparing the relationship between egg densities and HSC densities difficult. Recent work conducted by Botton et al. (2021) demonstrated there was a weak relationship among egg densities sampled from short (5cm) and long (20cm) cores and HSC spawning indices on spawning beaches in Jamaica Bay, New York. James-Pirri (2005) also found a weak relationship between HSC spawning indices and egg densities in Cape Cod, MA. Given these implications, spatial patchiness of egg densities, weak relationships, and high uncertainty the Panel understands why the WG did not incorporate egg densities into the ARM Framework. However, the Panel recommends the mismatch between egg sampling (i.e. short vs. deep sediment cores) and horseshoe crab spawning abundance be explored further because HSC eggs are a crucial food source for REKN. A recent study (Takahashi et al. 2021) found a strong correlation between REKN abundance and HSC egg densities in South Carolina.

Niles stated the inclusion of the Delaware and New Jersey trawl surveys are not directed at HSC and argued the use of only five years of data introduced bias into the CMSA (concern #6). The WG majority re-evaluated the surveys and argued they reliably catch HSC and are important to include during years when the VT trawl survey did not occur (2012-2015). The WG group also used the full time-series of the New Jersey and Delaware trawl survey (2003-2019) that is much longer than five years. For the most part, the Panel agrees with the WG that the New Jersey

and Delaware surveys can reliably track HSC abundance. However, the Panel recommends the Delaware trawl survey transition from a fixed-station to design based (random stratified sampling) survey because fixed-station surveys may not be adequately accounting for shifts in HSC spatial distribution across habitats or strata (i.e., depth).

Walsh minority opinion

The Walsh minority opinion described three concerns with the majority report: 1) the VT survey should be more heavily weighted in the CMSA, 2) the new utility function does not accurately represent the original intentions of the ARM process, and 3) given the desire to change the utility function, the WG should include broader stakeholder engagement and input to develop the utility and reward functions.

On point number 1, the Panel described for TOR 1 that applying equal weights to the three surveys is acceptable for the HSC CMSA. The Panel agreed with the WG that the Conn method would be inappropriate for devising survey weights, and furthermore requested the WG provide results for HSC estimates when weighting the surveys according to spatial coverage. The WG provided results of such a weighting scheme (Table 1) that indicated CMSA results were robust to such changes in survey weight. Based on the sensitivity analyses, the Panel concludes that equal weighting of the three survey programs in the CMSA is adequate.

Points 2 and 3 of the Walsh minority report describe concerns related to the utility function and whether the function accurately represents stakeholder desires. Walsh describes a number of concerns with the change in terms of structured decision making and risk related to REKN abundance. The ARM revision includes a change to the harvest function such that REKN population abundance has its own utility function, rather than being treated as a constraint to female HSC harvest. This utility function leads to less of a knife-edge outcome for female harvest that was all or nothing in the prior ARM Framework, although female harvest has never been recommended. The majority response describes in more detail the reasons for discontinuing the use of the original reward function, notably that the original function was deemed inappropriate. The Panel suggests the utility function itself does not lead to immediate resumption of female HSC harvest, as suggested in the minority report, but rather the new harvest function that includes utilities for HSC harvest and REKN abundance does lead to female HSC harvest.

The minority report suggests there are uncertainties that still plague the system that would potentially affect harvest management outcomes, such as recruitment of HSC. The Panel did suggest to the WG to use the entire time series of data for recruitment in the projection model for HSC because it encompasses a broader range of values and uncertainty (TOR 1 above). The Panel agrees uncertainty can affect harvest management outcomes, and therefore in TOR 3 suggested the WG evaluate the effects of key uncertainties through EVPI or sensitivity analyses. However, the Panel also understands the inability of the WG to convene a truly representative group of stakeholders for this revision, and therefore also recommended the WG use the outcomes of the sensitivity analyses to confirm the harvest function itself does truly represent the previously-articulated desires of stakeholders from the original ARM Framework (2009).

Overall, the Panel agrees with the majority response that reformulating the utility and harvest functions was necessary, given other updates to the modeling framework, and that the new models will lead to faster updates to reduce uncertainty than in the previous ARM Framework. The Panel simply cautions the WG to consider the effects of uncertainties on HSC management recommendations to ensure the current functions do adequately represent stakeholder concerns.

6. Prepare a Review Panel Report summarizing the Panel’s evaluation of the ARM revision and addressing each review term of reference. Develop a list of tasks to be completed following the workshop. Complete and submit the report within four weeks of workshop conclusion.

The Panel reviewed all materials provided by the WG and was given 13 presentations during the review. The Panel had a constructive discussion after each presentation with the WG. Based on the review and all the discussions, the Panel prepares this Review Panel Report summarizing the Panel’s evaluation of the ARM revision with respect to a set of TORs predefined for the Panel.

The Panel recommends the following tasks for the WG to consider before the January 2021 horseshoe crab fishery management board meeting:

- The full time series of recruitment estimates (i.e., 2003-2019) or recruitments for years when the VT HSC survey data are available are used in the simulation model to project future DB HSC stock dynamics for use in the ARM Framework and update the report accordingly.
- A model-based abundance index is developed for the Delaware trawl survey.
- The results of sensitivity analysis conducted during the review for different weighting schemes, increased discard mortality, and different proportions of DB-origin HSC in Virginia and Maryland are included in Tables 18 and 19 of the ARM Revision Report.
- The Panel encourages the WG to review the research recommendations (ToR 4) to develop a list of tasks to be included in the final report for further improvement of the ARM Revision parameterization.

Advisory Section

Status of Stocks: Current and projected

A Catch Multiple Survey Analysis (CMSA) model was used to assess the Delaware Bay HSC stock in the 2021 ARM Revision. The stock assessment covers the time duration from 2003 to 2019 and was done separately for females and males. The adult HSC abundance in 2019 is in high and stable condition for both females (Table 1) and males (Table 2). Fishing mortality is low ($\leq 1\%$) for both females (Table 1) and males. No limit biological reference points have been developed for stock abundance and fishing mortality. Thus, no conclusion can be made about “overfishing” and “overfished” status. However, given the stock abundance being much higher and fishing mortality lower in 2019 than in 2003, the 2019 Delaware HSC stock is unlikely to have a status

of “overfished” and “overfishing” for both females and males. The CMSA-estimated abundance and fishing mortality tend to be robust with different model parameterizations (Table 3), suggesting the derived stock status is robust to uncertainty.

A new HSC projection model, parameterized with the information derived from the CMSA stock assessment and studies of the Delaware Bay HSC stock, was developed in the 2021 ARM Revision. The projected future HSC stock abundance tends to be sensitive to the assumed future recruitment dynamics. There is large uncertainty for the years of 2013-2016 when the VT survey was not conducted, leading to large uncertainty in stock abundance estimates in the CMSA assessment (Figure 3), resulting in large variability in the projected HSC stock abundance for both females and males. The uncertainty associated with the projection will become smaller when more years of data become available to the CMSA stock assessment.

Stock Identification and Distribution

The ASMFC manages HSC from Maine to eastern Florida. Genetics, isotope analyses, and tagging data suggest the horseshoe crab population is composed of multiple units, some distributed across multiple states and others embayment-specific that are linked to varying degrees. This ARM Revision focuses on the Delaware Bay Region, although more studies are needed to better define the Delaware Bay stock, in particular, the HSC in the New York region.

Management Unit

The ARM Revision focuses on the Delaware Bay stock, including all of the catch in Delaware Bay and portions of the catch in Maryland and Virginia.

Landings

The commercial bait fishery consists primarily of trawl, hand harvest, and dredge fisheries. Since 1998, ASMFC has compiled landings by state in the annual FMP review report. The horseshoe crab fishery supplies bait for the American eel (*Anguilla rostrata*), conch (Buccinidae) and, to a lesser degree, catfish (Ictaluridae) fisheries. The American eel pot fishery prefers female horseshoe crabs to males, while the conch pot fishery uses both male and female horseshoe crabs. Most fishing effort for horseshoe crabs is concentrated within the mid-Atlantic coastal waters and adjacent federal waters. Since 1998, states have been required to report annual landings to ASMFC through the compliance reporting process. Landings used in this assessment for 2003 through 2019 were validated by state agencies through the Atlantic Coastal Cooperative Statistics Program (ACCSP). Harvest levels for the Delaware Bay region states have been set using the ARM Framework since Addendum VII (ASMFC 2012) and have constrained harvest in the region to 500,000 male-only crabs since its implementation.

The current ASMFC state quota for New Jersey is 162,136 male horseshoe crabs. However, since 2006 a moratorium has been in place on the harvest of horseshoe crabs and horseshoe crab eggs in the state. Delaware’s annual horseshoe crab harvest is determined in accordance with the annual sex-specific allocations identified in Addendum VII to the FMP. The current

quota for the state of Delaware is 162,136 male horseshoe crabs. The annual quota of horseshoe crabs for the commercial fishery in Maryland currently is 255,980 male crabs. There is no female harvest permitted. The current quota for Virginia is 172,828 horseshoe crabs, although the harvest is male-only east of the COLREGS line and limited to 81,331 horseshoe crabs.

Total bait landings in the Delaware Bay were relatively high in the late-1990s, decreased through the early-2000s, and have remained relatively stable through 2019 (Figure 1). Horseshoe crab harvest by sex has varied through time, reflecting the management shift to male-only harvest in the region with the implementation of the ARM model in 2013 (Figure 1).

Bait landings for the Delaware Bay states were developed to support the CMSA model for that region using only Delaware Bay-origin crabs. Horseshoe crab landings from New Jersey and Delaware are considered to be 100% Delaware Bay-origin (i.e., spawned at least once in Delaware Bay) whereas 45% of Maryland's harvest and 20% of Virginia's are believed to be Delaware Bay-origin based on genetic data and analysis. These percentages were applied to the Delaware Bay states' bait harvest.

Data and Assessment

The CMSA model was used for the Delaware Bay HSC stock. The stock assessment covers the time period from 2003 to 2019. The CMSA model uses catch data (commercial landings, bycatch mortality, and biomedical mortality) and abundance indices derived from the three fishery-independent survey programs (i.e., Virginia Tech HSC Trawl Survey, New Jersey Ocean Trawl Survey, and Delaware Adult Trawl Survey) to estimate the primiparous and multiparous abundances for both females and males. The results were not used for stock status determination but are recommended for use in the HSC projection model in the ARM Revision for providing management advice.

Biological Reference Points

There are no model-based biological reference points accepted for management use for horseshoe crab. There is no specific information in this ARM Revision on biological reference points for the Delaware Bay HSC stock.

Fishing Mortality

CMSA results indicate reduced fishing mortality from 2003 to 2019 and low fishing mortality for both female and male horseshoe crabs in Delaware Bay in recent years (Figure 2).

Recruitment

CMSA model estimates for both female and male primiparous horseshoe crabs indicate slightly higher recruitment than the average recruitment during 2017-2019 but the estimates are uncertain due to missing Virginia Tech survey data for 2013-2016 (Figure 3). No other direct information about recruitment is available.

Spawning Stock Biomass

CMSA-estimated primiparous and multiparous female abundance in Delaware Bay increases over time and is at a relatively high level in recent years (Figure 3).

Bycatch

The commercial dead discard estimates were updated following the previous peer review panel's comments and the revised values were used in this CMSA in addition to coastwide biomedical data, not Delaware Bay-specific biomedical data. After examining the NEFOP and ACCSP data in finer detail as recommended by the 2019 peer review panel, the data used in the analysis were filtered to include six statistical areas, and more specific gear categories generalized into trawl, gill nets, and dredges, and limited to fishery species targeted and landed. Calculating discard ratios annually by gear resulted in the best discard estimates. Following data filtering, NEFOP observer data were used to develop annual ratios of observed discarded horseshoe crab to observed landings of all species by gill nets, bottom trawls, and dredges from the statistical areas within for 2004-2019. Ratios were then applied to reported gill net, bottom trawl, and dredge landings of all species from those areas for 2004-2019 as queried from the ACCSP warehouse to estimate total discards of horseshoe crab.

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Table 1. Catch multiple survey analysis female horseshoe crab model outputs: q =catchability coefficients; R =primiparous abundance; N =multiparous abundance; μ =exploitation rate; Z =

instantaneous total mortality rate; A =annual mortality rate; and F =instantaneous fishing mortality rate.

Year	R	N	$R+N$	μ	Z	A	F
2003	1,544,840	5,070,510	6,615,350	0.035	0.341	0.289	0.041
2004	1,177,750	4,703,120	5,880,870	0.023	0.327	0.279	0.027
2005	413,385	4,240,680	4,654,065	0.028	0.333	0.283	0.033
2006	579,474	3,336,020	3,915,494	0.030	0.336	0.285	0.035
2007	2,334,590	2,799,440	5,134,030	0.018	0.321	0.274	0.021
2008	1,430,330	3,725,280	5,155,610	0.014	0.316	0.271	0.016
2009	1,249,240	3,759,070	5,008,310	0.015	0.317	0.272	0.017
2010	832,049	3,646,940	4,478,989	0.017	0.320	0.274	0.020
2011	1,834,400	3,253,520	5,087,920	0.016	0.319	0.273	0.019
2012	761,074	3,699,160	4,460,234	0.018	0.322	0.275	0.022
2013	9,366,720	3,233,560	12,600,280	0.005	0.306	0.263	0.006
2014	162,355	9,283,060	9,445,415	0.006	0.307	0.264	0.007
2015	3	6,950,580	6,950,583	0.008	0.309	0.266	0.009
2016	7,837,230	5,104,220	12,941,450	0.007	0.308	0.265	0.008
2017	2,004,180	9,513,410	11,517,590	0.006	0.307	0.265	0.007
2018	1,757,930	8,471,280	10,229,210	0.005	0.306	0.264	0.006
2019	2,247,290	7,533,500	9,780,790				
Average	2,090,167	5,195,491	7,285,658	0.016	0.318	0.273	0.018

q_{DE}	1.44E-07
q_{NJ}	3.81E-07

Table 2. Catch multiple survey analysis male horseshoe crab model outputs: q =catchability coefficients; R =primiparous abundance; N =multiparous abundance; μ =exploitation rate; Z = instantaneous total mortality rate; A =annual mortality rate; and F =instantaneous fishing mortality rate.

Year	R	N	$R+N$	μ	Z	A	F
2003	554,656	14,640,000	15,194,656	0.026	0.331	0.282	0.031
2004	81,794	10,915,400	10,997,194	0.017	0.320	0.274	0.020
2005	879,707	7,981,570	8,861,277	0.028	0.333	0.283	0.032
2006	841,100	6,353,920	7,195,020	0.025	0.329	0.280	0.029
2007	4,949,330	5,177,700	10,127,030	0.017	0.320	0.274	0.020
2008	3,433,970	7,350,140	10,784,110	0.018	0.322	0.275	0.021
2009	778,775	7,819,010	8,597,785	0.028	0.333	0.283	0.033
2010	870,926	6,161,840	7,032,766	0.026	0.331	0.282	0.031
2011	3,644,500	5,050,080	8,694,580	0.030	0.335	0.285	0.035
2012	739,524	6,219,030	6,958,554	0.032	0.337	0.286	0.037
2013	8,581,000	4,965,740	13,546,740	0.025	0.330	0.281	0.030
2014	14,922,600	9,742,110	24,664,710	0.013	0.315	0.270	0.015
2015	29	17,997,700	17,997,729	0.013	0.315	0.271	0.015
2016	29,623,200	13,128,900	42,752,100	0.007	0.308	0.265	0.008
2017	3,707,470	31,420,800	35,128,270	0.012	0.314	0.269	0.014
2018	1,645,680	25,665,300	27,310,980	0.009	0.310	0.267	0.010
2019	3,901,880	20,031,800	23,933,680				
Average	4,656,244	11,801,238	16,457,481	0.020	0.324	0.277	0.024

q_{DE}	6.97E-08
q_{NJ}	1.89E-07

Table 3. Sensitivity runs for the catch multiple survey analysis model for female horseshoe crabs. All runs that included CONFIDENTIAL biomedical data have been removed.

Name	M	λ			Biomed	Discard Mortality			Starting Values				Terminal Output Values			
		VT	DE	NJ		Dredge	Trawl	Gill Nets	R	N	q_{de}	q_{nj}	NegL	R'	N'	F
Modeling Base Run	0.3	1	1	1	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	87.9	2,247,290	7,533,500	0.006
M	0.274	1	1	1	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	86.5	2,204,475	7,834,127	0.006
Discard	0.3	1	1	1	Coastwide 15%	5%	5%	5%	14.1	15.5	-15.3	-14.3	87.9	2,247,210	7,533,130	0.006
Discard	0.3	1	1	1	Coastwide 15%	12%	12%	12%	14.1	15.5	-15.3	-14.3	88.1	2,251,259	7,511,908	0.007
Discard	0.3	1	1	1	Coastwide 15%	50%	50%	50%	14.1	15.5	-15.3	-14.3	89.3	2,278,436	7,385,285	0.015
No NJ OT	0.3	1	1	0	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	66.8	2,039,061	7,572,244	0.006
Biomed	0.3	1	1	1	0% mortality	5%	5%	12%	14.1	15.5	-15.3	-14.3	87.6	2,242,272	7,564,675	0.002
Real (DB) Base Run	0.3	1	1	1	Delaware Bay 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	Confidential			

Table 4. Sensitivity runs for the catch multiple survey analysis model for male horseshoe crabs. All runs that included CONFIDENTIAL biomedical data have been removed.

Name	M	λ			Biomed	Discard Mortality			Starting Values				Terminal Output Values			
		VT	DE	NJ		Dredge	Trawl	Gill Nets	R	N	q_de	q_nj	NegLL	R	N	F
Modeling Base Run	0.3	1	1	1	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	131.3	3,901,880	20,031,800	0.010
M	0.274	1	1	1	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	127.8	3,863,175	20,707,365	0.010
Discard	0.3	1	1	1	Coastwide 15%	5%	5%	5%	14.2	16.4	-15.8	-15.2	131.3	3,902,001	20,035,174	0.010
Discard	0.3	1	1	1	Coastwide 15%	12%	12%	12%	14.2	16.4	-15.8	-15.2	131.6	3,902,001	20,015,149	0.011
Discard	0.3	1	1	1	Coastwide 15%	50%	50%	50%	14.2	16.4	-15.8	-15.2	132.9	3,913,724	19,955,194	0.015
No NJ OT	0.3	1	1	0	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	105.7	3,741,511	20,957,350	0.009
Biomed	0.3	1	1	1	0% mortality	5%	5%	12%	14.2	16.4	-15.8	-15.2	130.8	3,898,101	20,055,219	0.008
Real (DB) Base Run	0.3	1	1	1	Delaware Bay 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	Confidential			

Table 5. Three estimates of apparent adult survival plus credible confidence intervals derived from contemporary studies (2005-2018) of resighting Red Knot in the Delaware Bay region.

Data	Apparent survival	Source (method)
Adult encounter histories from Delaware beaches, N = 10,058	0.89 (0.84-0.92)	Tucker et al. 2021 (Open robust design)
Adult encounter histories from all Delaware Bay beaches, N = 12,134	0.93 (0.90-0.96)	Sweka et al. 2021 (IPM, integrating robust design with aerial and ground counts for use as fecundity measures)
Adult encounter histories from all Delaware Bay beaches, N = 12,134	0.94 (0.92, 0.97)	A. Tucker additional analyses (Open robust design)

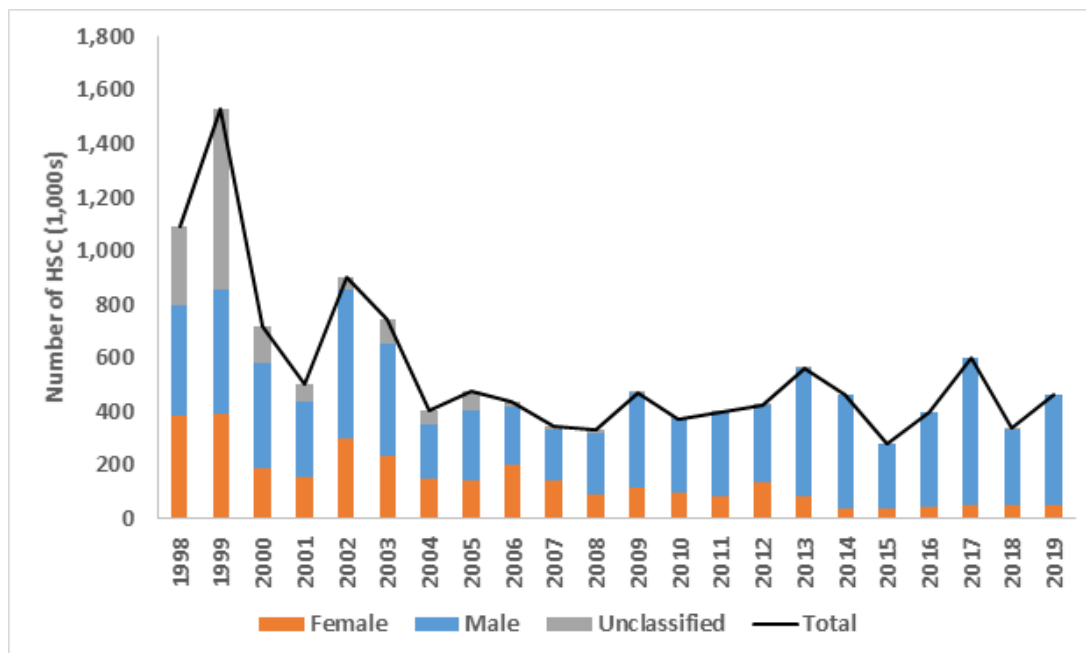


Figure 1. Commercial bait harvest of horseshoe crabs in the Delaware Bay region by sex (Source: ACCSP).

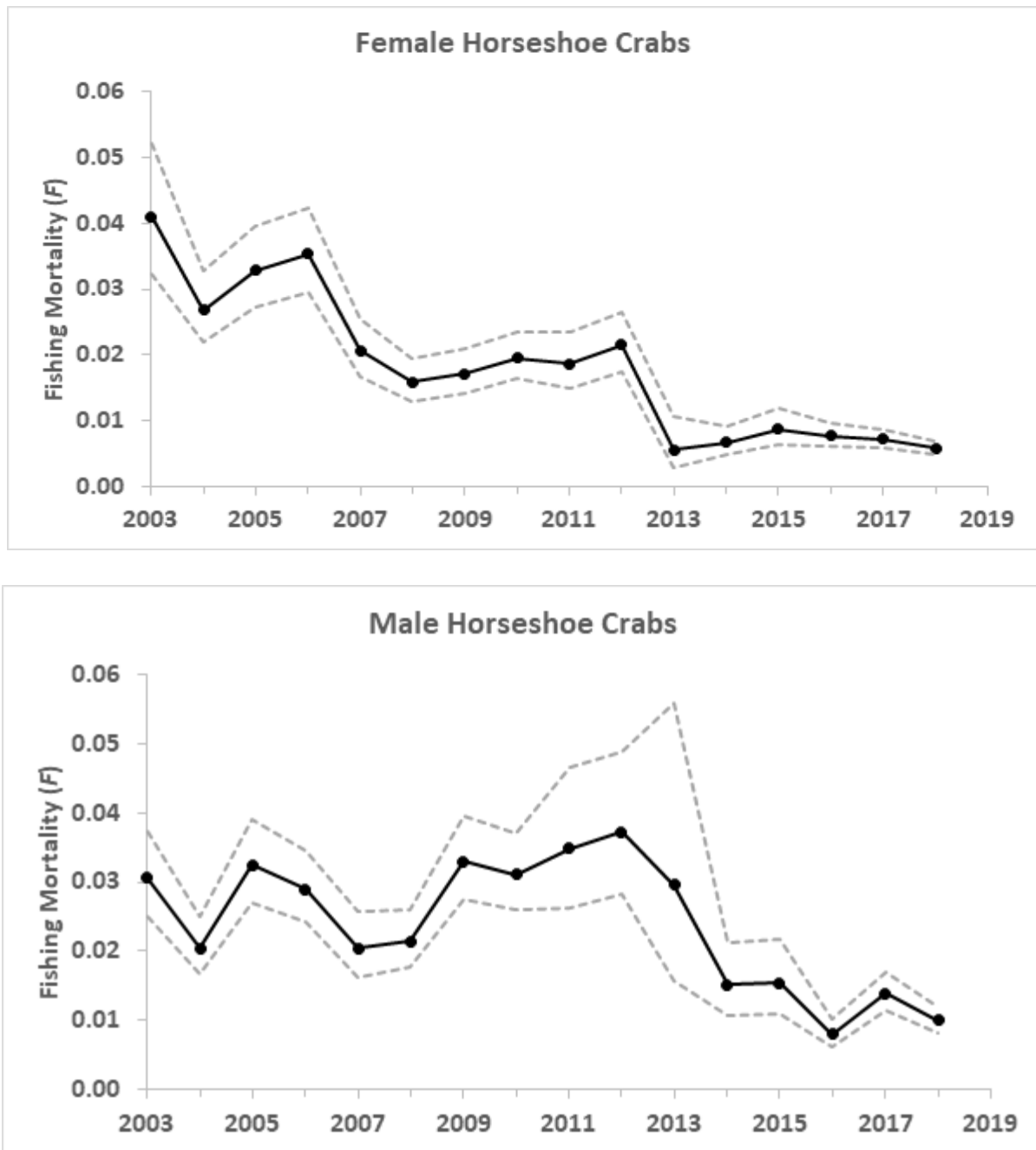


Figure 2. CMSA model estimates instantaneous fishing mortality rate (F) with lower and upper 95% confidence limits.

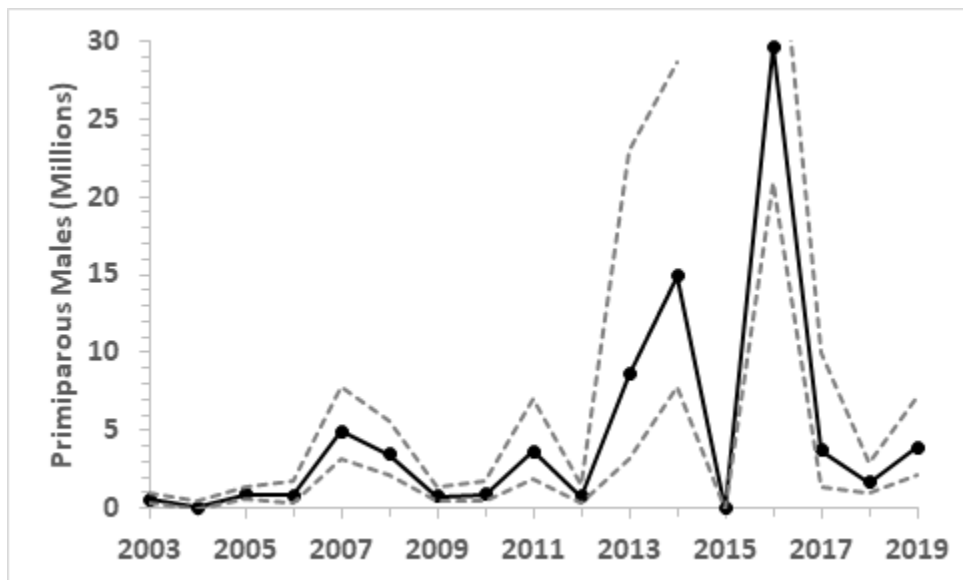
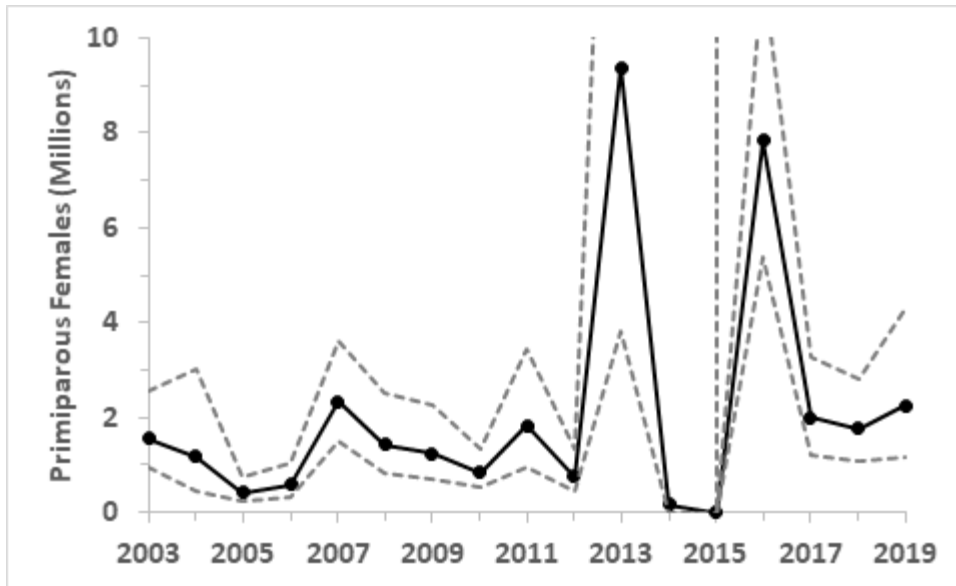
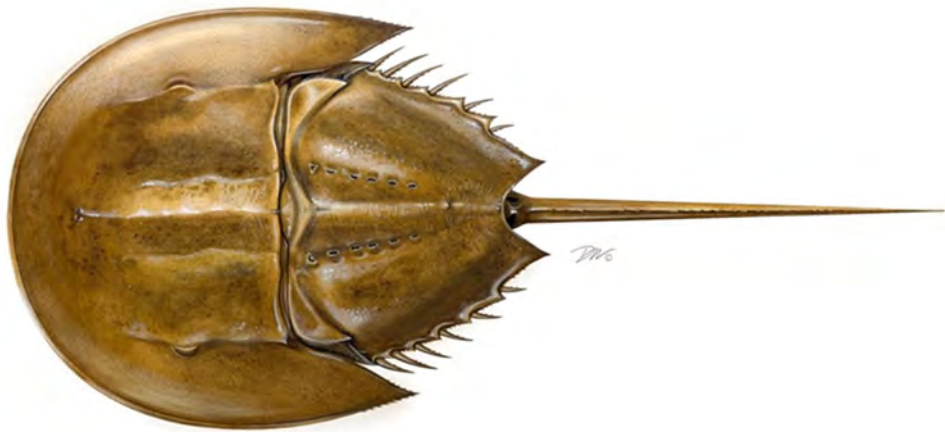


Figure 3. CMSA model estimated primiparous female (Top) and male (Bottom) abundance with lower and upper 95% confidence limits. Upper confidence limits for 2013-2016 extend beyond y-axis due to missing years of data from the Virginia Tech Trawl Survey.

Atlantic States Marine Fisheries Commission

Supplemental Report to the 2021 Revision to the Adaptive Resource Management Framework



Prepared by the
Adaptive Resource Management Subcommittee



Sustainable and Cooperative Management of Atlantic Coastal Fisheries

EXECUTIVE SUMMARY

The Peer Review Panel (Panel) for the 2021 Revision to the Framework for Adaptive Management (ARM) of Horseshoe Crab Harvest in the Delaware Bay Inclusive of Red Knot Conservation concluded that the ARM Modeling Work Group completed the Terms of Reference, revised the ARM Framework successfully, and results are suitable for management advice. The Panel did request a few changes be made to some of the modeling, which resulted in a different base run of the model from what was included in the final version of the ARM Revision report. This report, a supplement to the full ARM Revision report, describes the changes requested by the Panel and the revised base run.

Population Models and Revised ARM Framework

The Delaware Adult Trawl Survey index was recalculated based on Peer Review Panel recommendations and therefore the catch multiple survey analysis (CMSA), the model used to estimate male and female horseshoe crab abundances, was rerun. With the new base run, in 2019, the CMSA estimated that there were 21.9 million male and 9.4 million female horseshoe crabs. Additional sensitivity runs were done to test various assumptions and inputs for the CMSA during the Peer Review Workshop and are included in this supplemental report.

Because the CMSA population estimates are included in the integrated population model (IPM) for red knots, this model was also rerun. Estimates of adult survival probability and recruitment were nearly identical to the previous model run, again indicating high adult survival (average 0.93) and low recruitment (average 0.06) for this population.

The projection model for horseshoe crabs was rerun to include the full time series of CMSA estimates (2003-2019) rather than the shorter period used previously (2013-2019), as recommended by the Peer Review Panel. This resulted in more variable and lower mean values of primiparous abundances which resulted in lower projected mean equilibrium values of male and female abundances.

Due to the revised population models and the changes made in the horseshoe crab projection model, the ARM Framework was rerun.

Stock Status

Based on the base run of the revised ARM model, the recommended harvest in 2019 would have been 500,000 male and 144,803 female horseshoe crabs. Conversely, the previous ARM model recommended 500,000 male-only harvest.

It should be noted that this ARM Revision was developed using coastwide biomedical data so as to avoid data confidentiality issues. The population estimates for horseshoe crabs from the CMSA therefore represent an overestimate. If this ARM Revision is accepted for management use, the Delaware Bay-specific biomedical data will be used to determine the harvest package and the model will be run by someone (e.g., ASMFC staff) with confidential data access. Therefore, the final harvest recommendations are likely to be marginally lower than those reported here. No other model inputs were affected by data confidentiality.

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1 OVERVIEW

This report serves as supplemental material to the 2021 Revision to the Framework for Adaptive Management (ARM) of Horseshoe Crab Harvest in the Delaware Bay Inclusive of Red Knot Conservation (ASMFC 2021). During the Peer Review Workshop in November, 2021, the Peer Review Panel (Panel) requested additional information and report for peer review. A description of the additional information, analysis, and conclusions follows, but refer to ASMFC 2021 for a more thorough discussion of the life history, available data sources, analysis background, and stock status discussions for the ARM Framework.

1.1 Modeling Changes

The Panel made many suggestions in the Peer Review Report for both long-term and short-term considerations. Some of the short-term recommendations were made to the base run of the revised ARM model and were completed at or following the Peer Review Workshop. Three changes were made to the data or base run of the models which resulted in different results from those brought to peer review and described in ASMFC 2021:

1. A model-based abundance index for the Delaware Fish and Wildlife Adult Trawl Survey was developed since the design-based index previously used was deemed inappropriate for a fixed-survey design. The catch multiple survey analysis (CMSA) then was rerun with the revised Delaware index in order to estimate female and male horseshoe crab abundances in the Delaware Bay Region for use in the Integrated Population Model (IPM) for red knots and the horseshoe crab projection model.
2. The recruitment function in the horseshoe crab projection model was updated using all years of available primiparous data (2003-2019) instead of the limited years (2013-2019) used in base run.
3. The Revised ARM Framework was rerun to reflect those changes and is now considered the new base run for the model. Associated optimal harvest recommendations was also revised.

Additionally, the Panel made several research recommendations that have now been incorporated into the research recommendations in ASMFC 2021. The revised and complete list of research recommendations is found in this supplemental report, Section 7.

2 DELAWARE FISH AND WILDLIFE ADULT TRAWL SURVEY

Refer to ASMFC 2021 for a description of the survey's sampling design and biological sampling. In ASMFC 2021, the Delaware Adult Trawl Survey abundance index was developed using the delta distribution for the mean and variance for each year of the survey. During the Peer Review Workshop, this method was deemed inappropriate for a fixed-station survey design and

the Panel requested that the survey be recalculated and standardized using generalized linear or additive models (GLMs or GAMs).

2.1 Evaluation of Survey Data

This survey catches mainly adult horseshoe crabs and spring (April through July) indices were developed from this survey for male and female horseshoe crabs separately. This survey was standardized using R code to consider a variety of statistical models, including GLMs, as well as zero-inflated models and nominal indices. A full model that predicted catch as a linear function of year, month, water temperature, salinity, depth, and station 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 and station.

2.2 Abundance Index Trends

For all adult female horseshoe crabs in the spring (Figure 1), abundance began in 2003 with a mid-range value and then decreased in 2004-2005. There was a moderate increase in 2006 and 2007 before dropping to low abundance levels from 2008 through 2013. Since 2014 there has been a generally upward trend. A similar pattern was seen for the spring indices of adult males (Figure 2).

3 HORSESHOE CRAB POPULATION MODEL

3.1 Catch Multiple Survey Analysis (CMSA)

Refer to ASMFC 2021 for model background, description, configuration, and sensitivity runs. Since one of the inputs to the CMSA, the Delaware Bay Adult Trawl abundance index, was changed during the Peer Review Workshop, the CMSA base run had to re-run to calculate revised population estimates for male and female horseshoe crabs.

Revised input values for the CMSA can be found in Table 1 for female horseshoe crabs and Table 2 for male horseshoe crabs.

3.1.1 Results

Base model predictions fit indices well for both female and male horseshoe crabs, with excellent agreement with the primiparous index and well-behaved fits through observed multiparous indices (Figure 3-Figure 4).

Estimated female and male primiparous abundance was fairly stable through the time series with the exception of the missing years of the Virginia Tech trawl survey (2013-2016; Table 3-Table 4; Figure 5-Figure 6). Rising multiparous abundance was evident in both sexes and reflects some of the large increases seen in the multiparous trawl indices in later years (Table 3-Table 4; Figure 5-Figure 6).

3.1.2 Sensitivity Runs

In addition to the sensitivity runs provided in ASMFC 2021, several sensitivity runs were requested by the Panel during the Peer Review Workshop. The additional sensitivity runs requested included using the ASMFC 2019 survey weights, re-weighting the surveys based on area coverage, assuming all harvest is of Delaware Bay-origin, re-weighting the surveys based on area coverage and assuming all harvest is of Delaware Bay-origin, and the revised base run with the recalculated Delaware index. The results of previous sensitivity runs as well as the additional requested sensitivity runs can be found in Table 5-0.

3.2 Projection Model

The Peer Review Panel approved of the form of the horseshoe crab projection model as described in ASMFC 2021, but requested a change to the dataset used to inform the recruitment process used in the model (see Equations 6-7 of ASMFC 2021). The Panel concluded that the full time series of available CMSA estimates (2003-2019) of primiparous male and female horseshoe crabs should be used to determine the parameters of the recruitment process, rather than the shorter period used for ASMFC 2021 (i.e., 2013-2019). Primiparous abundances over the longer period are more variable and have lower mean values (Table 7), leading to lower projected median equilibrium values of male and female abundances (Figure 15) that are nevertheless bounded by wide confidence limits. Correlation between male and female primiparous abundances remains similar to that used in ASMFC 2021.

4 RED KNOT POPULATION MODEL

4.1 Integrated Population Model (IPM)

4.1.1 Model Description

No changes were made to the IPM model structure; refer to ASMFC 2021 for a detailed description of the model background, parameterization, and sensitivity runs. The model was rerun using the estimates of total female horseshoe crab abundance from the updated CMSA runs described above.

4.1.2 Results

4.1.2.1 Demographic rate estimates

Estimates of adult survival probability and recruitment were nearly identical to the previous model run (Table 8, Figure 7), again indicating high adult survival (average 0.93) and low recruitment (average 0.06) for this population.

4.1.2.2. Effects of environmental variables on red knot demographics

Regression coefficient estimates from this model run were very similar to the previous version (Table 9, Figure 8-Figure 9). The model indicated strong evidence for a positive association between female horseshoe crab abundance and apparent adult survival probability ($\beta_1 = 0.37$, 95% CRI: 0.12, 0.63) and no evidence of an effect or interaction with the timing of spawning. There was no clear evidence of a relationship between horseshoe crab abundance and red knot recruitment rate ($\beta_5 = -0.14$, 95% CRI: -0.53, 0.32).

5 REVISED ADAPTIVE RESOURCE MANAGEMENT FRAMEWORK

The Peer Review Panel concluded that the form of the decision model was appropriate and did not suggest any changes. However, changes to three inputs to the decision model had the potential to influence the optimal harvest policy for male and female horseshoe crabs. These were:

- 1) Revised CMSA estimates of primiparous and multiparous horseshoe crab abundances;
- 2) Revised red knot IPM parameter estimates that were influenced by the revision of CMSA estimates;
- 3) New parameters to the horseshoe crab recruitment process based on the full CMSA time series (2003-2019) instead of the shorter period used in ASMFC 2021 (2013-2019).

Time constraints precluded a full assessment of the sensitivity of the optimal harvest policy to each of the above changes independently. Rather, a new base run of the Approximate Dynamic Programming algorithm was conducted incorporating all three. The change to the recruitment process of the horseshoe crab projection model was expected to be quite influential since it represents a significant change to expected long-term equilibrium abundances and the annual variation around them. Broadly, it was expected that these lower projected horseshoe crab abundances would result in a more conservative harvest policy.

Results from the new base run (Figure 10-Figure 16; Table 10) differ from those in the previous base run (Figures 53-59 in ASMFC 2021) in several notable ways. First, as expected, projected equilibrium distributions for male and female horseshoe crab abundances are shifted lower (new median female abundance at projection year 100 is approximately 7.3 million, whereas it was 12.3 million in ASMFC 2021; year-100 median male abundance here is 14.9 million, it was 33.8 million in ASMFC 2021). For males in particular, however, uncertainty is still quite large.

The long-term distribution of red knot abundance has also shifted lower in the new base run (Figure 15), with a median of approximately 100,500 adults at year 100 (versus 128,400 in ASMFC 2021). Uncertainty around this expected value in the new base run is similarly large, compared with results in ASMFC 2021.

The combined influences of lower expected abundances of male and female horseshoe crabs and of adult red knots lead to differences in the optimal harvest strategies for male and female horseshoe crabs. For males, the policy is similar to that of ASMFC 2021, with maximum allowable harvest being the recommendation throughout most of the predicted range of male abundances (Figure 10). However, because those abundances are projected to be generally lower, the harvest curve rises toward maximum harvest at a lower absolute abundance than in ASMFC 2021.

The optimal female harvest surface in the new base run has a shallower slope than the one in ASMFC 2021, along both the female horseshoe crab and red knot axes (Figure 11-Figure 14; Table 10). In contrast to the ASMFC 2021 run, the new harvest policy is unlikely to recommend maximum allowable female harvest (210,000) within the projected range of female horseshoe crab and red knot abundances (green regions in Figure 11-Figure 14). However, its shallow slope results in recommendations of moderate female harvest even at low abundances of female horseshoe crabs and red knots.

6 STOCK STATUS AND CONCLUSIONS

Using the new base run with the recommended changes from the Peer Review Panel, the optimal harvest recommendations were also revised (Table 11; compare to Table 32 in ASMFC). In 2019, the harvest recommendation from the revised ARM Framework would have been 500,000 males and 144,803 females. Optimal harvest recommendations under the previous ARM Framework were for harvest package #3 (0 females, 500,000 males).

Again, it should be noted that this ARM Revision was developed using coastwide biomedical data so as to avoid data confidentiality issues. The population estimates for horseshoe crabs from the CMSA therefore represent an overestimate. If this Revision is accepted for management use, the Delaware Bay-specific biomedical data will be used to determine the harvest package and the model will be run by someone (e.g., ASMFC staff) with confidential data access. Therefore, the final harvest recommendations are likely to be marginally lower than those reported in Table 11 when the Delaware Bay-specific values are used.

7 RESEARCH RECOMMENDATIONS

The ARM subcommittee identified several recommendations that would benefit the adaptive management of horseshoe crabs and red knots in the Delaware Bay area. In section four of the Peer Review Panel's report, the Panel made several other recommendations that have been incorporated into the list. Below is the final and complete list of research recommendations.

The ARM subcommittee and the Peer Review Panel recommend that the ARM data be updated sooner than later (three years or less) as new data become available, notably when the Delaware and New Jersey trawl surveys collect new stage data to improve the estimation of HSC recruitment dynamics. Additionally, the ARM Framework should be revisited every five-ten years for possible revision to account for dynamic changes in the ecosystem.

7.1 Future Research

- Evaluate the effect of climate change on horseshoe crabs and red knots. This includes the effects of warming temperatures, sea level rise, and storm frequency and intensity on the timing and duration of spawning, movement of crabs into and out of Delaware Bay, and effects on spawning habitat. For red knots, this includes effects of climate change on breeding conditions in the arctic and resulting recruitment of red knots.
- Incorporate potential climate change effects into the optimization (e.g., predicted trends in arctic snow cover).
- Evaluate the relationship between horseshoe crab egg density on spawning beaches and abundance of horseshoe crabs in the bay-wide spawning survey and total population estimates derived from the catch multiple survey analysis.
- Improve the understanding of horseshoe crab recruitment for the purpose of updating the stock-recruitment relationship.
- Continue evaluation of catchability and factors influencing catchability of the Virginia Tech horseshoe crab trawl survey.
- Address the issue of gear saturation for spawning beach surveys and/or explore analyses that would be less sensitive to gear saturation. Explore the methodology and data collection of spawning beach surveys and the ability of these surveys to track spawning abundance.
- Quantify the amount of contemporary suitable horseshoe crab spawning habitat in the Delaware Bay.
- Further explore the multi-state mark-recapture analysis of red knot tagging data to estimate the probability of gaining weight and survival as a function of horseshoe crab abundance. Examine the effects of tagging biases, time periods of stopover, short-versus long-distance migrants, and selection of states (i.e., weight thresholds).
- Evaluate the proportion of New York bait landings that could be comprised of Delaware Bay-origin crabs and the movement between the two regions.
- If possible, include other sources of horseshoe crab removals (e.g., illegal take, poaching) in the CMSA. Other sources of removals are currently unknown, but can be added in the future if quantified.

7.2 Data Collection

- Continue funding and support for the annual Virginia Tech Trawl Survey. Consider increasing the sampling effort within the Delaware Bay region or expanding the survey along the Atlantic coast if future funding allows.
- Perform a simulation study to evaluate the performance of current Virginia Tech Survey design in capturing the Delaware Bay horseshoe crab stock dynamics. A simulation could

also potentially identify a more cost-effective survey program to ensure the quality of the survey abundance indices.

- Better characterize horseshoe crab discards in other commercial fisheries and refine estimates of discard mortality.
- Continue to collect horseshoe crab sex and stage (primi- and multiparous stages) information from the Delaware Bay Adult Trawl Survey and the New Jersey Ocean Trawl Survey.
- Continue monitoring natural mortality from tagging data within the Delaware Bay region. It is possible that natural mortality is not constant across all age stages post-maturation and future revisions should consider recording post-maturation age group data based on carapace wear, epibionts, and mating scar criteria defined by Botton et al. (2021) in order to estimate age group-specific mortality estimates. Exploring differences in natural mortality among primiparous and multiparous crabs would be beneficial for obtaining age-group specific mortality estimates that could be incorporated into the CMSA model to obtain more accurate abundance estimates.
- Continue to evaluate biomedically bled crabs' mortality rates and effects on spawning behavior. Consider a tagging study of biomedically bled horseshoe crabs to obtain relative survival and collaborations between researchers and biomedical facilities that would result in peer-reviewed mortality estimates.
- Maintain consistent data collection and survey designs for spawning beach surveys each year.
- Increase effort for tagging resights for horseshoe crabs and expand horseshoe crab tagging efforts throughout the US East Coast, particularly in North Carolina, to ameliorate movement and population exchange patterns adjacent to Delaware Bay. North Carolina has the lowest tagging effort (by tagged individuals and resighting effort) out of any state on the US East Coast. There is limited information regarding the migratory exchange between North Carolina and Delaware Bay that is also the boundary between stock units (ASMFC 2019).
- Improve estimates of counting error during red knot aerial surveys by recording and maintaining records of additional information such as observer ID, tide state, and weather conditions. The integration of simultaneous ground count data or a double-observer method could also be used to improve this component of the IPM.
- Evaluate phenology of horseshoe crab migration into Delaware Bay with more contemporary tools, such as satellite tags or acoustic telemetry. Understanding migration timing could improve understanding of temporal implications of trawl survey timing and horseshoe abundance index inference, as well as the timing of horseshoe crab spawning migrations relative to red knot arrival.

- Develop a survey targeting older juvenile horseshoe crabs within the subtidal zone to enhance the understanding of recruitment. The population dynamics and habitat use of juveniles (age 5-9) remains elusive within the literature, with the exception of the population in Pleasant Bay, Massachusetts.

7.3 Data analysis and modeling

- Update horseshoe crab stock-recruitment relationships as more data become available and refine methodologies to characterize uncertainty.
- Regularly updating the model runs with new information when it becomes available will continue to improve the estimates of recruitment dynamics for both horseshoe crabs and red knots. Although the recruitment dynamics are currently quantified with large uncertainty because of the short time period and missing years of data, the interannual variability in recruitment will be better understood when more data become available.
- Update parameters describing the influence of horseshoe crabs on red knot survival and recruitment through re-fitting the red knot integrated population model to new data.
- Integrate red knot “proportion marked” data into the IPM so that analyses conducted to determine the state of the system can be used to update model parameters with no additional effort.
- Conduct habitat suitability index modeling for primiparous and multiparous horseshoe crabs for both males and females to examine spatio-temporal variability in suitable habitat.
- Quantify and monitor the amount of suitable spawning habitat for horseshoe crabs throughout the Delaware Bay, including fringe marsh habitat which may affect horseshoe crab recruitment dynamics due to climate change.
- Conduct species distribution modeling to examine spatio-temporal changes in distributions of primiparous and multiparous female and male horseshoe crabs.
- Investigate alternative utility functions for red knots with additional stakeholder input.
- Continue to evaluate horseshoe crab tagging data by fitting capture-recapture models that include a short-term (1 year) bleeding effect, account for spatial distribution of harvest pressure, account for capture methodology, and account for disposition of recaptured tagged individuals. Potential methodological approaches include use of time-varying individual covariates to indicate which crabs are 1 year from bleeding and use of hierarchical models to estimate interannual variation in survival within time periods defined by major regulatory changes.
- Explore the possibility of modeling stopover persistence as a function of boreal-wintering area of marked birds using observations away from Delaware Bay.
- Continue to explore the apparent lack of relationship between horseshoe crab egg densities measured by beach surveys and red knot survival.

- Explore the use of expected value of perfect information (EVPI) to evaluate the effects of uncertainties in red knots and horseshoe crab dynamics on harvest decisions.

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9 TABLES

Table 1. CMSA base model inputs for female horseshoe crabs. Biomedical numbers represent coastwide mortality, not Delaware Bay-specific. Values shown for the Virginia Tech (VT) survey's swept area estimations for primiparous (*R*) and multiparous (*N*) are in millions of horseshoe crabs.

Year	Removals				Indices				CVs			
	Bait	Discard	Biomedical	Total	VT, <i>R</i>	VT, <i>N</i>	DE Adult	NJ OT	VT, <i>R</i>	VT, <i>N</i>	DE	NJ
2003	202,614	6,567	20,456	229,637	1.537	4.959	0.644	2.246	0.26	0.30	0.47	0.19
2004	92,855	9,554	32,337	134,747	0.794	3.379	0.015	2.502	0.49	0.25	1.05	0.23
2005	103,972	3,031	22,885	129,888	0.358	2.735	0.015	2.770	0.29	0.23	1.05	0.24
2006	83,295	8,664	25,654	117,613	0.479	3.138	0.949	1.856	0.27	0.27	0.37	0.26
2007	54,773	6,500	29,469	90,742	2.051	6.611	0.877	1.474	0.31	0.42	0.37	0.25
2008	35,838	5,084	29,141	70,063	2.373	7.746	0.118	2.370	0.40	0.31	0.50	0.32
2009	35,793	8,475	29,287	73,555	2.571	6.311	0.199	1.368	0.43	0.29	0.45	0.29
2010	30,362	11,527	33,165	75,055	0.885	2.975	0.109	0.579	0.26	0.32	0.51	0.30
2011	24,906	14,742	41,754	81,403	1.338	5.178	0.156	2.215	0.59	0.23	0.47	0.26
2012	40,745	4,673	36,675	82,093	0.845	5.290	0.161	1.804	0.30	0.18	0.47	0.25
2013	16,635	10,933	32,222	59,790			0.014	7.996			1.08	0.35
2014	7,663	15,787	30,865	54,315			0.809	3.358			0.37	0.24
2015	6,680	11,593	33,897	52,169			0.396	3.145			0.40	0.25
2016	8,527	51,069	26,204	85,800			0.714	3.989			0.38	0.24
2017	10,136	31,295	29,635	71,066	1.608	6.024	1.159	5.613	0.23	0.21	0.36	0.25
2018	10,096	9,184	32,405	51,686	1.480	7.185	2.123	3.118	0.26	0.23	0.35	0.23
2019					1.773	7.326	1.349	6.966	0.31	0.21	0.36	0.40

<i>M</i>	Starting Values				
	<i>R</i>	<i>N</i>	<i>q</i> _{DE}	<i>q</i> _{NJ}	<i>s</i>
0.3	1.4E+06	5.3E+06	1.1E-07	5.9E-07	1

Table 2. CMSA base model inputs for male horseshoe crabs. Biomedical numbers represent coastwide mortality, not Delaware Bay-specific. Values shown for the Virginia Tech (VT) survey's swept area estimations for primiparous (R) and multiparous (N) are in millions of horseshoe crabs.

Year	Removals				Indices				CVs			
	Bait	Discard	Biomedical	Total	VT, R	VT, N	DE Adult	NJ OT	VT, R	VT, N	DE	NJ
2003	364,132	9,117	23,028	396,277	0.548	11.584	0.337	2.647	0.28	0.24	0.55	0.22
2004	144,729	13,265	34,115	192,109	0.078	8.069	0.000	2.077	0.84	0.29	1.00	0.25
2005	208,670	4,209	31,889	244,768	0.789	5.150	0.000	3.260	0.21	0.25	1.00	0.28
2006	134,617	12,028	30,536	177,181	0.597	5.844	0.328	1.783	0.33	0.22	0.44	0.27
2007	122,272	9,024	45,468	176,764	3.113	15.825	0.870	1.016	0.31	0.27	0.41	0.26
2008	153,516	7,059	37,007	197,581	3.129	15.795	0.105	2.319	0.28	0.28	0.52	0.34
2009	194,426	11,767	34,948	241,141	0.757	14.647	0.151	1.421	0.31	0.33	0.49	0.30
2010	134,223	16,004	35,581	185,809	0.725	6.240	0.240	0.684	0.34	0.30	0.46	0.31
2011	182,131	20,468	55,412	258,011	1.422	13.963	0.305	1.726	0.55	0.28	0.44	0.25
2012	168,034	6,488	45,389	219,911	0.749	15.060	0.112	2.069	0.36	0.40	0.51	0.30
2013	286,609	15,179	39,285	341,073			0.055	8.248			0.60	0.39
2014	256,155	21,919	40,712	318,786			0.874	3.610			0.41	0.27
2015	177,402	16,096	43,710	237,207			0.444	3.205			0.43	0.29
2016	197,734	70,904	22,579	291,218			0.527	5.041			0.42	0.31
2017	329,840	43,451	43,039	416,330	2.608	21.941	1.300	7.183	0.42	0.29	0.40	0.29
2018	175,031	12,752	45,420	233,203	1.523	20.664	3.071	4.564	0.28	0.25	0.39	0.28
2019					3.341	15.749	1.804	7.683	0.29	0.18	0.40	0.48

M	Starting Values				
	R	N	q_DE	q_NJ	s
0.3	1.5E+06	1.3E+07	4.7E-08	2.6E-07	1

Table 3. CMSA female horseshoe crab model outputs: q =catchability coefficients; R =primiparous abundance; N =multiparous abundance; and F =instantaneous fishing mortality rate.

Year	R	N	$R+N$	F
2003	1,544,190	5,061,010	6,605,200	0.041
2004	1,254,290	4,695,600	5,949,890	0.027
2005	415,565	4,291,810	4,707,375	0.032
2006	584,244	3,375,510	3,959,754	0.035
2007	2,337,530	2,832,230	5,169,760	0.021
2008	1,573,060	3,751,750	5,324,810	0.015
2009	1,292,980	3,884,420	5,177,400	0.017
2010	822,549	3,772,200	4,594,749	0.019
2011	2,074,450	3,339,270	5,413,720	0.018
2012	802,266	3,940,520	4,742,786	0.020
2013	9,569,380	3,442,890	13,012,270	0.005
2014	2	9,588,260	9,588,262	0.007
2015	299,411	7,056,410	7,355,821	0.008
2016	6,977,790	5,404,420	12,382,210	0.008
2017	1,867,980	9,099,120	10,967,100	0.008
2018	1,672,230	8,063,460	9,735,690	0.006
2019	2,189,510	7,167,890	9,357,400	

q_{DE}	7.41E-08
q_{NJ}	3.77E-07

Table 4. CMSA male horseshoe crab model outputs : q =catchability coefficients; R =primiparous abundance; N =multiparous abundance; and F =instantaneous fishing mortality rate.

Year	R	N	$R+N$	F
2003	555,967	15,597,600	16,153,567	0.029
2004	83,631	11,625,800	11,709,431	0.019
2005	880,457	8,509,190	9,389,647	0.031
2006	798,084	6,745,350	7,543,434	0.028
2007	4,929,030	5,435,810	10,364,840	0.020
2008	3,681,160	7,526,320	11,207,480	0.021
2009	788,876	8,132,640	8,921,516	0.032
2010	834,793	6,401,670	7,236,463	0.030
2011	3,822,740	5,200,980	9,023,720	0.034
2012	768,416	6,462,870	7,231,286	0.036
2013	11,581,300	5,167,790	16,749,090	0.024
2014	9,233,350	12,114,500	21,347,850	0.017
2015	436,065	15,540,500	15,976,565	0.017
2016	26,978,600	11,631,500	38,610,100	0.009
2017	3,312,030	28,352,400	31,664,430	0.015
2018	1,615,990	23,099,300	24,715,290	0.011
2019	3,789,120	18,108,800	21,897,920	

q_{DE}	3.17E-08
q_{NJ}	1.89E-07

Table 5. Sensitivity runs for the CMSA for female horseshoe crabs. All runs that included CONFIDENTIAL biomedical data have been removed. The “modeling base run” is the previous base run from ASMFC 2021, the “post-pr base run” is the post-peer review base run, and the “real (DB) base run” uses the confidential Delaware Bay biomedical data instead of the coastwide. The sensitivity to natural mortality (*M*), different discard mortality rates, leaving out the New Jersey Ocean Trawl (OT) or biomedical (biomed 0% mortality) data, using different survey weighting approaches, and assuming all harvest in the CMSA is Delaware Bay-origin was explored. Primiparous (*R*), multiparous (*N*) and fishing mortality (*F*) estimates are included.

Name	M	λ			Biomed	Discard Mortality			Starting Values				Terminal Output Values			
		VT	DE	NJ		Dredge	Trawl	Gill Nets	<i>R</i>	<i>N</i>	<i>q_de</i>	<i>q_nj</i>	<i>NegLL</i>	<i>R</i>	<i>N</i>	<i>F</i>
Modeling Base Run	0.3	1	1	1	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	87.9	2,247,290	7,533,500	0.006
M	0.274	1	1	1	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	86.5	2,204,475	7,834,127	0.006
Discard	0.3	1	1	1	Coastwide 15%	5%	5%	5%	14.1	15.5	-15.3	-14.3	87.9	2,247,210	7,533,130	0.006
Discard	0.3	1	1	1	Coastwide 15%	12%	12%	12%	14.1	15.5	-15.3	-14.3	88.1	2,251,259	7,511,908	0.007
Discard	0.3	1	1	1	Coastwide 15%	50%	50%	50%	14.1	15.5	-15.3	-14.3	89.3	2,278,436	7,385,285	0.015
No NJ OT	0.3	1	1	0	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	66.8	2,039,061	7,572,244	0.006
2019 Survey Weights	0.3	0.59	0.16	0.25	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	22.2	1,934,390	6,734,470	0.007
Area Survey Weights	0.3	0.45	0.15	0.40	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	22.1	2,045,187	6,955,199	0.006
Biomed	0.3	1	1	1	0% mortality	5%	5%	12%	14.1	15.5	-15.3	-14.3	87.6	2,242,272	7,564,675	0.002
All Harvest DB-origin	0.3	1	1	1	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	88.8	2,253,511	7,504,399	0.010
Area Wts All DB-origin	0.3	0.45	0.15	0.40	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	22.5	2,049,282	6,920,510	0.011
Post-PR Base Run	0.3	1	1	1	Coastwide 15%	5%	5%	12%	14.1	15.5	-16.0	-14.3	75.0	2,189,510	7,167,890	0.006
Real (DB) Base Run	0.3	1	1	1	Delaware Bay 15%	5%	5%	12%	14.1	15.5	-16	-14.3	Confidential			

Table 6. Sensitivity runs for the CMSA model for male horseshoe crabs. All runs that included CONFIDENTIAL biomedical data have been removed. The “modeling base run” is the previous base run from ASMFC 2021, the “post-pr base run” is the post-peer review base run, and the “real (DB) base run” uses the confidential Delaware Bay biomedical data instead of the coastwide. The sensitivity to natural mortality (M), different discard mortality rates, leaving out the New Jersey Ocean Trawl (OT) or biomedical (biomed 0% mortality) data, using different survey weighting approaches, and assuming all harvest in the CMSA is Delaware Bay-origin was explored. Primiparous (R), multiparous (N) and fishing mortality (F) estimates are included.

Name	M	λ			Biomed	Discard Mortality			Starting Values				Terminal Output Values			
		VT	DE	NJ		Dredge	Trawl	Gill Nets	R	N	q_de	q_nj	NegLL	R	N	F
Modeling Base Run	0.3	1	1	1	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	131.3	3,901,880	20,031,800	0.010
M	0.274	1	1	1	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	127.8	3,863,175	20,707,365	0.010
Discard	0.3	1	1	1	Coastwide 15%	5%	5%	5%	14.2	16.4	-15.8	-15.2	131.3	3,902,001	20,035,174	0.010
Discard	0.3	1	1	1	Coastwide 15%	12%	12%	12%	14.2	16.4	-15.8	-15.2	131.6	3,902,001	20,015,149	0.011
Discard	0.3	1	1	1	Coastwide 15%	50%	50%	50%	14.2	16.4	-15.8	-15.2	132.9	3,913,724	19,955,194	0.015
No NJ OT	0.3	1	1	0	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	105.7	3,741,511	20,957,350	0.009
2019 Survey Weights	0.3	0.59	0.16	0.25	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	35.0	3,532,410	17,504,300	0.011
Area Survey Weights	0.3	0.45	0.15	0.40	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	32.2	3,627,303	17,966,150	0.011
Biomed	0.3	1	1	1	0% mortality	5%	5%	12%	14.2	16.4	-15.8	-15.2	130.8	3,898,101	20,055,219	0.008
All Harvest DB-origin	0.3	1	1	1	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	133.3	3,909,813	20,015,149	0.015
Area Wts All DB-origin	0.3	0.45	0.15	0.40	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	33.0	3,630,932	17,912,332	0.016
Post-PR Base Run	0.3	1	1	1	Coastwide 15%	5%	5%	12%	14.2	16.4	-16.9	-15.2	102.19	3,789,120	18,108,800	0.011
Real (DB) Base Run	0.3	1	1	1	Delaware Bay 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	Confidential			

Table 7. Parameter values of the horseshoe crab recruitment process used in the projection model, for both the pre- and post-peer review versions of the model. See Equations 6-7 of ASMFC 2021 for a description of the bivariate lognormal distribution that generates male and female primiparous abundances annually.

Name	Symbol	Pre-peer review value (ASMFC 2021)	Post-peer review value
Primiparous female mean	μ^f	14.9493	14.3334
Primiparous female standard deviation	σ^f	0.4909	0.74505
Primiparous male mean	μ^m	15.7447	14.5869
Primiparous male standard deviation	σ^m	0.8837	1.4022
Correlation	ρ	0.6871	0.6712

Table 8. Estimates of average survival (ϕ) and recruitment (ρ) for red knot from 2005-2018. Average survival probability and recruitment rate were calculated using the average horseshoe crab abundance. 95% CRI (credible intervals) are the upper and lower bounds that contain 95% of the posterior distribution.

Parameter	Mean	95% CRI
Annual apparent survival probability (ϕ)	0.93	0.90, 0.95
Recruitment rate (ρ)	0.063	0.005, 0.149

Table 9. Estimated effects of horseshoe crab abundance, timing of spawning, and Arctic snow cover on red knot survival probability and recruitment rate, presented as the mean and 95% credible interval of the posterior distribution.

Demographic rate	Covariate	Mean	95% CRI
Survival probability	HSC	0.37	0.12, 0.63
	MaySpawnPct	-0.04	-3.31, 3.31
	HSC x MaySpawnPct	0	-0.61, 0.57
	Arctic snow	-1.02	-3.74, 1.83
Recruitment rate	HSC	-0.14	-0.53, 0.32

Table 10. Comparison of harvest policy parameters from the new base run of the decision model with those from ASMFC 2021 (Table 31).

Symbol	Description	New base run	ASMFC 2021
α^f	Slope of the female HSC harvest factor.	3.573 / (2×10^7)	5.017 / (2×10^7)
β^f	Inflection point of the female HSC harvest factor.	10.638×10^6	7.219×10^6
α^m	Slope of the male HSC harvest factor.	25.422 / (3×10^7)	16.908 / (3×10^7)
β^m	Inflection point of the male HSC harvest factor.	0.9121×10^6	7.953×10^6
α^k	Slope of the red knot harvest factor.	2.162 / (1.8×10^5)	15.783 / (1.8×10^5)
β^k	Inflection point of the red knot harvest factor.	6.433×10^4	9.929×10^4

Table 11. Comparison of harvest recommendations from the previous (top section) and revised (bottom section) ARM models when applied to recent abundance estimates of horseshoe crabs and red knots in the Delaware Bay. Coastwide biomedical mortality was used for model development, so actual Delaware-Bay specific values will result in slightly lower population estimates.

Year	VA Tech Swept Area Estimates		Red knots	Optimal HSC Harvest (previous ARM)	
	Female HSC	Male HSC		Female	Male
2017	6,654,877	21,405,997	49,405	0	500,000
2018	7,555,622	19,346,403	45,221	0	500,000
2019	7,934,057	16,645,912	45,133	0	500,000
Year	CMSA Estimates		Red knots	Optimal HSC Harvest (revised ARM)	
	Female HSC	Male HSC		Female	Male
2017	10,967,100	31,664,430	49,405	154,483	500,000
2018	9,735,690	24,715,290	45,221	146,792	500,000
2019	9,357,400	21,897,920	45,133	144,803	500,000

10 FIGURES

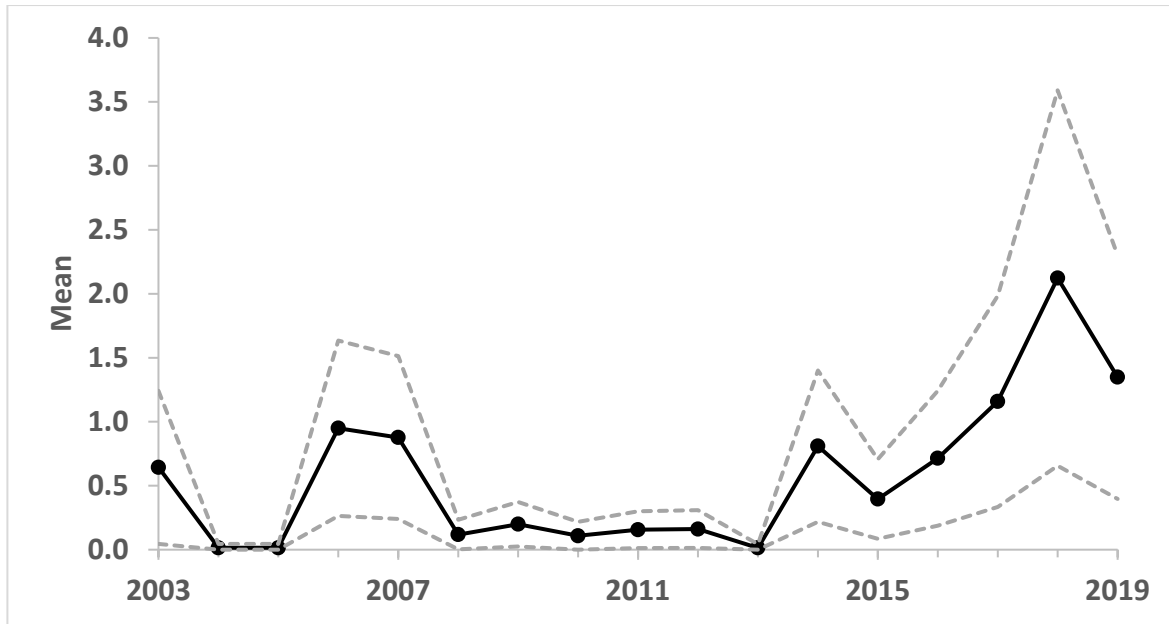


Figure 1. Delaware Fish and Wildlife Adult Trawl Survey abundance index for all adult female horseshoe crabs in the spring.

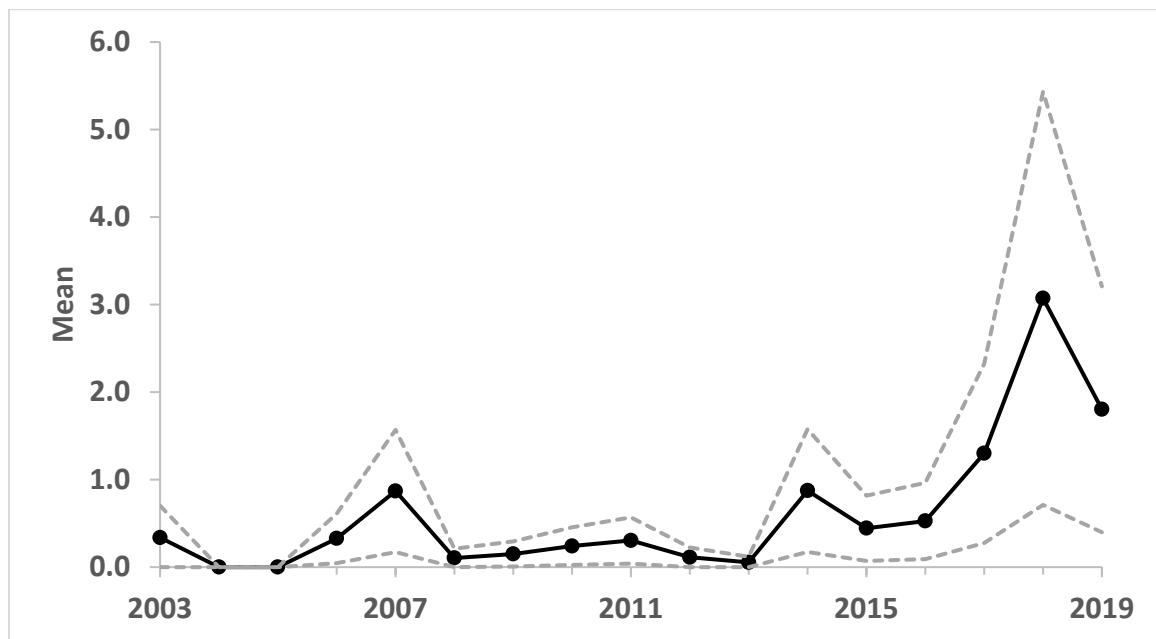


Figure 2. Delaware Fish and Wildlife Adult Trawl Survey abundance index for all adult male horseshoe crabs in the spring.

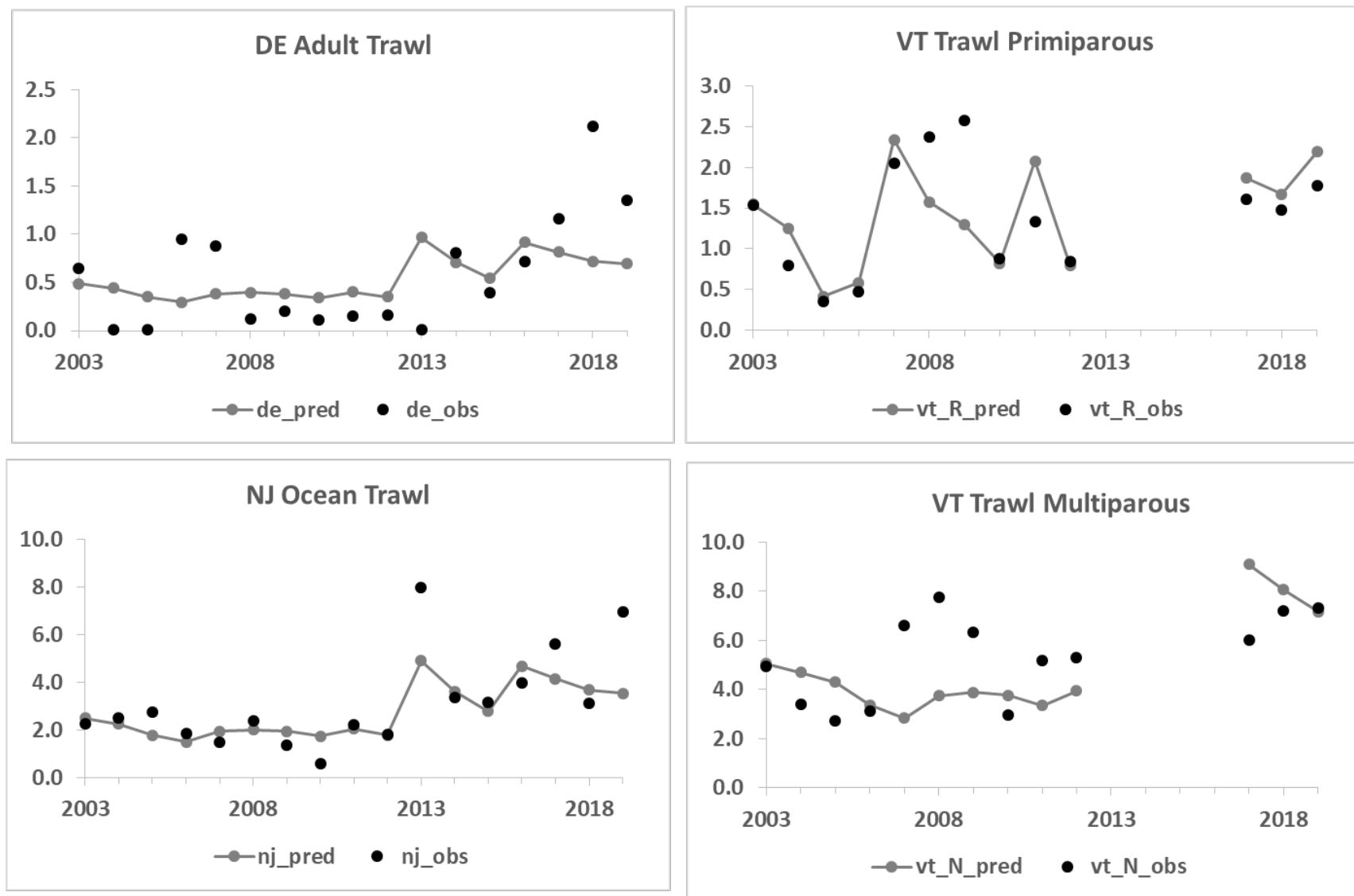


Figure 3. CMSA model fits to the indices for the Delaware (DE) Adult Trawl, New Jersey (NJ) Ocean Trawl, and Virginia Tech (VT) Trawl Surveys for primiparous and multiparous female horseshoe crabs.

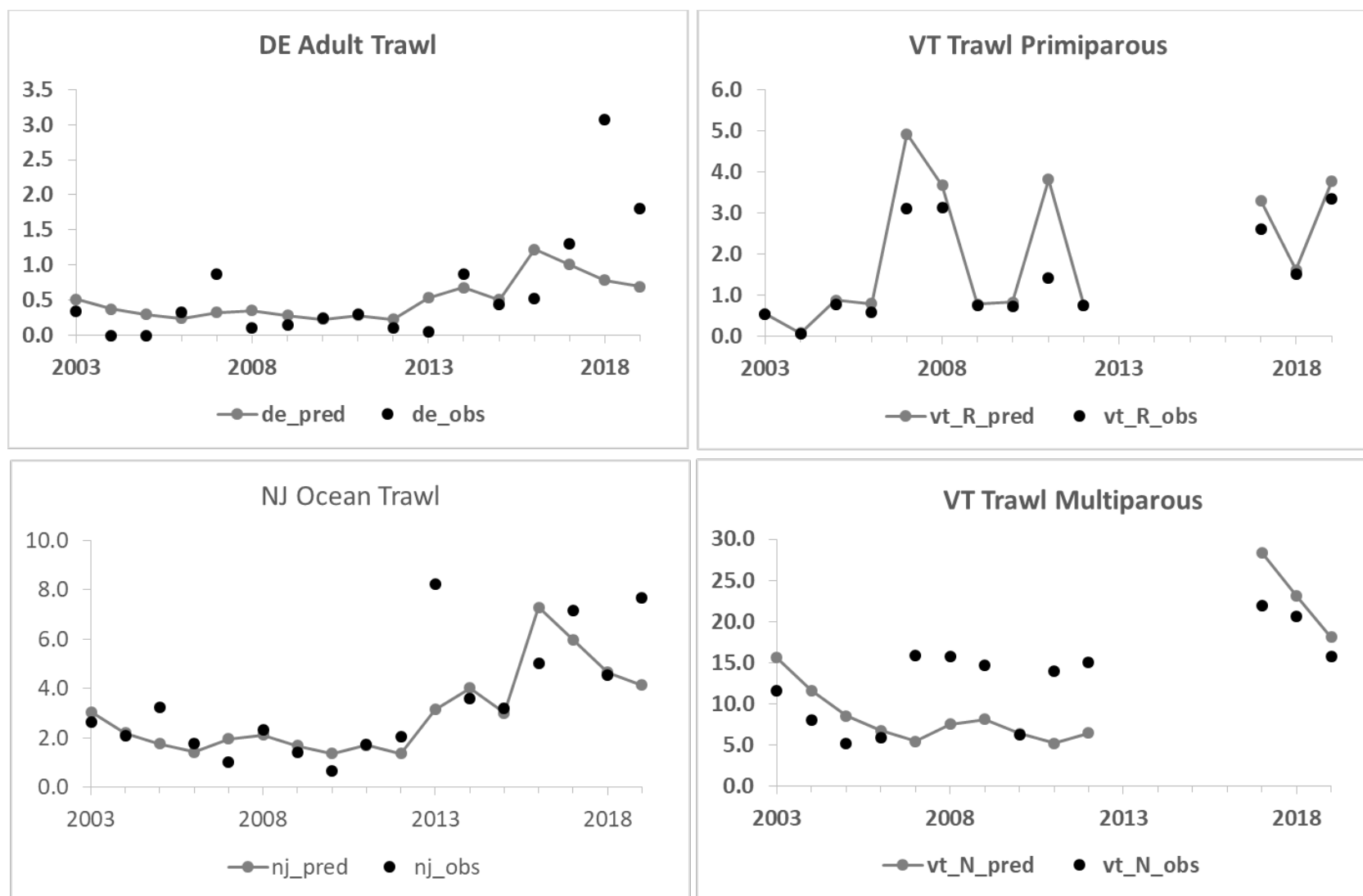


Figure 4. CMSA model fits to the indices for the Delaware (DE) Adult Trawl, New Jersey (NJ) Ocean Trawl, and Virginia Tech (VT) Trawl Surveys for primiparous and multiparous male horseshoe crabs.

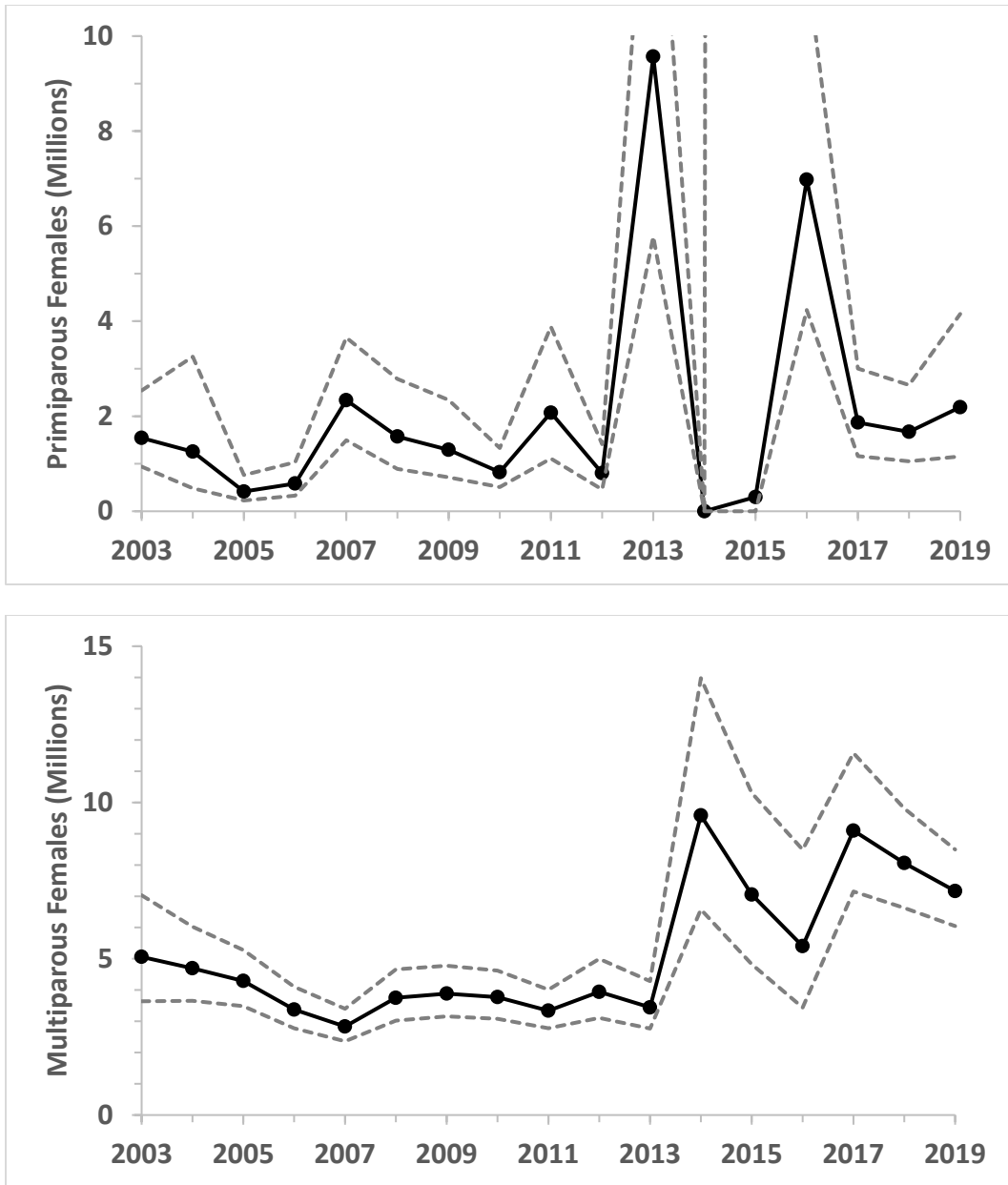


Figure 5. CMSA model estimated primiparous and multiparous female abundance with lower and upper 95% confidence limits. Upper confidence limits for 2013-2016 extend beyond y-axis for primiparous crabs due to missing years of data from the Virginia Tech Trawl Survey.

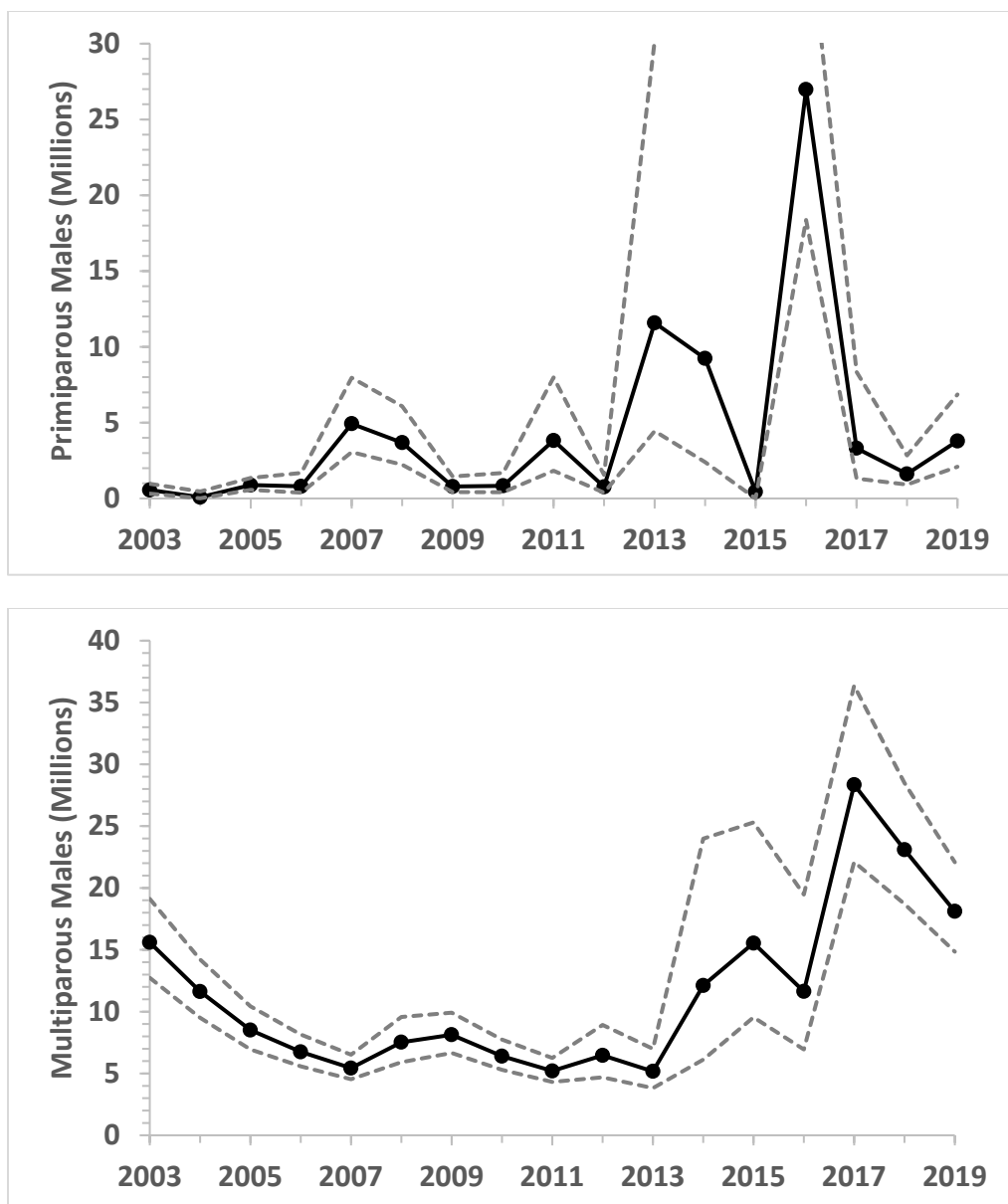


Figure 6. CMSA model estimated primiparous and multiparous male abundance with lower and upper 95% confidence limits. Upper confidence limits for 2013-2016 extend beyond y-axis for primiparous crabs due to missing years of data from the Virginia Tech Trawl Survey.

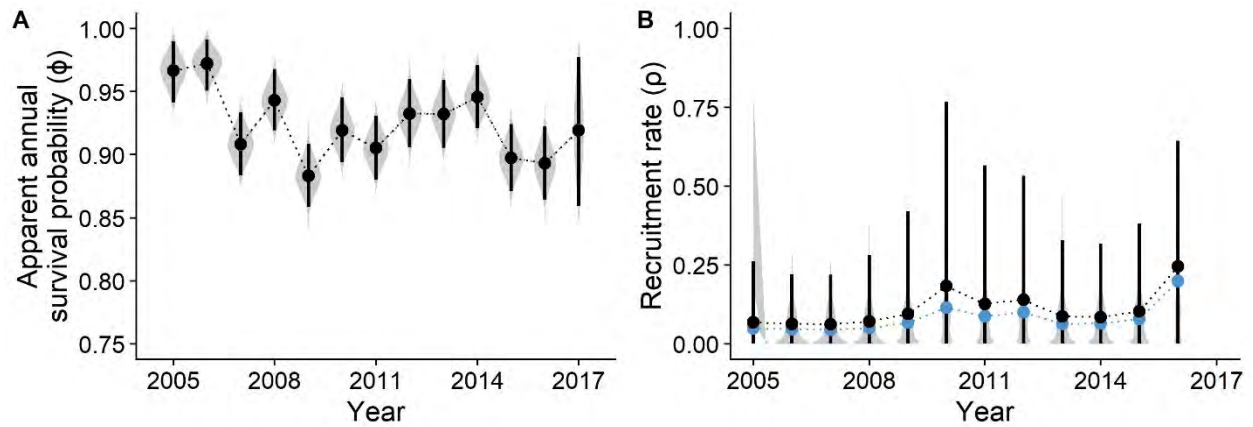


Figure 7. Estimates of survival (A) and recruitment (B) over time for red knot , 2005-2018. Gray shaded regions show the full posterior distributions. Black points and vertical lines represent posterior means and 95% credible intervals. Blue points represent the medians of the posterior distributions.

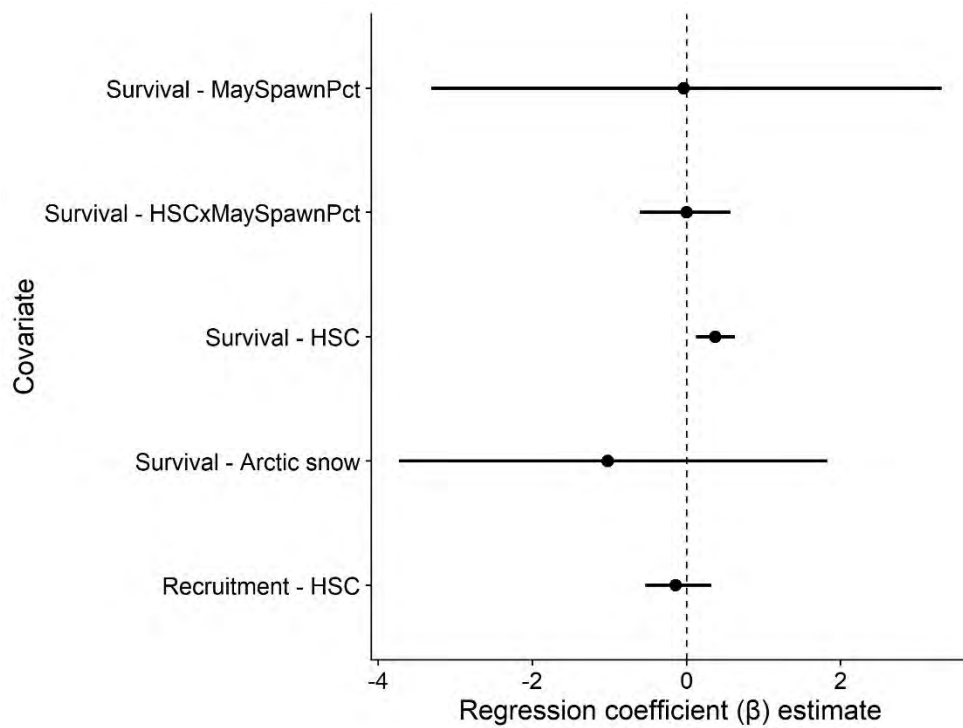


Figure 8. Estimated effects of horseshoe crab abundance, spawn timing, and Arctic snow on red knot survival probability and recruitment rate. Points represent posterior means of the standardized regression coefficients and vertical lines represent 95% credible intervals.

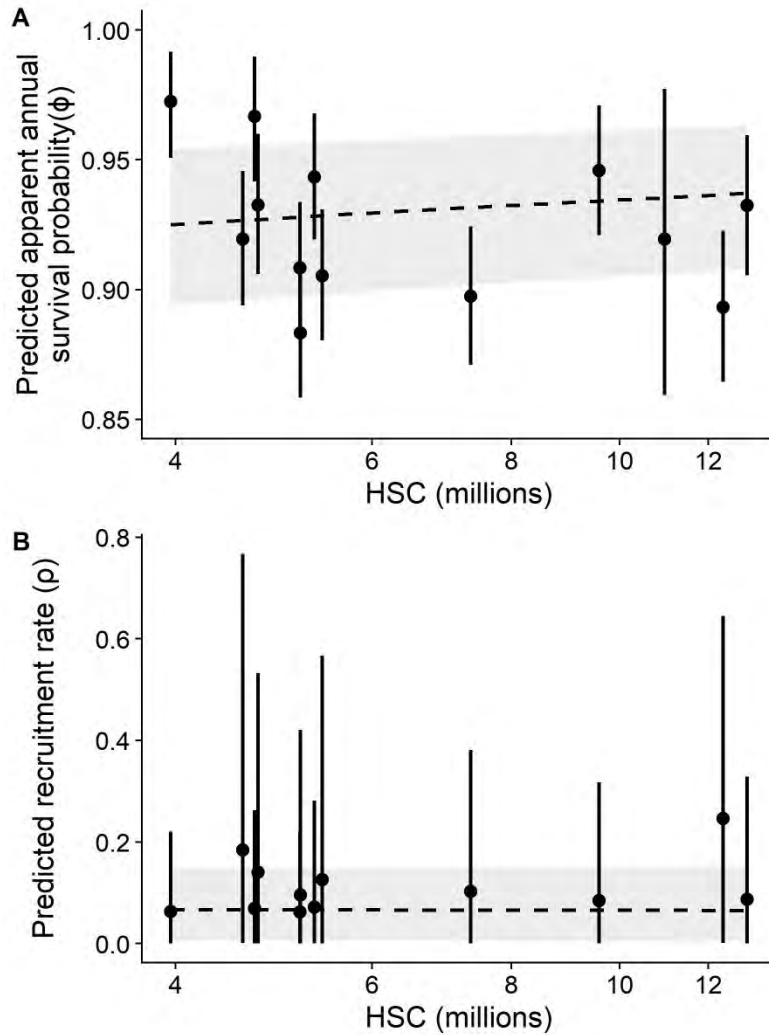


Figure 9. Estimated relationship between horseshoe crab abundance and red knot demographic rates. The black dashed line and gray shaded region show the mean and 95% credible interval of the predicted values. Points and vertical lines show the mean and 95% credible interval of model estimates.

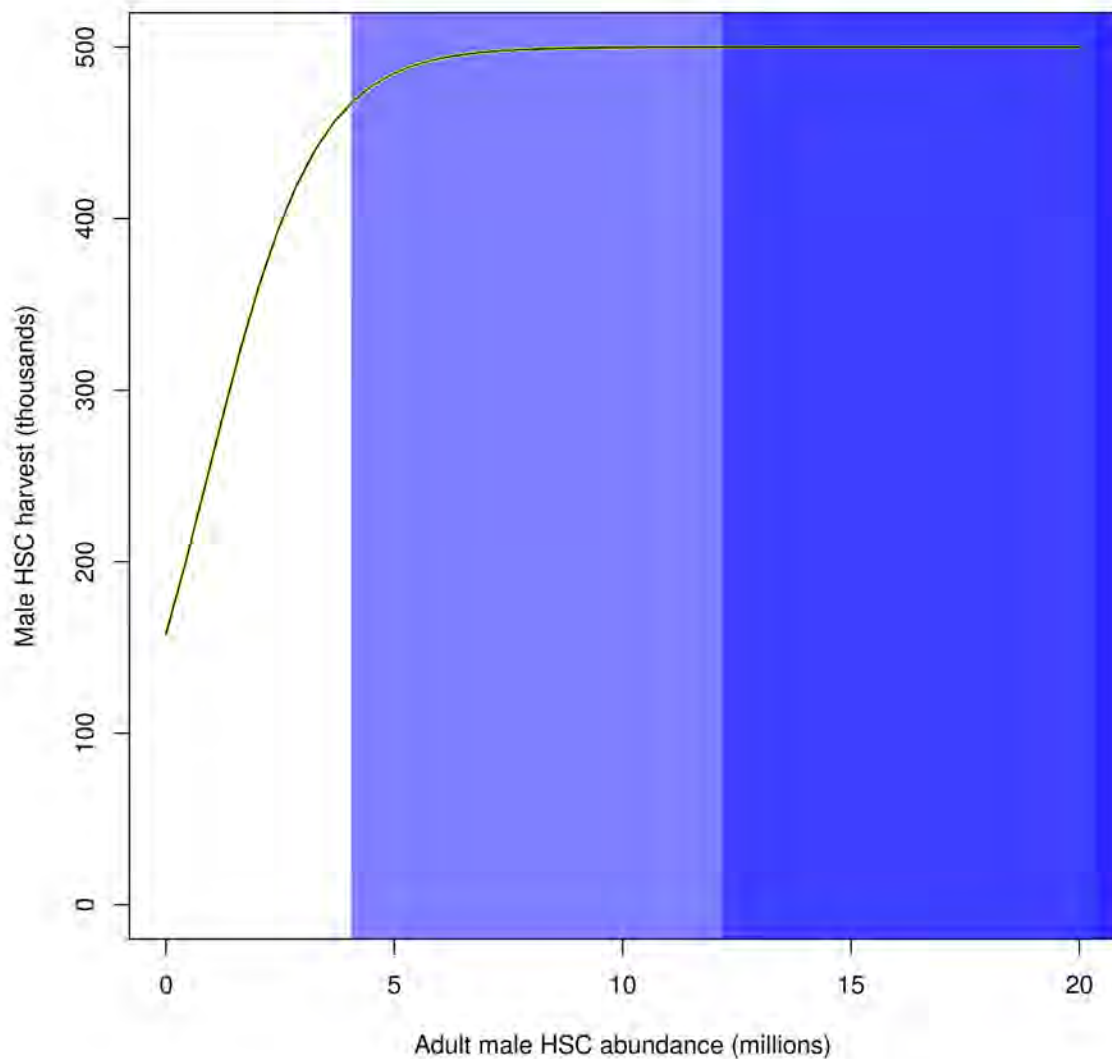


Figure 10. Optimal male bait harvest function for the canonical version of the revised ARM model , with $H_{\max}^f = 210,000$ and $H_{\max}^m = 500,000$. Vertical blue lines indicate actual male abundance values in a particular year, in one of 10,000 simulated horseshoe crab populations; many of these values are larger than the upper limit of the x-axis used here and thus are not shown.

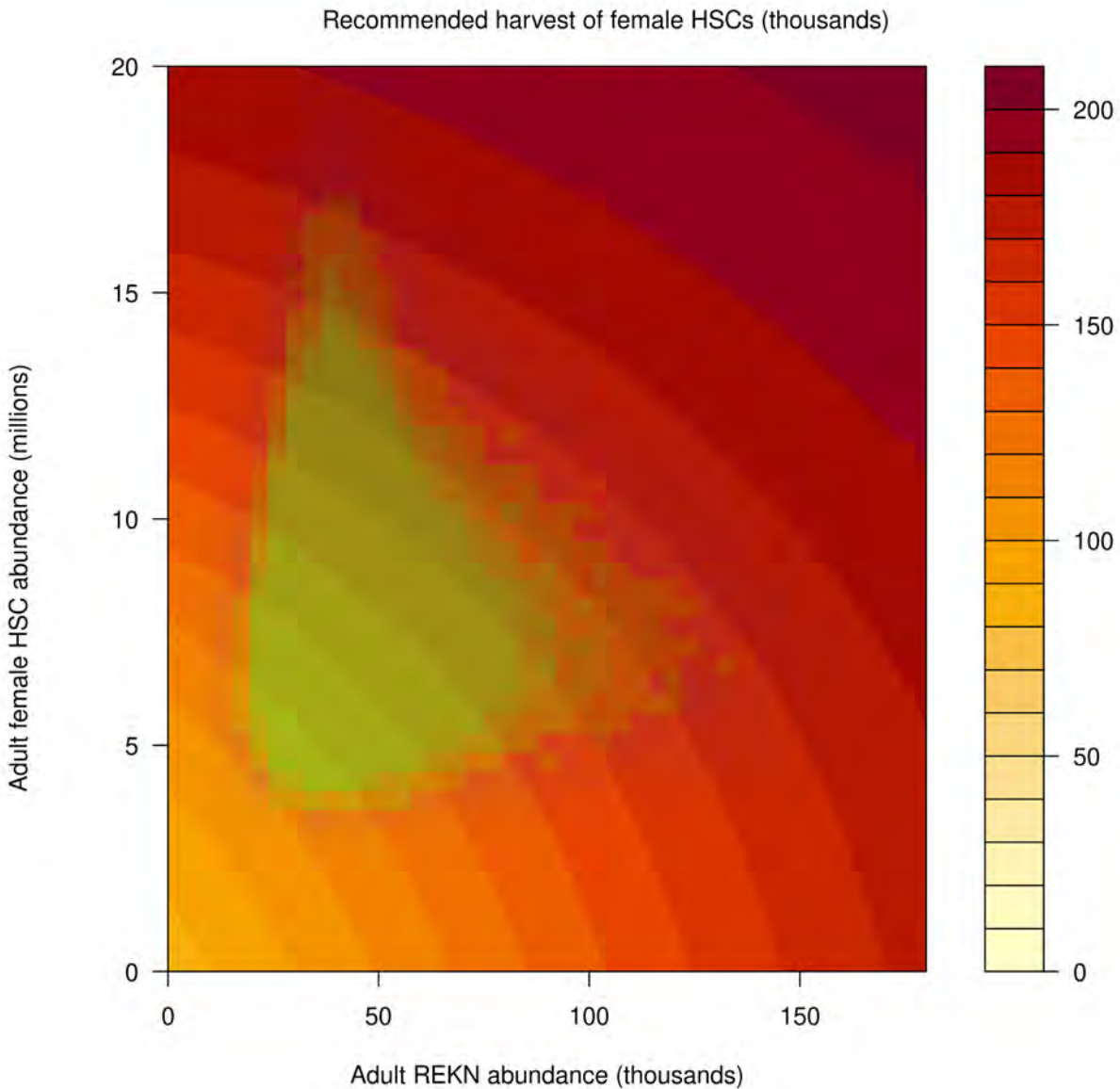


Figure 11. Optimal female bait harvest function for the canonical version of the revised ARM model , with $H_{\max}^f = 210,000$ and $H_{\max}^m = 500,000$. Recommended harvest depends on both female horseshoe crab (HSC) and adult red knot (REKN) abundances. Transparent green and blue overlay represents a non-parametric kernel, indicating where the bulk of the values of HSC and REKN abundances for the first 10 years of 10,000 simulations over 100 years: the green cells collectively contain 75% of the observations, the blue an additional 20%.

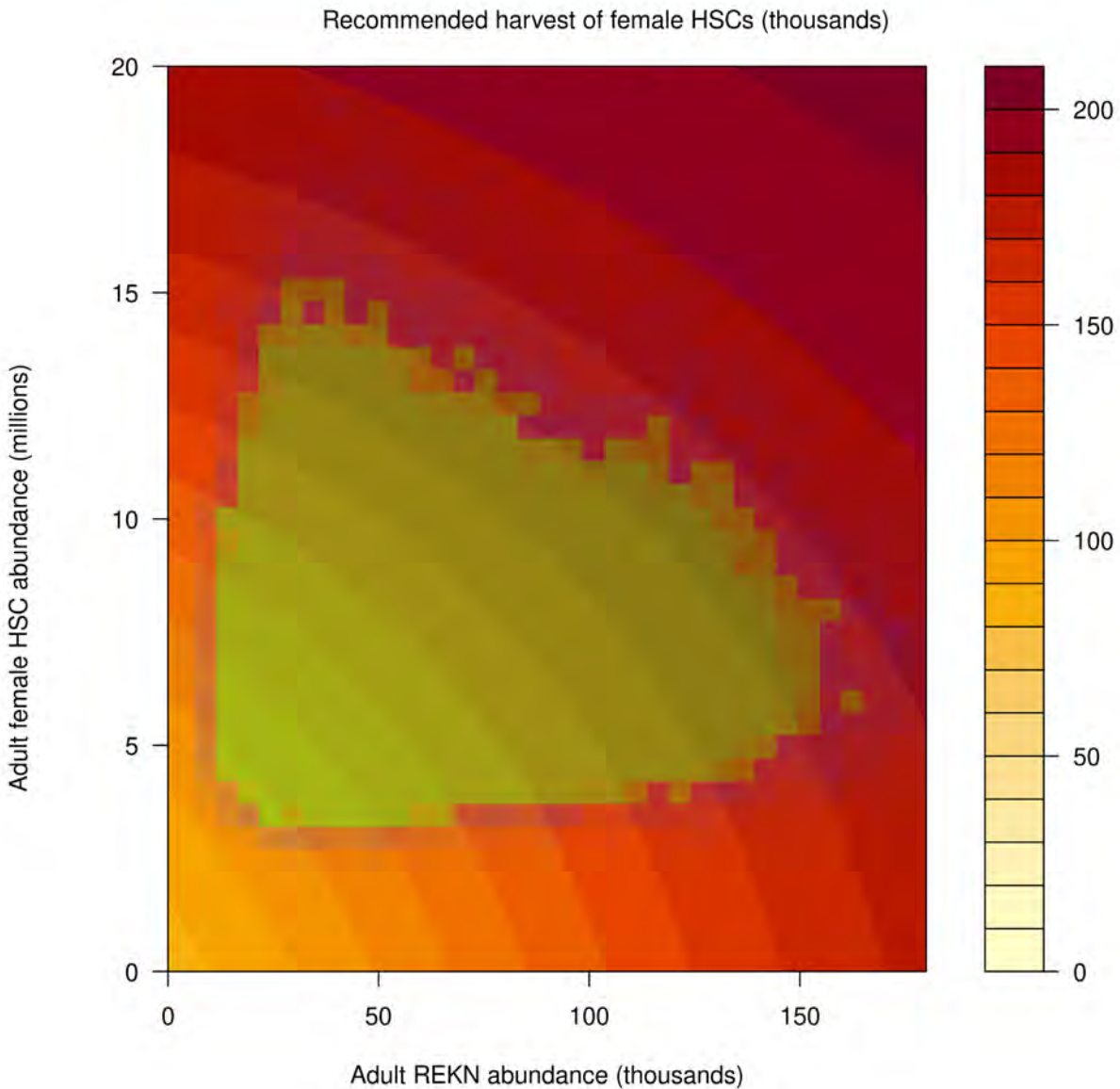


Figure 12. Optimal female bait harvest function for the canonical version of the revised ARM model , with $H_{\max}^f = 210,000$ and $H_{\max}^m = 500,000$. Recommended harvest depends on both female horseshoe crab (HSC) and adult red knot (REKN) abundances. Transparent green and blue overlay represents a non-parametric kernel, indicating where the bulk of the values of HSC and REKN abundances for years 11-20 of 10,000 simulations over 100 years: the green cells collectively contain 75% of the observations, the blue an additional 20%.

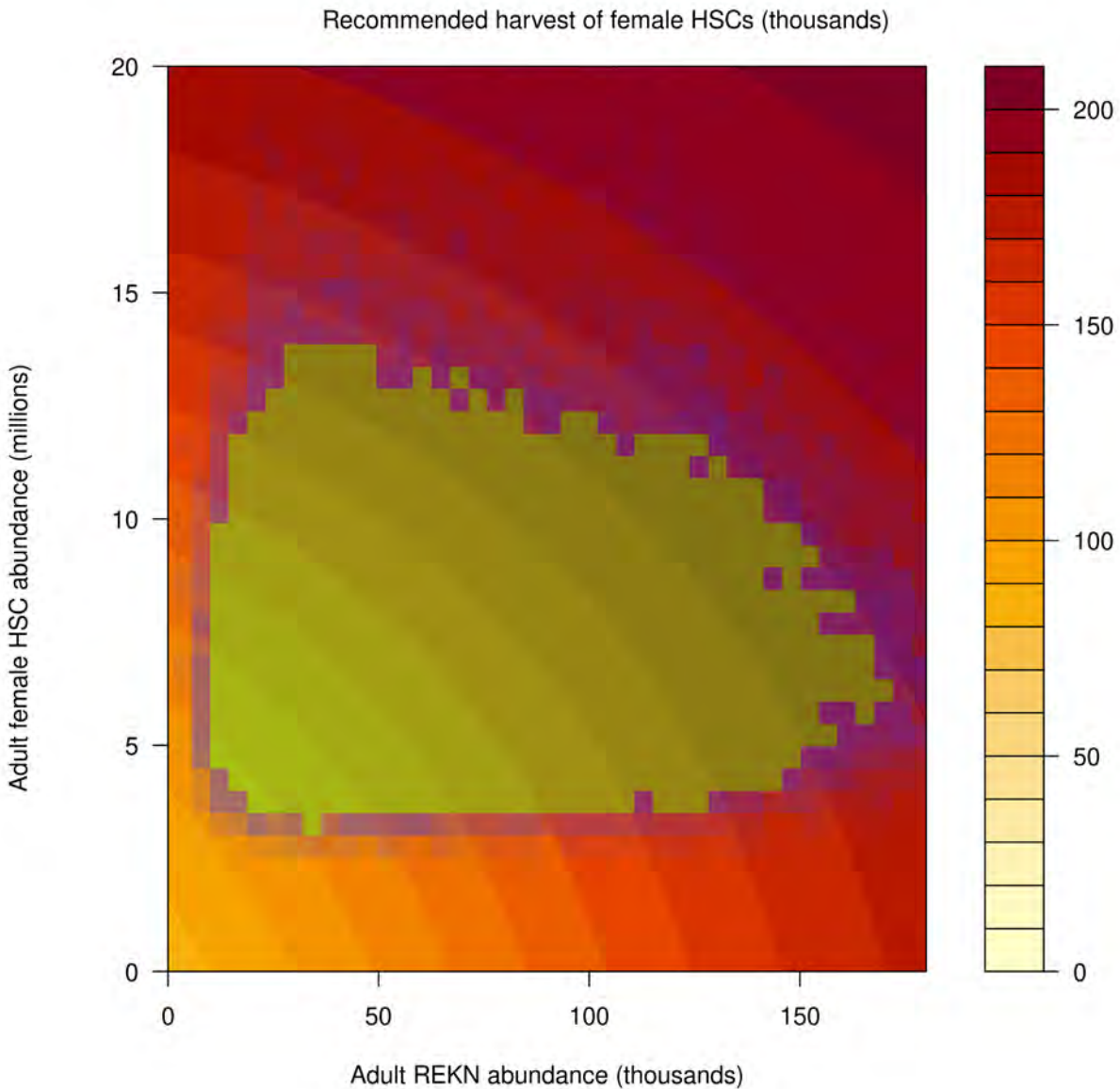


Figure 13. Optimal female bait harvest function for the canonical version of the revised ARM model , with $H_{\max}^f = 210,000$ and $H_{\max}^m = 500,000$. Recommended harvest depends on both female horseshoe crab (HSC) and adult red knot (REKN) abundances. Transparent green and blue overlay represents a non-parametric kernel, indicating where the bulk of the values of HSC and REKN abundances for years 21-30 of 10,000 simulations over 100 years: the green cells collectively contain 75% of the observations, the blue an additional 20%.

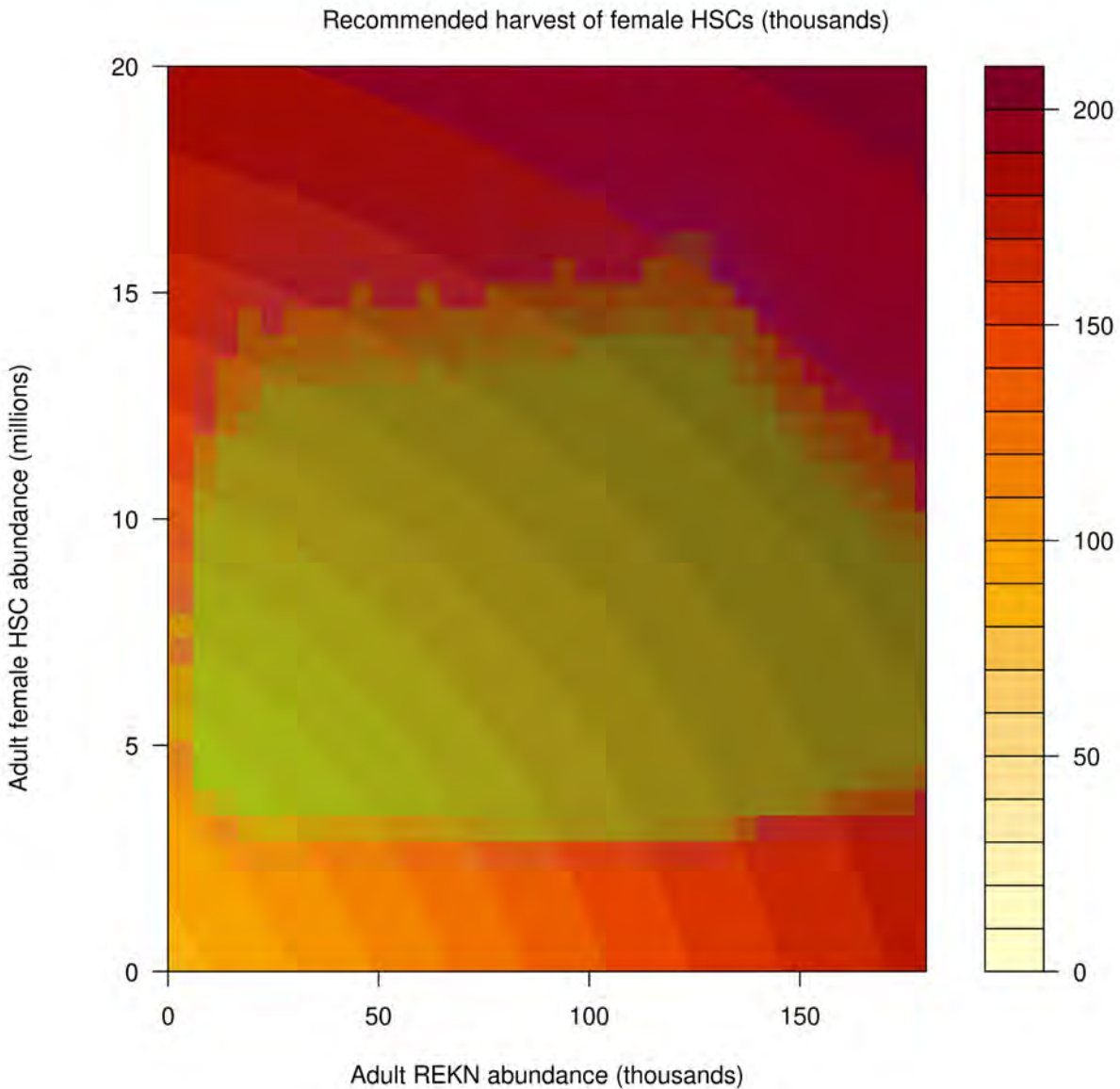


Figure 14. Optimal female bait harvest function for the canonical version of the revised ARM model, with $H_{\max}^f = 210,000$ and $H_{\max}^m = 500,000$. Recommended harvest depends on both female horseshoe crab (HSC) and adult red knot (REKN) abundances. Transparent green and blue overlay represents a non-parametric kernel, indicating where the bulk of the values of HSC and REKN abundances for years 31-100 of 10,000 simulations over 100 years: the green cells collectively contain 75% of the observations, the blue an additional 20%.

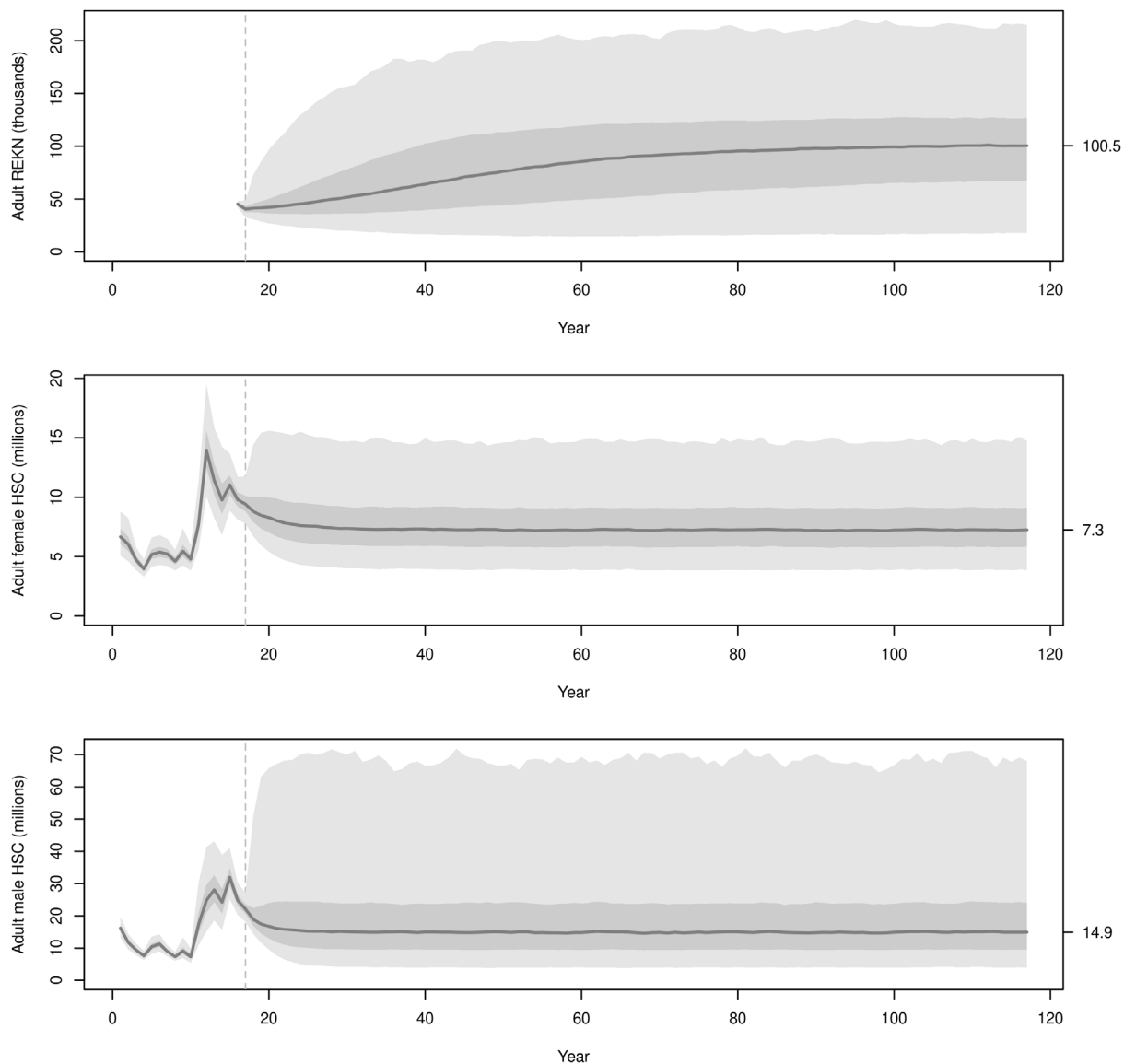


Figure 15. Summary of population trajectories for 10,000 simulated populations of horseshoe crabs and red knots under the optimal harvest policy for the canonical ARM model. Curves to the left of the vertical dashed gray line shows random draws from distributions based on actual estimates; simulated values begin to the right of the line. The dark gray line shows the median; dark gray region indicates the 25th and 75th percentile, or the 50% confidence interval; light gray region is bounded by the 2.5th and 97.5th percentiles, or the 95% confidence interval. Value in the right margin is the median at year 100 of the simulation (year 118 of the time series). Year 1 corresponds to 2003; dashed line is at 2019.

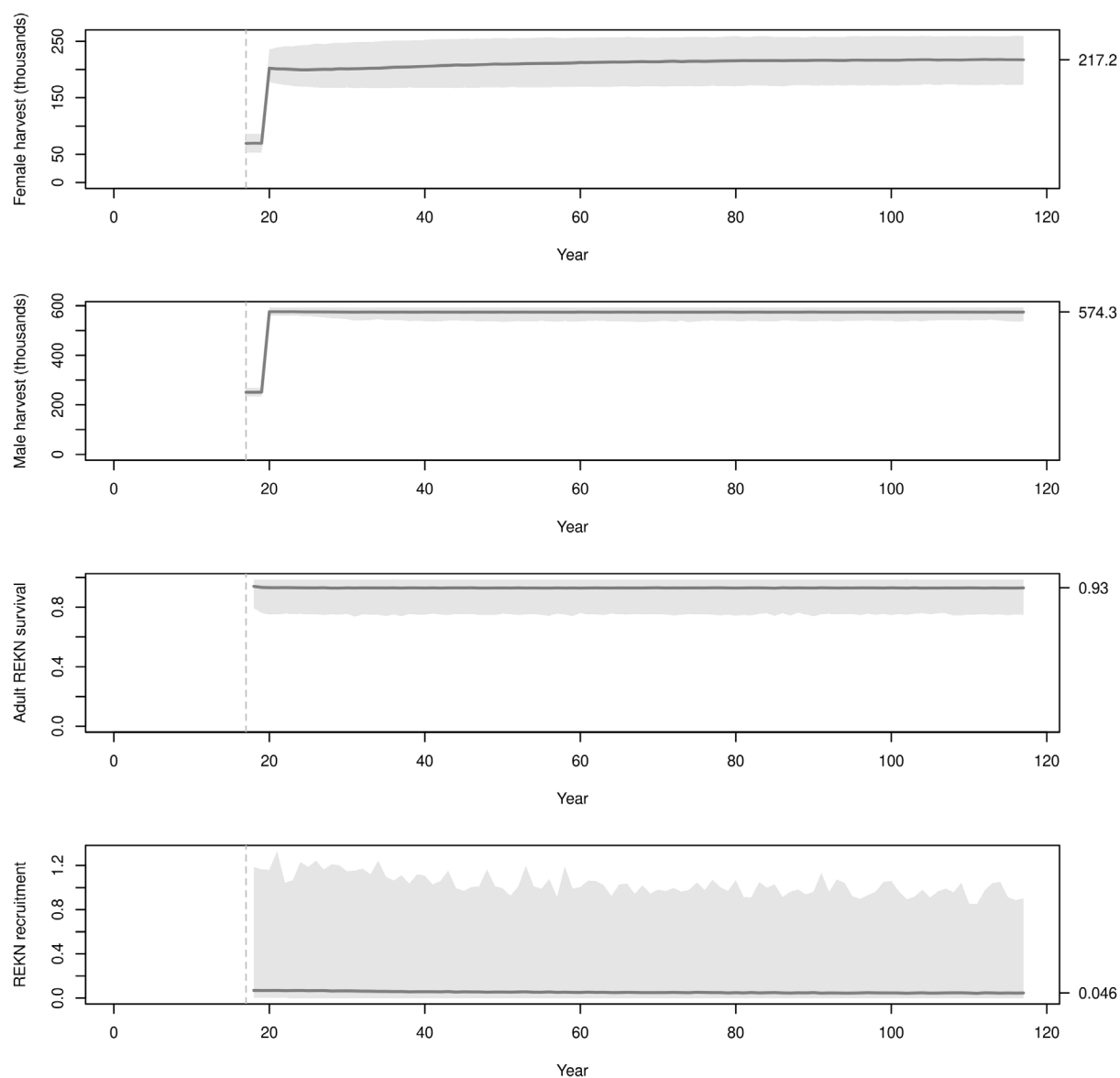
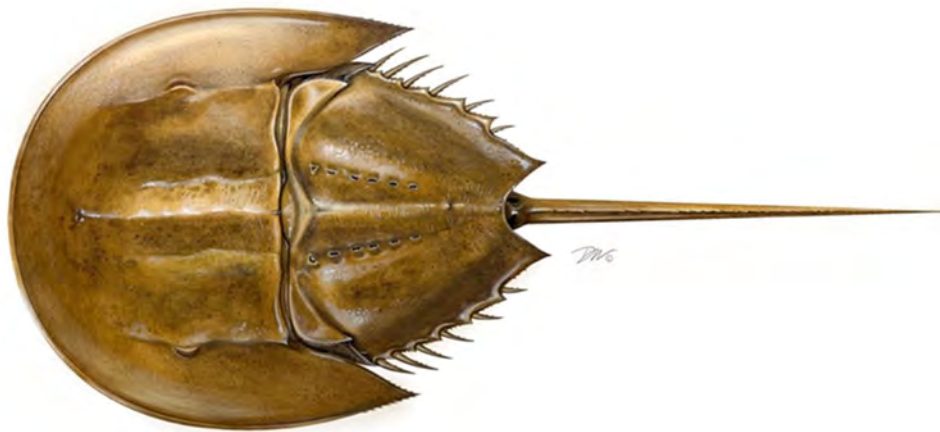


Figure 16. Summary of female and male horseshoe crab bait harvest and red knot (REKN) population parameters for 10,000 simulated populations under the optimal harvest policy for the canonical ARM model. The vertical dashed gray line lies at 2019; year 1 is 2003. The dark gray line shows the median; gray region is bounded by the 2.5th and 97.5th percentiles. Value in the right margin is the median at year 100 of the simulation (year 118 of the time series). Year 1 corresponds to 2003; dashed line is at 2019. Note that female and male harvest here include the ‘background harvest’ due to biomedical use and bycatch.

Atlantic States Marine Fisheries Commission

Revision to the Framework for Adaptive Management of Horseshoe Crab Harvest in the Delaware Bay Inclusive of Red Knot Conservation



**Accepted for Management Use
by the Horseshoe Crab Management Board
January 26, 2022**



Sustainable and Cooperative Management of Atlantic Coastal Fisheries

Prepared by the

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Statement Regarding Confidential Data

Note: The Adaptive Resource Management Revision and peer review was conducted using **coastwide** biomedical data, which is not confidential. When the model is run for the purpose of determining harvest in the Delaware Bay, the confidential data from the Delaware Bay states will be used by a person with confidential data access. The annual harvest package will be determined using Delaware Bay state confidential biomedical data but the public and managers will be shown the resulting population estimates using the coastwide non-confidential data only.

Confidential data are data such as commercial landings, including biomedical harvest, which can be identified down to an individual or single entity. Federal and state laws prohibit the disclosure of confidential data, and the Atlantic States Marine Fisheries Commission abides by those laws. In determining what data are confidential, most agencies use the “rule of 3” for commercial catch and effort data. The “rule of 3” requires three separate contributors to fisheries data in order for the data to be considered non-confidential. This protects the identity of any single contributor. In some cases, annual summaries by state and species may still be confidential because only one or two dealers process the catch. Alternatively, if there is only one known harvester of a species in a state, the harvester’s identity is implicit and the data for that species from that state is confidential.

EXECUTIVE SUMMARY

The purpose of this assessment was to revise the Adaptive Resource Management (ARM) Framework that was established through Addendum VII (2012) to the Horseshoe Crab fisheries management plan (FMP). The ARM Framework incorporates both shorebird and horseshoe crab abundance levels to set optimized harvest levels for Delaware Bay-origin horseshoe crabs. The objectives of the ARM Revision were to address previous peer review critiques, include many new sources of data and horseshoe crab mortality, and adopt advances in modeling and optimization approaches. This ARM Revision incorporates significant changes from the original version. However, the conceptual model of horseshoe crab abundance influencing red knot survival and reproduction remains intact with the intent of insuring that the abundance of horseshoe crabs does not become a factor limiting the population growth of red knots.

Red Knot Status

The red knot is one of the many shorebird species that feed on horseshoe crab eggs in the Delaware Bay Region during their migration. The red knot was listed as “threatened” under the United States Endangered Species Act in January, 2014, due to loss of habitat, climate change, timing mismatches between the birds’ migration and food availability, and other threats. In May 2021, the USFWS released for public comment a draft recovery plan for red knots to ensure the species recovery and resiliency with a goal of delisting by 2080. In July 2021, the USFWS published a proposed rule to designate critical habitat for the red knot. Both the final recovery plan and final critical habitat rule are expected in 2022.

Horseshoe Crab Stock Identification and Management Unit

The Atlantic States Marine Fisheries Commission (ASMFC) manages horseshoe crabs from Maine to eastern Florida, although the ARM Revision focuses on the Delaware Bay Region (i.e., New Jersey-Virginia). The percentages of Delaware Bay-origin crabs in each of the Delaware Bay state’s harvest was revised from the previous ARM Framework based on genetics data to be 100% Delaware Bay-origin for New Jersey and Delaware, 45% for Maryland, and 20% for Virginia. These Delaware Bay-origin values are lower than the previously used values of 51% for Maryland and 35% for Virginia.

Commercial Fisheries

Horseshoe crabs in the Delaware Bay Region are harvested commercially as bait for the commercial American eel and conch/whelk fisheries. Since 1998, states have been required to report annual landings to ASMFC through the compliance reporting process and bait landings were validated for 1998-2019 during this assessment. Bait harvest in the Delaware Bay has been limited to 500,000 male-only horseshoe crabs since the implementation of the ARM Framework in Addendum VII (2012).

Horseshoe crabs are also collected by the biomedical industry and a portion of their blood is extracted to support the production of *Limulus* ameocyte lysate (LAL), a clotting agent that aids in the detection of endotoxins in patients, drugs, and intravenous devices. Most crabs

collected and bled by the biomedical industry are released alive to the water from where they were collected; however, a portion of these crabs die from the procedure. A 15% mortality rate is applied to the number of horseshoe crabs bled and released alive to estimate the number of crabs that die each year. This source of removals was not accounted for in the previous ARM Framework but is now included in the ARM Revision. The biomedical harvest data is confidential, so coastwide biomedical data has been used for the revised ARM model development although annual harvest recommendations will be determined based on the region-specific confidential biomedical data.

Horseshoe crabs are also encountered in several other commercial fisheries. Commercial dead discards were estimated for the Delaware Bay Region as part of this ARM Revision with data from the Northeast Fisheries Science Center's Northeast Fisheries Observer Program. Commercial dead discards were not considered as a source of removals in the previous ARM Framework, but are now included in this ARM Revision.

Abundance Surveys

Three fishery-independent surveys were used for the ARM Revision to estimate horseshoe crab abundance: New Jersey Ocean Trawl, Delaware Fish and Wildlife Adult Trawl Survey, and Virginia Tech Horseshoe Crab Trawl Survey. All three surveys indicate stable abundance from 2003 through the early 2010s, then variable but increasing through 2019. Additionally, the Delaware Bay Horseshoe Crab Spawning Survey was used to estimate spawning beach sex ratios which has varied annually from three to five males for every female.

Mark-resight and count data from New Jersey and Delaware were used to estimate red knot passage population size. The passage population estimates were fairly stable between 2011 and 2020 at approximately 45,000 birds.

Population Models

The previous ARM used a horseshoe crab model based on life history parameters taken from the literature, most of which came from areas outside the Delaware Bay. In this ARM Revision, a catch multiple survey analysis (CMSA) was used to estimate male and female horseshoe crab population estimates for 2003-2019 using all quantifiable sources of mortality (i.e., natural mortality, bait harvest, coastwide biomedical mortality, and commercial dead discards). The CMSA indicated that adult abundance in the Delaware Bay was stable from 2003-2013 and then began increasing in the last few years for both sexes. This finding is consistent with stock rebuilding due to a period of significantly reduced commercial landings and tight management controls on the fishery beginning in the 2000s in this region. Estimated recruitment is less stable throughout the time series due to the missing years of data from the Virginia Tech Horseshoe Crab Trawl Survey. In 2019, the CMSA estimates that there were 23.9 million male and 7.3 million female horseshoe crabs*. Sensitivity runs were done to test various assumptions and inputs for the CMSA and the model was robust to the changes explored.

The previous models describing red knot population dynamics were also largely based on life history parameters taken from the literature and not specific to the Delaware Bay. For the ARM Revision, an integrated population model (IPM) was developed to quantify the effects of horseshoe crab abundance on red knot survival and recruitment based on data collected in the Delaware Bay. Estimates of adult red knot apparent survival probability were consistently high, with an average of 0.93. Estimates of recruitment rate were fairly low and showed little year-to-year variation. Estimates of population growth rate indicate that the red knot population was most likely stable to increasing from 2005-2018. Several iterations of the IPM were run to test the sensitivity of model outputs and fit. The IPM showed a positive effect of horseshoe crab abundance on red knot survival, but no effect of horseshoe crab abundance on red knot recruitment.

Projection models were developed to simulate the system state into the future. Because the state of the Delaware Bay system is represented in the ARM model via abundances of horseshoe crabs and red knots, population projection models are required for both species in the previous and revised ARM. The horseshoe crab projection model used in the ARM Revision derives directly from the CMSA population estimates and model structure. The predictions were not very sensitive to the harvest but were to recruitment. The revised red knot projection model mirrors the structure of the IPM.

Revised ARM Framework

The previous ARM Framework used Adaptive Stochastic Dynamic Programing (ASDP) software to determine an optimal harvest level of horseshoe crabs. This software is now antiquated, not supported, does not run on current computer operating systems, and was limited in its capacity to incorporate uncertainty when determining optimum harvest strategies. This ARM Revision uses an Approximate Dynamic Programing (ADP) approach implemented through the readily available R software. This new approach also incorporates uncertainty on all life history parameters for both horseshoe crabs and red knots.

The ADP optimization seeks to maximize the average total reward from the system. Reward is indexed as proportion of maximum allowable harvest value for horseshoe crabs plus the abundance of red knots relative to a target threshold of 81,900 birds. The previous ARM Framework only considered reward from the harvest of horseshoe crabs with red knot abundance as a constraint. Incorporation of both horseshoe crab harvest and red knot abundance in the reward function of the ARM Revision is more appropriate in that reward cannot be gained solely from one species (i.e., horseshoe crab harvest) which better reflects the values of all stakeholders. Maximum reward occurs when red knots are at high abundance and horseshoe crab harvest is high relative to the maximum allowable harvest. During the ADP optimization routine, many simulations of the linked population dynamics models for horseshoe crabs and red knots are ran, and parameters of harvest policy functions which maximize the average total reward over a 100 year time horizon are solved for. These harvest policy functions are logistic functions that determine the proportion of maximum male and female horseshoe crab harvest (500,000 and 210,000, respectively) that could be harvested

given the current abundances of male and female horseshoe crabs as well as the current abundance of red knots.

The annual decision of allowable horseshoe crab harvest is based on current state of the system (abundances of both species) and the optimal harvest policy functions from ADP. Annual estimates of horseshoe crab and red knot abundances are used as input to the harvest policy functions, which then output the optimal horseshoe crab harvest to be implemented. The previous ARM Framework used horseshoe crab abundance estimates derived from the Virginia Tech Trawl swept area population estimates, however CMSA estimates of abundance are used in the ARM Revision. Both the previous ARM Framework and this ARM Revision use the annual mark-resight population estimates of red knots as annual input.

Harvest recommendations under the ARM Revision are based on a continuous scale rather than discrete harvest packages as in the previous Framework. Also, the harvest of females is decoupled from the harvest of males in this revision. However, the maximum harvest possible was maintained for females at 210,000 and for males at 500,000. Although harvest is treated as continuous in the new ARM Framework, harvest could be rounded to some fixed values to more closely approximate previous harvest packages and minimize changes to allowable harvest between years. For example, an optimal continuous harvest of 135,400 females could be rounded down to 100,000 females.

Stock Status

There have been no overfishing or overfished definitions adopted by the Management Board for horseshoe crabs in the Delaware Bay. The 2019 benchmark stock assessment characterized the status of the Delaware Bay area as “neutral” based on trend analysis. The purpose of this ARM effort in the Delaware Bay was not to determine stock status in the traditional sense of commercial fishery management (e.g., overfished and/or overfishing). Rather, the purpose was to determine the optimal harvest strategy given the abundance of horseshoe crabs and red knots. Based on the base run of the revised ARM model, the recommended harvest in 2019 would have been 499,939 male and 138,243 female* horseshoe crabs. Conversely, the previous ARM model recommended 500,000 male-only harvest.

It should be noted that this ARM Revision was developed using coastwide biomedical data so as to avoid data confidentiality issues. The population estimates for horseshoe crabs from the CMSA therefore represent an overestimate. If this Revision is accepted for management use, the Delaware Bay-specific biomedical data will be used to determine the harvest package and the model will be run by someone (e.g., ASMFC staff) with confidential data access. Therefore, the final harvest recommendations are likely to be marginally lower than those reported here. No other model inputs were affected by data confidentiality.

This revision of the ARM Framework represents several advancements in not only the knowledge of the population dynamics of horseshoe crabs and red knots, but also how to efficiently model them. The population dynamics models for both species are now parameterized with empirical data from the Delaware Bay rather than based on literature values for life history parameters coming from elsewhere. Because they are based on empirical

data from the Delaware Bay, model updating will be more efficient and transparent as new data for both species is collected through routine monitoring efforts.

*NOTE: The base run of the ARM model was amended during the Peer Review Workshop and a supplemental report was provided to the Board with the new base run. The changes effect the Delaware Adult Trawl Survey and thus the population estimates for horseshoe crabs from the CMSA, the results of the IPM, and the revised ARM Framework including the final recommended harvest. The values cited in this Executive Summary will change.

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TERMS OF REFERENCE

For the 2021 ASMFC Adaptive Resource Management Revision

Board Approved October 2020

Terms of Reference for the Adaptive Resource Management Revision

- 1. Use and further develop, as needed, the peer reviewed and accepted 2019 benchmark stock assessment catch multiple survey analysis (CMSA) model as the underlying horseshoe crab population model in the Adaptive Resource Management (ARM) Framework. Include and account for commercial bycatch (dead discards) and biomedical mortality in the Delaware Bay Region as an input to the CMSA model.**

The CMSA model was used in this ARM Revision and further developed to address previous peer review comments (Section 6.1). The same model structure was used as the 2019 benchmark assessment but the time series was extended by two additional years of data. Survey weights for the three fishery-independent surveys were dropped as recommended by the peer review panel since the weights were calculated in a way that might have resulted in double-counting the abundance indices' errors. The value of natural mortality was also slightly increased based on an updated analysis of tagging data (Section 2.1.4). The commercial dead discard estimates were updated following the previous peer review panel's comments and the revised values were used in this CMSA (Section 3.3) in addition to coastwide biomedical data, not Delaware Bay-specific biomedical data (Section 3.2). For each change made from the 2019 benchmark, a sensitivity run was done to evaluate the effects of that change (Section 6.1.5). The model was developed with coastwide biomedical to avoid the use of confidential data, but if the Revised Framework is approved for management use, the Delaware Bay confidential biomedical data will be used for recommending harvest in the region.

During the 2019 benchmark assessment, the assessment team focused on the CMSA model development of female horseshoe crabs. While a male model was attempted at that time, there were initially some convergence issues and poor survey fits and further development was not attempted due to the timeline of the benchmark. For this ARM Revision, more time was dedicated to explore starting values and stability of the male model, and a male model was successfully developed using the same data sources as the female model.

- 2. Reassess ARM utility of female horseshoe crab harvest as a function of female abundance.**

The horseshoe crab utility in this ARM Revision depends upon the number of female and male horseshoe crabs harvested relative to the maximum allowable harvest in the original ARM Framework. The horseshoe crab utility reflects a precedent established in the original ARM model, that the monetary value of harvested female horseshoe crabs is twice that of males (Section 8.5). Further, the reward function has been revised to promote a balance between horseshoe crab and red knot utilities, because although some reward can be obtained when the harvest of crabs and abundance of red knots is high, higher reward values are only possible when both are high.

3. Update red knot survival and mass gain model with most recent data.

The ARM Revision attempted to replicate the multi-state framework used in the previous ARM Framework (ASMFC 2009a) and McGowan et al. (2011a) using the most recent data available (Section 7.1). The multi-state model in the original ARM Framework estimated annual survival of red knots that stop at Delaware Bay based on their body mass at departure and estimated the probability of gaining weight during stopover. Because of the hypothesized relationship between female horseshoe crab abundance and mass gain of red knots, the survival modeling provided a direct link between red knot population dynamics and female horseshoe crab abundance. When the time series was extended and the inputs were revised to reflect the most recent data, the model produced counterintuitive results that were not consistent with the ARM workgroup's hypotheses and predictions about the effects of horseshoe crab abundance on refueling energy needs of red knots during stopover at Delaware Bay. Furthermore, the results were inconsistent with the results of ASMFC (2009a) and McGowan et al. (2011a). Therefore, this approach was abandoned and an integrated population model (IPM) was pursued (Section 7.2). The IPM produced estimates of adult apparent survival probabilities and estimates of recruitment rate for red knots. A mass gain model was no longer needed with the revised modeling approach.

4. Evaluate red knot model weights.

The previous ARM Framework made use of three competing models of red knot population dynamics, which differed mainly in the influence of horseshoe crabs they specified (ASMFC 2009a). The models were assigned weights, and all three were employed in simulating red knot populations with predicted abundances representing a weighted average of the three models' predictions. In a 'passive' approach to adaptive management, these model weights would be periodically updated using monitoring data. However, model weight updating was not pursued since the ARM Revision abandoned the multi-state framework and used the IPM (see TOR3). The IPM did not require the use of model weights (Section 7.2).

5. Request the disclosure of confidential biomedical data for use in the base run CMSA estimate. If the companies say no to the disclosure: Run the CMSA with the confidential biomedical data with 15% applied mortality, without biomedical data, and with non-confidential coastwide biomedical data with 15% applied mortality. The harvest package will be made based on the population estimates from the CMSA that includes confidential data, as it represents the best data set available. Publish 0% biomedical and coastwide biomedical population estimates as population bounds.

The ASMFC circulated a letter to each of the biomedical facilities requesting the disclosure of confidential biomedical data for use in the base run of the CMSA estimate. This request was denied and thus the ARM Revision proceeded with using coastwide biomedical data with a 15% mortality for the model development. A sensitivity run of the CMSA was done using 0% biomedical mortality (Section 6.1.5).

6. Reevaluate definition of Delaware Bay crabs and the implications towards the population estimates and harvest allocations.

The definition of Delaware Bay-origin horseshoe crabs was reevaluated based on the most recent genetics work (Section 2.1.1). The proportion of each states' bait landings that were of Delaware Bay origin were revised to reflect the new analyses done in the region.

Terms of Reference for the Adaptive Resource Management Revision Peer Review

1. Evaluate adequacy of the proposed models for estimating horseshoe crab population dynamics and projections for use in the ARM Framework, including the definition of Delaware Bay crabs.
2. Evaluate the proposed changes to the red knot population dynamics model and model weights.
3. Evaluate adequacy of the fishery-dependent, fishery-independent, and life history data used in the ARM Framework revisions for both horseshoe crabs and red knots, including the use of biomedical data.
4. Develop recommendations for improving assessment methodology and data collection.
5. If a minority report has been filed, review minority opinion(s) and associated analyses. If possible, make recommendation on current or future use of alternative approaches presented in minority report(s).
6. Prepare a peer review panel terms of reference 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 four weeks of workshop conclusion.

1 INTRODUCTION

1.1 Brief Overview

Since 1998, the horseshoe crab fishery has been managed cooperatively by Atlantic coast states through the Atlantic States Marine Fisheries Commission (ASMFC; ASMFC 1998). The Horseshoe Crab Management Board approved the Horseshoe Crab Fishery Management Plan (FMP) in October 1998. The goal of the FMP is “management of horseshoe crab populations for continued use by: current and future generations of the fishing and non-fishing public (including the biomedical industry, scientific and educational research); migratory shorebirds; and other dependent fish and wildlife (including federally listed sea turtles).” The FMP outlined a comprehensive monitoring program and maintained controls on the harvest of horseshoe crabs put in place by New Jersey, Delaware, and Maryland prior to the approval of the FMP. These measures were necessary to protect horseshoe crabs within and adjacent to the Delaware Bay, which is the epicenter of spawning activity along the Atlantic coast.

Because much of the concern about a reduced horseshoe crab population centered on the ecosystem services provided by high abundance of horseshoe crabs within Delaware Bay, an effort began in 2007 (Breese et al. 2007) to develop a multi-species approach to managing horseshoe crabs by employing the tools of structured decision making and adaptive management. In 2007, the Horseshoe Crab and Shorebird Technical Committees met and endorsed the development of a structured decision making (SDM) framework and adaptive management approach to harvest management. An adaptive resource management (ARM) subcommittee was formed with representatives from state and federal partners, as well as horseshoe crab and shorebird biologists. The subcommittee produced a framework for adaptive management of horseshoe crabs in the Delaware Bay that was constrained by red knots which was peer-reviewed with a coastwide benchmark stock assessment for horseshoe crab in 2009 (ASMFC 2009a, 2009b).

Addendum VII was approved in February 2012 (ASMFC 2012). The addendum implemented the Adaptive Resource Management (ARM) Framework for use during the 2013 fishing season and beyond. The Framework considered the abundance levels of horseshoe crabs and shorebirds in determining the optimal harvest level for the Delaware Bay states of New Jersey, Delaware, Maryland, and Virginia (east of the COLREGS). Since then, the Board annually reviews recommended harvest levels from the ARM Subcommittee, who run the ARM model, and specifies harvest levels for the following year in New Jersey, Delaware, Maryland, and Virginia.

This report revises the ARM model structure, as described in the Terms of Reference, in addition to migrating the model to a new software platform.

1.2 Structured Decision Making and Adaptive Management

Structured decision making (SDM) is a formal and transparent approach to decision making (Hammond et al. 2002; Gregory et al. 2012; Runge et al. 2020) that incorporates views of all stakeholders and uses predictive modeling to assess the potential consequences of alternative

actions (Gregory and Keeney 2002; McGowan et al. 2011a; McGowan et al. 2015a). The key to successful decision making is to break a complex decision down into its component parts and address each part sequentially (Hammond et al. 2002; Gregory and Keeney 2002). The decision analysis follows a sequence in which the problem is defined, the management objectives are identified, potential alternative actions are determined, and models are developed for the purpose of projecting the consequences of the actions. For management of natural resource systems, estimates of system state (e.g., population size) are obtained and then used with the above components to make the decision, often with the help of an optimization algorithm.

Adaptive management, which can be viewed as structured decision making for sequential decision processes, is becoming increasingly important and has been endorsed by federal management agencies (Williams et al. 2007; Runge 2020). The approach entails making predictions about how a system will respond to management actions, followed by implementation and monitoring of the system to evaluate the accuracy of the a priori predictions. The ARM approach builds on existing approaches in several important ways. First, there is a great emphasis on complete elicitation of objectives and management actions from a full range of stakeholders. Second, this process facilitates learning while managing and uncertainty about system dynamics including competing models of how the system works (e.g., how species respond to management actions, how species interact with other species and their environment) can be incorporated into the decision process. Third, a variety of optimization tools are available to identify the optimal action under multiple, and sometimes conflicting, objectives. Fourth, monitoring data are used to update knowledge about system dynamics by either refining parameter estimates or updating weights assigned to competing system models. This last point illustrates that in an iterative setting where decisions are made repeatedly over time, the system models can be improved based on the accuracy of their predictions, and future decisions can be improved (Williams et al. 2007; Runge 2020). Four types of uncertainty characterize natural resources management (Regan et al. 2002): 1) ecological or structural uncertainty, 2) environmental uncertainty, 3) partial controllability, and 4) partial observability. In the face of uncertainty, dynamic programming is a powerful tool that can be used to find an optimal management policy given the objectives and available actions, the understanding of the system as reflected by the system models, and the estimated state of the system.

1.3 Original Adaptive Resource Management Framework for Horseshoe Crabs and Red Knots (2009)

Underlying the original (2009a) ARM model are population models for both red knots and horseshoe crabs (ASMFC 2009a; McGowan et al. 2011a, 2015b). The optimization routine in the ARM model determines the best choice among five potential harvest packages (numbers of male and females that can be harvested) given the current abundance of each species in order to maximize the long-term value of horseshoe crab harvest. The ARM model values female harvest only when the abundance of red knots reaches 81,900 birds (a value related to the historic abundance of red knots in the Delaware Bay) or when the abundance of female horseshoe crabs reaches 80% of their predicted carrying capacity (11.2 million assuming a carrying capacity of 14 million; ASMFC 2009a). On an annual basis, the ARM model is used to

select the optimal harvest package to implement for the next year given the current year's estimate of horseshoe crab abundance from the swept area estimate from the VA Tech trawl survey and a mark-resight estimate of red knot abundance.

A stage-structured population model was used for horseshoe crabs based on an age-structured model by Sweka et al. (2007). Multiple juvenile years were condensed into a single stage with a constant probability of transition out of that stage and into either a pre-breeding stage or breeding adult stage. Horseshoe crabs are partitioned into different sexes as they enter the breeding stage and there are different survival rates applied to pre-breeders and breeding adults annually. A fertility factor (Caswell 2001) was used to reduce reproduction when the operational sex ratio (Section 2.1.5) of adult stages falls below a target and the number of eggs laid per female, egg survival, and age-zero survival were incorporated as a multiplier on fecundity in the state dynamics equations.

Construction of the red knot population model was more straightforward and a modified version of the Baker et al. (2004) three-stage population model was used. Within the adult stage, birds are in one of two weight states, above or below a threshold weight of 180g. The model tracked arrival time and weight, weight gain, and departure probabilities in the Delaware Bay. The weight gain probabilities were tied to horseshoe crab abundance and the proportion of the crab population that spawns during the stopover period. From this basic matrix model structure, there were three alternative ways that horseshoe crab abundance could affect red knot population dynamics: 1) a "no interaction" model, where red knot weight gain and horseshoe crab status were disconnected, allowing the two species to operate independently of each other, 2) a fecundity only effect model, where horseshoe crabs affect only the fecundity or productivity of the red knot population, and 3) a full effect model where horseshoe crab abundance affects both fecundity and annual survival of adult red knots. Each of the three models was assigned a weight based on committee consensus. At the end of the stopover season, the two weight states of adult red knots survive and reproduce at different rates, depending on the model.

On an annual basis, the ARM model is used to select the optimal harvest package to implement for the next year given the current year's estimate of horseshoe crab abundance from the swept area estimate from the VA Tech trawl survey and a mark-resight estimate of red knot abundance. The harvest packages for horseshoe crab bait harvest that can be selected by the ARM model are:

- Package 1) Full harvest moratorium on both sexes
- Package 2) Harvest up to 250,000 males and 0 females
- Package 3) Harvest up to 500,000 males and 0 females
- Package 4) Harvest up to 280,000 males and 140,000 females
- Package 5) Harvest up to 420,000 males and 210,000 females

Since its implementation in 2013, neither the 81,900 red knot threshold nor the 11.2 million female horseshoe crab thresholds have been met and harvest package 3 has been selected every year by the Framework.

1.4 Status of Horseshoe Crabs

1.4.1 Horseshoe Crab Assessment History

1.4.1.1 Previous stock assessments

The initial stock assessment for horseshoe crab was completed and peer reviewed in 1999 (ASMFC 1999). A new assessment framework was proposed in 2000 (ASMFC 2000a), and an internally peer-reviewed assessment was produced in 2004 and another in 2009 (ASMFC 2009b) and updated in 2013 (ASMFC 2013). The most recent benchmark stock assessment for the coastwide horseshoe crab population was completed, peer-reviewed, and approved for management in 2019 (ASMFC 2019).

The ARM Framework, which went through peer review in 2009 and was established through Addendum VII (2012) to the FMP, has been used to manage horseshoe crabs in the Delaware Bay region since the 2013 fishing year.

1.4.1.2 Summary of Previous Assessment Models

1.4.1.2.1 ARM Model (2009)

See Section 1.3.

1.4.1.2.2 Benchmark Stock Assessment (2019)

The coastwide benchmark stock assessment (ASMFC 2019) for horseshoe crabs used several fishery-independent surveys to characterize trends in abundance in four regions. Two surveys were located in the Northeast region, four in the New York region, seven in the Delaware Bay region, and five in the Southeast region. Tagging data from the U.S. Fish and Wildlife Service horseshoe crab database were explored by region to estimate survival. The highest survival rates were in the Delaware Bay and coastal Delaware-Virginia regions. The lowest survival rates were in coastal New York-New Jersey and the Southeast. A trend analysis, Autoregressive Integrated Moving Average (ARIMA), was used to assess regional and coastwide stocks. For the trend analysis, 1998 was used as the benchmark year for comparison of survey trends since it was the first year of FMP implementation.

An additional stage-based model, a catch multiple survey analysis (CMSA), used pre-recruits and full recruits to assess the Delaware Bay region. This model included several sources of removals from the population: bait harvest, dead discards from commercial bycatch, mortality associated with biomedical bleeding, and natural mortality. The CMSA indicated adult

abundance in the Delaware Bay was stable from 2003-2012 and then considerably increased through 2017, the terminal year of the model.

1.4.1.2.3 Previous Peer Review Comments

The Peer Review Panel for the original ARM report (ASMFC 2009a) supported the use of the Framework for managing horseshoe crabs in the Delaware Bay. The Panel provided positive feedback on the model development and data handling but also some criticisms and suggestions for future work. For example, they were concerned about the use of a knife-edge utility function to represent the value of harvest associated with differing levels of female crabs and adult red knot abundance. The reviewers recommended a distribution of values for the parameter representing survival of lower weight red knot birds given its importance to the population trajectory and there were concerns that the three models used for the red knots may not be the most suitable candidates for the optimization analysis. They also criticized the report for not providing the results of any simulation work, sensitivity runs, assumptions for either model, or a summary table of parameter values.

The ARM model went through an internal committee review in 2016 to monitor and evaluate the model performance (summarized in McGowan et al. 2020). As part of the review, the ARM subcommittee evaluated the monitoring programs for horseshoe crabs and red knots and found that while the surveys used were appropriate and represented the best data available, future consideration should be given to incorporating mortality due to the biomedical industry in the region. The subcommittee also evaluated the harvest of the Delaware Bay states relative to the quotas and the harvest packages in the model and did not recommend any changes. Finally, the structure of the objective function was assessed, specifically to determine if the approach is still the most appropriate and if the thresholds are set at appropriate levels. No changes were made except for removing a sex ratio constraint from the utility function because it was deemed to be conceptually redundant within the model. Following the review, the committee recommended that a larger revision of the ARM model should be conducted that considered changing the model platform and updating the Framework with new models, if available, and updating and revising parameters to incorporate new analyses and data as needed. The recommendations from that review were the basis of the Terms of Reference (TORs; page 1) for this ARM Revision.

The Peer Review Panel for the 2019 benchmark stock assessment supported the CMSA as a stock assessment method for horseshoe crab in the Delaware Bay, but did not approve the reference point developed by the Stock Assessment Subcommittee for determining overfished and overfishing status to compare with the model output. Regardless, the Panel acknowledged that the CMSA abundance estimates represent the best available data and recommended using the CMSA estimates in the ARM Framework.

1.4.2 Stock Status

The 2019 Horseshoe Crab Benchmark Stock Assessment evaluated the stock status of the resource by region, finding populations within the Delaware Bay and Southeast regions

remaining consistently stable and in good status, respectively, through time. The status of the Northeast region population has changed from poor to stable, while the status of the New York region population has trended downward from good, to stable, and now to poor. The Benchmark Assessment was endorsed by the Peer Review Panel and accepted by the Horseshoe Crab Management Board for management use.

To date, no overfishing or overfished definitions have been adopted for management use. For the assessment, biological reference points were developed for the Delaware Bay region horseshoe crab population although not endorsed by the Peer Review Panel for use in management. However, given the assessment results of low fishing mortality and relatively high abundance, overfishing and an overfished status are unlikely for female horseshoe crabs in the Delaware Bay region.

1.5 Status of Red Knots

The *rufa* red knot (*Calidris canutus rufa*) was added to the United States List of Endangered and Threatened Wildlife as threatened in January 2014 (USFWS 2014), due to loss of habitat, climate change, and timing mismatches between the birds' migration and food availability, among other threats. Additionally, red knots have been listed as endangered under the Canadian Species at Risk Act since 2012. In May 2021, the USFWS released for public comment a draft recovery plan for red knots to ensure the species recovery and resiliency with a goal of delisting by 2080. In July 2021, the USFWS published a proposed rule to designate critical habitat for the red knot. Both the final recovery plan and final critical habitat rule are expected in 2022. The draft recovery plan, critical habitat maps, a 2020 Species Status Assessment, and additional information can be found on the USFWS website: <https://fws.gov/northeast/red-knot/>.

1.6 Changes to ARM Framework in this Revision

The purpose of revising the ARM Framework was to address previous critiques, include newly available data, and adopt advances in modeling and optimization approaches (Section 1.4.1.2.3). This revision of the ARM Framework incorporates significant changes from the original version that was peer reviewed in 2009 and adopted for management use in 2012. However, the conceptual model of horseshoe crab abundance influencing red knot survival and reproduction remains intact with the intent of insuring that the abundance of horseshoe crabs does not become a factor limiting the population growth of red knots. The original objective statement was:

Manage harvest of horseshoe crabs in the Delaware Bay to maximize harvest but also maintain ecosystem integrity and provide adequate stopover habitat for migrating shorebirds.

Over the years, this objective statement has been criticized because the conservation intent for commensal species such as red knots was not apparent to all stakeholders and seemed, to some, less explicit than the harvest intent. With the listing of the red knot as a threatened

species under the endangered species act in 2015, and the need to be more explicit about the intent of the ARM Framework, the ARM workgroup rephrased the objective statement to:

Manage harvest of horseshoe crabs in the Delaware Bay to maximize harvest but also to maintain ecosystem integrity, provide adequate stopover habitat for migrating shorebirds, and ensure that the abundance of horseshoe crabs is not limiting the red knot stopover population or slowing recovery.

The changes to the original ARM Framework and modeling made during this revision represent an increase in not only the amount of data available for each species, but also an evolution of modeling techniques and experience. The major changes are described in detail throughout this report, but are summarized below.

- Abandonment of Adaptive Stochastic Dynamic Programming (ASDP) software – ASDP is an antiquated software that is no longer supported and is not compatible with contemporary computer operating systems. ASDP also suffered from capacity issues that constrained the degree of biological realism that could be incorporated in population projection models.
- Revised Horseshoe Crab Population Dynamics Model – The previous horseshoe crab model was based on life history parameters taken from the literature, most of which came from areas outside the Delaware Bay. The revised model has the same structure as the Catch Multiple Survey Analysis (CMSA) model which was approved for management use following the 2019 stock assessment. This new model is based on empirical data directly from the Delaware Bay and includes all quantifiable sources of removals from the population including bait harvest, biomedical mortality, discards from other fisheries, and natural mortality.
- Revised Red Knot Population Dynamics Models – The previous models describing red knot population dynamics were also largely based on life history parameters taken from the literature and not specific to the Delaware Bay. The three models represented uncertain alternative hypotheses about the influence of horseshoe crab on red knots. The revised red knot model is an integrated population model (IPM) developed specifically for red knots stopping in Delaware Bay and directly quantifies the effects of horseshoe crab abundance on red knot survival and recruitment based on empirical data collected from Delaware Bay.
- Revised Reward Function – The original reward function in the ASDP optimization only valued the harvest of horseshoe crabs. The revised reward function now values both horseshoe crab harvest and the abundance of red knots, and it does so in a way in which greatest value is recognized only when horseshoe crab harvest and red knots are both abundant, rather than one or the other.
- Adoption of Approximate Dynamic Programming (ADP) – Optimization in this revision was conducted using ADP coded in the program R. This has several advantages over the

previously used ASDP program including: use of computer software that is readily available with code that is easily modified, greatly shortened run times, incorporation of more uncertainty and structural detail in life history parameters, and elimination of the capacity constraints in ASDP.

- Harvest Recommendations on a Continuous Scale – Output from the previous ARM Framework using ASDP gave one of five possible harvest packages as the optimal harvest to be instituted given the state (abundance) of horseshoe crabs and red knots. Except for the upper limit of possible horseshoe crab harvest, these packages were defined arbitrarily to accommodate the capacity constraints of the ASDP program. In addition, harvest levels of males and females were not independent within these packages. In this revision, the optimization conducted with ADP can recommend harvest levels on a continuous scale while still imposing an upper limit on sex-specific harvest. These recommendations can then be discretized for implementation (e.g., managers may round down to the nearest fifty or hundred thousand horseshoe crabs of each sex).
- More Direct Process for Harvest Policy Adaptation – Adaptation in the harvest policy occurs through a more straightforward process than implemented before, where predictions generated by the three competing models of red knot population dynamics were assessed against highly uncertain red knot population data. In this revision, annual monitoring data on horseshoe crabs and red knots directly update the parameters within the predictive models and ultimately the optimal policy itself.

The large methodological changes represent an evolution of the ARM Framework that increases the transparency of the decision process. The most significant advance in these updates is in moving the population dynamics models for each species from a suite of theoretical models to models based on empirical data specific to the Delaware Bay ecosystem.

2 LIFE HISTORY

2.1 Horseshoe Crabs

Horseshoe crabs are characterized by high fecundity, high egg and larval mortality, and low adult mortality (Botton and Loveland 1989; Loveland and Botton 1992). They breed in late spring on Atlantic coast beaches, laying eggs in nests buried in the sand. Larvae typically hatch from the eggs within 2 to 5 weeks, then settle within a week of hatching and begin molting. Juvenile crabs initially remain in intertidal flats, near breeding beaches. Older juveniles move out of intertidal areas to deeper bay and shelf waters and then return as adults to spawn on beaches in the spring. Adults overwinter in the bays or shelf waters. Horseshoe crabs mature between 9 to 11 years of age depending on sex and live over 20 years. Horseshoe crabs undergo stepwise growth by periodically shedding their shells (molting) until a terminal molt at maturity, with females typically maturing later and attaining larger sizes than males.

2.1.1 Definition of Delaware Bay-Origin Crabs

Delaware Bay-origin horseshoe crabs have been defined as crabs that spawn at least once in the Delaware Bay for the purposes of the ARM Framework. In 2011, the Delaware Bay Ecosystem Technical Committee (DBETC) reviewed genetic data to develop lambda values, representing how much of a state's harvest is of Delaware Bay-origin, as analyzed and presented by Dr. Eric Hallerman (Virginia Polytechnic Institute and State University). The genetics data indicated that the horseshoe crabs from Cape Cod to Cape Hatteras comprise a genetically related stock, the Mid-Atlantic horseshoe crab stock, which in turn is comprised of smaller subunits. Within this geographic region, evidence indicated that the Delaware Bay subunit extends from Cape Cod, Massachusetts, to near Tom's Cove in Virginia, where it begins to mix with a separate and distinct Chesapeake Bay subunit. Dr. Hallerman noted that these results agreed well with tagging work reported by Shuster and Botton (1985) that also suggested genetic overlap of Delaware Bay and Chesapeake Bay stocks in the Tom's Cove region.

The lambda values for Maryland and Virginia were based on genetics results, as well as expert opinion from the DBETC based on their work and knowledge of the horseshoe crab populations and the genetic tests. As this analysis uses genetic data, the term "of Delaware Bay origin" implies that these crabs are of the same genetic subunit originating in the Delaware Bay area. This interpretation is more conservative than the ARM-defined criteria of a Delaware Bay origin crab, as the ARM defines such a crab as being one that would spawn at least once inside the geographic Delaware Bay. The DBETC felt that, since the Delaware Bay population has only begun to show a slightly increasing trend, the use of this more conservative definition should be considered. During the development of the previous Framework, the DBETC determined that the lambda values should be 1.0 for New Jersey and Delaware (or 100% Delaware Bay-origin), 0.51 for Maryland, and 0.35 for Virginia.

2.1.1.1 Updated Values

As part of the ARM Revision, the ARM Subcommittee requested a review of current genetic work on Delaware Bay-origin crabs from Dr. Eric Hallerman (Virginia Polytechnic Institute and State University).

Delaware Bay-origin horseshoe crabs encompass not only the crabs that spawn in the Delaware Bay itself, but also spawning assemblages that are demographically linked to Delaware Bay spawners by high rates of gene flow. These demographic/genetic linkages were established in a series of population genetic studies (King et al. 2005, 2015), including a study of the composition of seven fisheries (Hallerman et al., *in review*). Roughly 45% of individuals landed in commercial fisheries in Maryland were of Delaware Bay origin. In Virginia, Chincoteague Island had 34% Delaware Bay-origin horseshoe crabs and Assateague Island had 6%. The ARM Subcommittee agreed that the samples from Assateague and Chincoteague were not representative of the area in Virginia east of the COLREGS as a whole and perhaps an average would be appropriate. Since the composition of the population east of the COLREGS line is unknown, the ARM Subcommittee estimated the proportion for Virginia to be 20%. Therefore,

the ARM Subcommittee recommended updating the lambda values to be 1.0 for New Jersey and Delaware, .45 for Maryland, and 0.20 for Virginia. These Delaware Bay-origin values are lower than the previously used values of 0.51 for Maryland and 0.35 for Virginia.

2.1.2 Growth

Horseshoe crabs undergo stepwise growth, with females typically attaining larger sizes than males. Growth is relatively rapid during the first several years with several molts within the first year and then a single molt per year until reaching maturity (Shuster 1982). Upon reaching maturity, horseshoe crabs are believed to stop molting, although there is evidence that in some regions, such as Pleasant Bay, horseshoe crabs continue to molt throughout their lives (Carmichael et al. 2003). However, an analysis of Delaware Bay crabs found that they do experience a terminal molt when the crabs reach maturity in that region (Smith et al. 2009). That analysis also demonstrated that Delaware Bay crabs exhibit sexual dimorphism and that males in Delaware Bay tended to mature at age 10 and 11, while females tended to mature at ages 10, 11, and 12.

2.1.3 Stage Classification

Horseshoe crabs can be sexed by visual examination and categorized into three maturity stages: immature, primiparous (newly mature), and multiparous (mature). Horseshoe crabs have six pairs of legs on the underside of their shells. The first pair, the chelicera, are used for eating. The second pair are the first pedipalps, or walking legs, and vary between the sexes. For male horseshoe crabs, these legs are grasping appendages in the shape of “boxing gloves” that allow them to hold onto a female horseshoe crab shell when mating. Juvenile male crabs do not have boxing gloves but can be sexed by the nozzles (gonopores) present under the operculum or first gill flap, primiparous male crabs have boxing gloves with thumbs present, and multiparous male crabs have boxing gloves and no thumbs (Figure 1). The nozzles (gonopores) in males are hard, round, and protruded whereas in females they appear oblong or oval and are flat (J. Zimmerman, *personal communication*).

Since mature horseshoe crabs in the Delaware Bay do not molt or do very rarely, spawning activity leaves marks on female horseshoe crab shells and can be used to categorize maturity stages (Walls et al. 2002). If there are no rubs present on the shell but there are eggs present, that crab is categorized as primiparous (Figure 2) – it is newly mature and will spawn for the first time that year. If there are rubs present on the shell and eggs present, the horseshoe crab is categorized as multiparous or mature.

These stages are recorded by the Virginia Tech Trawl Survey (Section 4.4) and used for modeling the population in the most recent stock assessment report (ASMFC 2019). Additionally, in recent years, several other surveys in the Delaware Bay have begun to collect sex-specific stage data for horseshoe crabs.

2.1.4 Natural Mortality

Sweka et al. (2007) developed an age-specific schedule of natural mortality, relying on reports by Botton et al. (2003) and Carmichael et al. (2003), for the life-history model that has been used in early stock assessments (e.g., ASMFC 2009b) and adaptive resource management models (McGowan et al. 2011a). The mortality schedule for horseshoe crabs is characterized by very high mortality during the first several instars, dramatically reduced mortality during juvenile ages, and increasing mortality on adult stages. This pattern reflects changing vulnerability to predation among sub-adults followed by stranding and harvest mortality emerging at sexual maturity. Only sexually mature individuals are subject to harvest. And stranding is thought to be the main source of natural mortality due to risk associated with spawning as excessive energy expenditure, stranding, desiccation, and predation are directly due to mating and egg-burying behaviors (Botton and Loveland 1989). The age-related condition of the individual is thought to be a factor in stranding-related mortality (Penn and Brockmann 1995). Smith et al. (2010) found that the probability of stranding increased strongly with age class in both males and females; they estimated stranding related mortality to be between 6% and 18%.

The most recent stock assessment investigated multiple lines of evidence from the US FWS tagging database and VA Tech Trawl Survey to update natural mortality estimates (ASMFC 2019). Animals tagged as adults have been observed to remain at large up to 17 years indicating maximum age is at least 27 years based on a maturity schedule from 9 to 11 years of age. This updated estimate of longevity exceeds the previously assumed maximum age of 20 years. As reported in the most recent stock assessment (ASMFC 2019), indirect estimates of age-invariant natural mortality (M) based on a maximum age of 27 years would range between 0.11 and 0.17 (depending on selected mortality model), as opposed to a range of 0.15 to 0.22 given a maximum age of 20 years (Hoenig 1983; Hewitt and Hoenig 2005). Additional indirect estimates of natural mortality were reported in ASMFC (2019) based on von Bertalanffy growth, but those models are not consistent with horseshoe crab life history, do not result in maturity at age 9-11, and do not attain maximum age of 27 years.

As reported in the recent stock assessment (ASMFC 2019), a natural mortality between 0.2 and 0.3 is supported by the empirical ratio of multiparous to primiparous females (ratio=3.8) observed in the Virginia Tech Trawl Survey. Given its biology, newly mature primiparous females will spawn in the upcoming year, generally occurring between ages 9 and 10, and exhibit multiparous behavior thereafter. Given a longevity of 20 or 27 years, M would need to be 0.22 or 0.23 to produce a 3.8 multiparous (ages 10+) to primiparous (age 9) ratio.

Tag-based analysis estimates of annual survival rates (S) reflect avoidance of both natural (M) and fishing (F) mortality. Thus, mortality based on the finite survival rate ($-\ln[S]$) is a conservative estimate, which is to say an overestimate, of natural mortality because it assumes $F=0$. Furthermore, recent survival estimates from Delaware Bay (ASMFC 2019; Smith et al. 2020) exceed the previously assumed rate of 0.62 from Cape Cod (Carmichael et al. 2003). The tagging analysis in ASMFC (2019) report embayment specific constant annual survival between 0.59 to 0.79 with the Delaware Bay estimate of 0.76 and associated $M = 0.274$.

Since the 2019 stock assessment, tagging data from Delaware Bay have been analyzed using multi-state models where the states were defined by geographic subregions: in-bay Delaware, in-bay New Jersey, and the ocean north and south of the midline at the mouth Delaware Bay. The time was partitioned into the periods before and after the New Jersey moratorium was enacted (2003-2005 and 2006-2016) because fishing mortality should be reduced significantly within the New Jersey subregions during the post-moratorium period. Thus, an estimate from the subregion during the post-moratorium period would provide a reasonable basis for natural mortality estimation. The annual survival for the post-moratorium New Jersey subregion was 0.74 (95% CI: 0.71, 0.77) based on the minimum AIC candidate model. Thus, instantaneous natural mortality, assuming negligible fishing mortality, was 0.30 (SD: 0.0183; 95% CI: 0.27, 0.34).

In summary, multiple lines of evidence indicate that natural mortality among adults in Delaware Bay is approximately 0.3 with some indications from life history traits and demographics that M is closer to 0.2 than 0.3. The most recent estimates of constant annual survival from Delaware Bay after 2005 during a period of constrained harvest indicate M between 0.27 and 0.34. Although the recent estimates for natural mortality are based on data from Delaware Bay, which is a significant advance, understanding natural mortality across all ages remains an important research need.

2.1.5 Sex Ratio

Two types of sex ratios are useful for understanding horseshoe crab ecology and informing management decisions. The population sex ratio is the ratio of males to females among individuals in the population. The operational sex ratio is the ratio of males to females among adults that are actively spawning, which is a function of population sex ratio and sex-specific spawning behavior. While juveniles show a balanced population sex ratio (Shuster and Sekiguchi 2003; Smith et al. 2009), the population sex ratio among adults has been observed to be skewed toward males in Delaware Bay (2.2:1 M:F; Smith et al. 2006). The operational sex ratio of horseshoe crabs on the spawning beaches is highly skewed toward males because males exhibit a higher frequency of spawning bouts than females (Brockmann and Smith 2009). While one male attaches to a female in amplexus prior to spawning, the amplexed pair is surrounded by unattached (i.e. satellite) males during fertilization (Brockmann and Penn 1992). Hence, the operational sex ratio on spawning beaches is expected to be more male biased than the population sex ratio among adults.

A population sex ratio over 1 is likely to be required among adults to ensure that reproduction is not limited by sex ratio. Brockmann (1990) found that female horseshoe crabs will tend not to nest unless they are in amplexus with a single male and that satellite males are not needed to fertilize eggs. Some males (approximately 30%) are not capable of amplexus because of their condition (Brockmann and Smith 2009). Thus, there needs to be an excess of males in the population to ensure enough capable males are available to pair with the females ready to spawn.

Since its adoption (ASMFC 2012), the ARM has given value to male harvest if an operational sex ratio of 2 males to 1 female is maintained in the Delaware Bay region. The ARM relies on the Delaware Bay Horseshoe Crab Survey for the annual sex ratio, which has never fallen below the 2:1 ratio since the ARM model has been in use (Section 4.3).

2.2 Red Knots

The red knot is a medium sized migratory shorebird with several subspecies distributed in distinct flyways throughout the world (Niles et al. 2008). The work here is focused on the Western Atlantic flyway subspecies *Calidris canutus rufa* (hereafter red knots), which overwinter in the southeastern United States, the Caribbean and Northern Brazil, and in Tierra del Fuego in southern South America (Niles et al. 2008). The birds migrate in the spring, northward to Arctic Canada, stopping at various locations along the route to rest and refuel, most notably, for this assessment, in the mid-Atlantic coast of the United States with especially large concentrations in Delaware Bay (Atkinson et al. 2005; Niles et al. 2008). The birds travel to the northern portions of Nunavut, Canada, where they breed, typically nesting in drier, upland habitats (Niles et al. 2008). Red knots are ground nesters, laying 4 eggs in a single nest per season. Like most shorebird species, the chicks are precocial and thus mobile and foraging for their own food soon after hatching.

After breeding the females depart the breeding range soon after nests hatch (or fail) and begin their southward migration. Males stay with the developing chicks for 3-4 weeks until fledging and then depart, leaving the chicks to continue foraging and building strength for their own southward migration a few weeks thereafter (Niles et al. 2008). Though data are limited, the birds seem to exhibit moderate site fidelity in the wintering and breeding grounds, in that they generally return to same area each season, though not necessarily to the same breeding or wintering territory. Some evidence suggests that they may exhibit inter-annual plasticity in migration stopover site use (Tucker et al. 2021).

Red knots are thought to be long-lived birds, with many survival analyses showing annual survival over 90% annually (e.g., McGowan et al. 2011b, Schwarzer et al. 2012) and longevity records (i.e., life span of known individuals) greater than 20 years (Niles et al. 2008). Very little is known about red knot reproductive rates at the population scale, or about first year and juvenile survival rates (Niles et al. 2008; McGowan et al. 2011a). However, recent applications of integrated population models, statistical tools that integrate multiple sources of data within a life-cycle framework to improve inference, have enabled estimation of population level recruitment rates for the Western Atlantic flyway population (Tucker 2019).

For this adaptive management plan, the most relevant details about red knot life history and annual cycle are the spring migration period and their stopover ecology in Delaware Bay. Northward migrating birds begin arriving in Delaware Bay in early May and remain for two to four weeks resting, foraging, and gaining mass (Karpanty et al. 2006; Atkinson et al. 2007; McGowan et al. 2011b; Tucker et al. 2019a, 2019b). Red knots time their arrival to exploit horseshoe crab eggs deposited on the sandy beaches of Delaware Bay during annual spawning

events that coincide with the new and full moon spring tides in May (Tanacredi et al. 2009; Tucker et al. 2021) but that also depend on suitable water temperature and weather conditions. Individual birds arrive in Delaware Bay throughout the stopover season and depart throughout the season as well, typically reaching peak abundances between May 20th and May 27th. The flow-through nature of the stopover population (i.e., constant arrivals and departures) makes monitoring the population difficult and makes analyzing data about this system difficult (Lyons et al. 2016; Tucker et al. 2021)

In the early 2000s, *rufa* red knot populations in Tierra del Fuego and in Delaware Bay exhibited precipitous year after year declines, and many conservation biologists hypothesized that the unregulated harvest of horseshoe crabs in Delaware Bay during the late 1990s prevented birds from gaining enough weight during stopover to avoid significant mortality risks. For birds with high adult survival and low productivity, even small changes in adult survival can have large consequences for population dynamics, and large declines in survival can lead to population collapse (Baker et al. 2004). Some analyses supported the hypothesis (e.g., Baker et al. 2004, Niles et al. 2009), while others found mixed results (e.g., Karpanty et al. 2011, McGowan et al. 2011b, Cohen et al. 2009), with some research suggesting that conditions in the Arctic during the breeding season may play an important role (McGowan et al. 2011b; Fraser et al. 2013; McGowan 2015). These alternative research results left uncertainty in the strength of the effect of horseshoe crab populations on red knot population dynamics, and previous efforts to manage this system acknowledge these uncertainties by using multiple system models in an adaptive management framework (McGowan et al. 2015).

3 HORSESHOE CRAB FISHERY DEPENDENT DATA SOURCES

3.1 Commercial Bait Fishery

The commercial bait fishery consists primarily of trawl, hand harvest, and dredge fisheries. Since 1998, ASMFC has compiled landings by state in the annual FMP review report. The horseshoe crab fishery supplies bait for the American eel (*Anguilla rostrata*), conch (*Buccinidae*) and, to a lesser degree, catfish (*Ictaluridae*) fisheries. The American eel pot fishery prefers female horseshoe crabs to males, while the conch pot fishery uses both male and female horseshoe crabs. The conch fishery uses horseshoe crabs more frequently than the American eel fishery, with eel baits using blue crabs (*Callinectes sapidus*) or fish more often than horseshoe crabs (ASMFC 2017). Most fishing effort for horseshoe crabs is concentrated within the mid-Atlantic coastal waters and adjacent federal waters. Since 1998, states have been required to report annual landings to ASMFC through the compliance reporting process. Landings used in this assessment for 1998 through 2019 were validated by state agencies through the Atlantic Coastal Cooperative Statistics Program (ACCSP). Harvest levels for the Delaware Bay region states have been set using the ARM Framework since Addendum VII (ASMFC 2012) and have constrained harvest in the region to 500,000 male-only crabs since its implementation.

3.1.1 State Management

3.1.1.1 New Jersey

The current ASMFC state quota for New Jersey is 162,136 male horseshoe crabs, but since 2006 a moratorium has been in place on the harvest of horseshoe crabs and horseshoe crab eggs in the state. The law prohibits the possession of horseshoe crabs and horseshoe crab eggs except for those individuals in possession of a scientific collecting permit, allowing them to possess horseshoe crabs or horseshoe crab eggs for research or educational purposes only. Those fishermen using horseshoe crabs as bait must provide adequate documentation that the horseshoe crabs in their possession were not harvested in New Jersey. For those commercial fishermen in possession of horseshoe crabs, documentation shall include a receipt or bill that provides the name, address, and phone number of the person or company that provided the horseshoe crabs, the permit or license number of the person or company named, and the state and, if possible, the location where the horseshoe crabs were harvested.

3.1.1.2 Delaware

Delaware's annual horseshoe crab harvest is determined in accordance with the annual sex-specific allocations identified in Addendum VII to the FMP. The current quota for the state of Delaware is 162,136 male horseshoe crabs. Harvest is required to be reported by phone to the Delaware Department of Natural Resources Division of Fish and Wildlife (DNREC DDFW) daily. Upon reaching 95% of the annual allocation, DNREC establishes a date and time to close the fishery, based on recent fishery performance and landings. Any overages incurred are subtracted from the following year's horseshoe crab quota allocation.

Two methods of harvest are permitted and employed in Delaware's horseshoe crab fishery. Hand harvest licenses were capped in 1998, although transfer of licenses between qualified individuals is lawful. Individuals that have a current commercial eel license are also allowed to harvest horseshoe crabs for personal bait use. Harvest by eel licensees may not be sold or combined with any other commercial harvest of horseshoe crabs. Annual hand harvest may not begin until June 8 and ends upon reaching the quota allocation. No more than 300 cubic feet of horseshoe crabs may be collected in a 24-hour period. If the quota has not been reached by June 30, five horseshoe crab dredge permits are issued via lottery, if more than five applications are received. Only current holders of oyster harvesting licenses are eligible for horseshoe crab dredge permits. Dredge harvest is limited to 1,500 horseshoe crabs per day. No harvest, by any method, is allowed to occur between sunset and sunrise.

Delaware has prohibited the use of more than one-half of a female horseshoe crab or one male horseshoe crab as bait in any type of pot on any one day. Bait saving devices are mandatory in all whelk pots employed in the state. Possession of Asian horseshoe crabs or parts thereof are prohibited without written authorization from the Director of the Division of Fish and Wildlife.

3.1.1.3 Maryland

The annual quota of horseshoe crabs for the commercial fishery in Maryland currently is 255,980 male crabs. There is no female harvest permitted. Harvest is subject to daily catch limits, determined by whether the harvester has a valid landing permit. Non-permitted harvesters may not land more than 25 horseshoe crabs per day. Permitted harvesters may not land more than 150 horseshoe crabs per day from May 1-July 9. From July 10-November 30, permitted harvesters are subject to daily limits as designated on their respective permits.

The bait fishery is subject to seasonal restrictions. From May 1-July 9, horseshoe crabs from outside one mile of the Atlantic coast or from Maryland's coastal bays and tidal tributaries may be caught and landed, but crabs may not be caught within one mile of the Atlantic Coast or the Chesapeake Bay and its tidal tributaries. From July 10-November 30, horseshoe crabs from the state tidal waters may be caught and landed. From December 1-April 30, horseshoe crabs may not be caught or landed in Maryland.

Horseshoe crabs used for scientific purposes (including biomedical use) must be collected by individuals with scientific collection permits. These permits are only granted with proof that collected crabs are being supplied to a facility approved by the US Food and Drug Administration (FDA). Only male crabs may be collected from January 1-June 6. Crabs must be transported in a refrigerated truck and returned within 48 hours. A chain of custody form must follow the crabs from collection to release, and an annual report detailing use of horseshoe crabs is due to the state by January 31 of the following year.

3.1.1.4 Virginia

The current quota for Virginia is 172,828 horseshoe crabs, although the harvest is male-only east of the COLREGS line and limited to 81,331 horseshoe crabs. Virginia allocates its quota annually among five different harvest gear types including trawl, dredge, pound nets, by-hand, and by other gear. Each one of these gear types is limited entry and requires a gear-specific harvesting permit to participate in the fishery. The harvest of horseshoe crabs in Virginia requires a Commercial Fishing Registration License as well as a gear-specific horseshoe crab harvesting permit. The daily landing limits for each gear-specific license are 2,500 crabs by Trawl Permit, 2,500 crabs by Class A Dredge Permit, 1,000 crabs by Class B Dredge Permit, 500 crabs by Hand Harvest Permit, 500 crabs by Pound Net Permit, and 250 crabs by General Category Permit.

3.1.2 Commercial Bait Landings

Total bait landings in the Delaware Bay by state are shown in Figure 3 and Table 1. Landings were relatively high in the late-1990s, decreased through the early-2000s, and have remained relatively stable through 2019. Horseshoe crab harvest by sex has varied through time, reflecting the management shift to male-only harvest in the region with the implementation of the ARM model in 2013 (Figure 4).

Bait landings for the Delaware Bay states were developed to support the catch multiple survey analysis (CMSA) model for that region using only Delaware Bay-origin crabs. Horseshoe crab landings from New Jersey and Delaware are considered to be 100% Delaware Bay origin (i.e., spawned at least once in Delaware Bay) whereas 45% of Maryland's harvest and 20% of Virginia's are believed to be Delaware Bay origin based on genetic data and analysis (Section 2.1.1.1). These percentages were applied to the Delaware Bay states' bait harvest. Horseshoe crabs that were not sexed were portioned into males and females based on sex ratios. The CMSA model used data from 2003-2019 and while the female harvest decreased over this time, male horseshoe crab harvest has varied (Figure 5 and Table 2). Due to the implementation of the ARM Framework through Addendum VII (ASMFC 2012), harvest in the region has been restricted to male-only harvest and this can be seen in the sex ratio of the catch.

3.2 Biomedical Fishery

Research on horseshoe crabs for use in the biomedical industry began in the early 1900s (Shuster 1950). Scientists have used horseshoe crabs in eye research, surgical suture wound dressing development, and detection of bacterial endotoxins in pharmaceuticals (Hall 1992). The current major biomedical use of horseshoe crabs is in the production of limulus amebocyte lysate (LAL). LAL is a clotting agent in horseshoe crab blood that makes it possible to detect endotoxins in patients, drugs, and all intravenous devices. The LAL test was commercialized in the 1970s (J. Cooper, *personal communication*), and is currently the worldwide standard for screening medical equipment for bacterial contamination.

Blood from horseshoe crabs is obtained by collecting horseshoe crabs, extracting a portion of their blood, and releasing them alive. Crabs collected for LAL production are typically collected by hand or trawl. Crabs are inspected to cull out damaged or moribund animals, and transported to the bleeding facility. Following bleeding, most crabs are returned near the location of capture; however, some states allow facilities to bleed crabs caught by the bait industry prior to these crabs going to the market for sale (ASMFC 2004).

There are four companies in the Delaware Bay region that extracted horseshoe crab blood during the time period examined by this assessment, 1999-2019: Limuli Labs (New Jersey), Lonza (Maryland, formerly Cambrex Bioscience), Wako Chemicals (Maryland, previously Virginia), and Heptest Labs (Virginia). Addendum III requires states where horseshoe crabs are collected for biomedical bleeding to collect and report total collection numbers, crabs rejected, crabs bled (by sex) and to characterize mortality. Coastwide there currently are six facilities, one in Massachusetts (Associates of Cape Cod) and one in South Carolina (Charles River Endosafe) in addition to the four in the Delaware Bay.

3.2.1 Biomedical Mortality Rate

As part of the peer-reviewed benchmark stock assessment (ASMFC 2019), a literature search of all studies regarding biomedical bleeding mortality was compiled and a meta-analysis of bleeding studies was conducted. In order to determine what mortality should be applied to

crabs that were bled by the facility and released alive, the mortality rates and sample sizes were compiled from the studies. Some studies had multiple rates from multiple treatments and each were treated independently. The rates and samples sizes were analyzed to estimate an overall mortality rate distribution by simulating results from mortality rate study as a separate random variable with its own binomial distribution and sample size. Then the quantiles from the overall mortality rate distribution were used to calculate an expected biomedical mortality of 15% with a 95% confidence interval of 4-30%. Therefore, the mortality rate of 15% is applied to those crabs that were bled and released alive in order to estimate the number of horseshoe crabs that die from biomedical bleeding practices.

3.2.2 Biomedical Data Estimation

Since 2004, ASMFC has required states to monitor the biomedical use of horseshoe crabs to determine the source of crabs, track total harvest, and characterize pre- and post-bleeding mortality. These values are reported in annual compliance reports but the amount, quality, and completeness varied, particularly in the early part of the time series. Additionally, the time series needed to be extended back to 2003 for use in the CMSA. Biomedical company representatives and state permitting records were consulted to confirm whether and which facilities were operating during years without data. To extend the time series of all facilities and account for biomedical mortality in as many years as possible, missing years were estimated based on available data as part of the benchmark assessment (ASMFC 2019) and that time series is used in this report.

The bleeding mortality estimate from the meta-analysis of bleeding studies (15%) was applied to numbers of bled crabs to estimate bleeding mortality. This was added to the number of crabs observed dead during the biomedical process to estimate the total mortality attributable to biomedical use (Figure 6 and Table 3). These values represent the number of horseshoe crabs estimated to have died coastwide as a result of the biomedical industry.

3.2.3 Biomedical Mortality in the Delaware Bay

Only the Delaware Bay region is modeled in the ARM Framework, yet the biomedical data on a regional basis is confidential (see Statement Regarding Confidential Data). During the update of the ARM model, the coastwide values were used to develop the model, as outlined in the Terms of Reference. These provide an upper bound on harvest. Conversely, the ARM model was also run assuming zero biomedical mortality to provide a lower bound on harvest.

Following peer review, if the revised ARM model is accepted for use, the real, confidential Delaware Bay biomedical harvest will be used to determine the amount of mortality to attribute to the region. These mortality estimates will include apportioning of Virginia and Maryland crabs, with 20% and 45% of crabs from each state, respectively, to represent Delaware Bay origin. Then, the ARM model will be run using the confidential data by ASMFC staff who has access to the data and a harvest package will be determined and shared with the

public, without showing the regional biomedical data or CMSA population estimates, the latter of which could be used to back calculate confidential harvest.

3.3 Commercial Discards

3.3.1 Northeast Fisheries Observer Program

Discard information from observed commercial fishing trips was obtained from NMFS' Northeast Fisheries Science Center's (NEFSC) Northeast Fisheries Observer Program (NEFOP). The NEFOP program collects data on harvested and discarded catch, gear, effort, and species' lengths and weights using trained fishery observers from Maine to North Carolina. The total catch and a subsample of the total catch from each observation (e.g., towed trawl net) are weighed. The observer program is mandatory for federally-permitted vessels which are selected for observation during fishing trips based on number of sea days needed to achieve a 30% CV in the dataset. Fisheries that require observer coverage fall under the federally managed fishery plans, such as groundfish, herring, squid, surfclam, ocean quahog, and the lobster fisheries. Horseshoe crab does not have a federal fishery plan and is not one of the target species of the program, but data is still collected on the species when it is encountered by NEFOP observers.

The program began in 1989 but data on horseshoe crab was available beginning in 2004. Horseshoe crab landings and observed discards were used to develop discard estimates from gillnets, trawls, and dredges in the Delaware Bay states for use in the catch multiple survey analysis (CMSA). See the NEFOP website for additional details about the program (<http://nefsc.noaa.gov/fsb/program.html>).

3.3.2 Methods

The first commercial discard estimates for horseshoe crab were done as part of the 2019 benchmark stock assessment (ASMFC 2019). Simply, the method developed annual ratios of observed discarded horseshoe crabs to observed landings of all species by gear in the data that encountered horseshoe crabs: gill nets, trawls, and dredges. It was assumed that the discarding rates during observed trips are representative of overall discarding rates in these fisheries. Therefore, the ratios were then applied to reported gill net, trawl, and dredge landings of all species in the region to estimate total horseshoe crab discards in the Delaware Bay. The landings used to scale up the discard ratios were queried from the Atlantic Coastal Cooperative Statistics Program (ACCSP) warehouse. The 2019 peer review panel made several recommendations regarding the discard estimates, including to further examine the NEFOP data for horseshoe crab by area, gear, and season. Additionally, the panel suggested that the federal Vessel Trip Reporting (VTR) data should be considered for scaling up the ratios to the landings and that more work should be done to match NEFOP data and the landings data, whatever the source (VTR or ACCSP).

3.3.2.1 Data Filtering and Addressing Peer Review Comments

3.3.2.1.1 Statistical Area

The NEFOP dataset included all landings from observed trips, including those where no horseshoe crabs were encountered, as well as horseshoe crabs discarded and horseshoe crabs kept, in pounds. To address the peer review comments that statistical area should be used to develop discard ratios, not state, statistical areas within the Delaware Bay region (Delaware, New Jersey, Maryland, and Virginia; Figure 7) were examined. Only statistical areas within the region where horseshoe crabs were encountered, either discarded or kept, were included in the analysis. Of the observed trips in NEFOP that kept horseshoe crabs coastwide, 99% of the trips occurred in area 621 (95% of all trips that kept horseshoe crabs) and 625 (4%). Of the observed trips in NEFOP that discarded horseshoe crabs, 96% of the trips occurred in areas 621 (72% of all trips that caught and discarded horseshoe crabs), 612 (10%), 626 (6%), 625 (5%), 614 (2%), and 615 (1%). Therefore, the NEFOP data was limited for the analysis to areas that encounter horseshoe crabs which were 612, 614, 615, 621, 625, and 626. Statistical areas 613, 631, and 635 also accounted for approximately 1% each of the discarded horseshoe crabs but were outside of the Delaware Bay region and were not used for this analysis. Discard estimates were attempted by statistical area, rather than by gear, which resulted in poor estimates and it was not pursued further.

3.3.2.1.2 Landings Data Source

Federal VTR data was considered for scaling up the discard ratios, as recommended by the peer review panel, but there were challenges using the reported quantity, or the amount of landed product, which was a non-standardized unit of measure in the dataset. Additionally, VTR data has a complicated species coding system which ACCSP formats to be in the same format as the state data it receives. Upon consulting with ACCSP, it was recommended that for the purposes of this analysis, the best data to use for scaling up discard ratios to the region's all-species landings was the fisherman trips in ACCSP, as opposed to the commercial landings in ACCSP which were used for the 2019 benchmark. While commercial landings represent the best compilation of state and federal landings submitted by both dealers and fishermen, fishermen reports have more reliable data for statistical area. A custom data request was made in ACCSP for the landings that most closely matched the NEFOP data fields of interest (e.g., statistical area, gear, species).

3.3.2.1.3 Gear

The gears that encountered horseshoe crabs in the NEFOP dataset were more closely examined and matched with the queried ACCSP data compared to the 2019 benchmark. In NEFOP, the gears that kept or discarded horseshoe crabs within the region were determined and grouped by more general type for the larger analysis (e.g., "TRAWL, OTTER, BOTTOM, SCALLOP" was categorized as "trawl"). Most of the trips that discarded and kept horseshoe crabs occurred on bottom otter trawls, sea scallop dredges, fixed or anchored sink gill nets, or clam dredges, although other trawls, dredges, and gill net codes also encountered horseshoe crabs on observed trips. NEFOP gears excluded from the analysis because they did not encounter

horseshoe crabs included, for example, longlines, pots and traps (e.g., pots and traps for lobster, blue crab, and conch), handlines, midwater trawls, drifting or floating gill nets, and purse seines. With the collaboration of ACCSP staff, these gears were matched with ACCSP gears, which are not coded in the same format, and grouped in a similar way. The gears used in the analysis are in Table 4. Some gears were general in ACCSP, such as “GILL NETS,” but were included in the initial data pull to be filtered later to exclude species caught in the gear that do not commonly encounter horseshoe crab.

In ACCSP, some landings were not available at the gear level and appear in the database as “NOT CODED.” These landings were partitioned into trawl, gillnet, and dredge landings by calculating the annual proportion of landings by these gear categories and then these proportions were applied to the “NOT CODED” landings. The proportioning of NOT CODED landings were done after all data filtering was complete so that it did not include general gears, such as “GILL NETS” that represented species trips that were unlikely to encounter horseshoe crabs.

3.3.2.1.4 Season

Discard ratios by season was also considered, as recommended by the 2019 peer review panel. While the percent of horseshoe crabs discarded by trip varied throughout the year, generally more horseshoe crab discards occurred in the second half of the year (Figure 8). Ratios of discarded horseshoe crabs to all species kept in NEFOP were examined by year, month, gear, and statistical area (Figure 9). Discard estimates using one variable over another often resulted in poor estimates (i.e., estimates went to infinity or had very large associated errors) since some combinations, for example gear and area or month and gear, were not represented in the data for horseshoe crabs. Because the NEFOP dataset is not designed to target horseshoe crab trips specifically, it was difficult to determine if, for example, there were more discards in January 2012 than other years or if it was an artifact of sampling that year. Limiting the data to month or season resulted in poor estimates and this approach was not pursued further.

3.3.2.1.5 Species

To further filter the data to better represent trips that would encounter horseshoe crabs, species in NEFOP and ACCSP were closer examined. In NEFOP, pounds of horseshoe crabs kept and discarded, as well as pounds of all species landed on observed trips, are reported but the landed pounds are not reported by species. In NEFOP, “trip target” is provided and only refers to what the captain indicated he or she was targeting at the trip level, not necessarily what was landed. Species landed is not keypunched in NEFOP (Gina Shields, NEFOP data contact, *personal communication*) and does not exist as a queried data field. So, for example, a trip in NEFOP may have targeted summer flounder, discarded 100 pounds of horseshoe crab, and landed 1700 pounds, but those 1700 pounds are not necessarily summer flounder. Therefore, trip target was used to further refine and limit the data to species thought to be captured with horseshoe crabs, but a guild approach was not pursued. In observed trips in the Delaware Bay region, the trip target that resulted in the most horseshoe crab discards was summer flounder (38% of discarded horseshoe crabs occurred on trips where the captain indicated that the targeted

species of the trip was summer flounder), horseshoe crabs (35%), sea scallops (18%), and monkfish (3%). Of the 33 species targeted in NEFOP that discarded horseshoe crabs, 10 species represented approximately 99% of the discards (Table 5). Having already limited the NEFOP and ACCSP datasets to the six statistical areas and three gear categories, data was further filtered to include only trips and landings that were likely to interact with horseshoe crabs. This included the 33 species targeted in NEFOP which were paired to species categories in ACCSP. For example, from ACCSP, all trawl trips that occurred in the Delaware Bay region that landed flounder were included, not just summer flounder. Trips that landed species such as sharks, tunas, sea turtles, catfish, pufferfish, tilefish, and shad, for example, were excluded because while they occurred within the region and gears that captured horseshoe crabs, they were unlikely to encounter them. To test the sensitivity of limiting the trips by species, discard estimates were done with all species landed within the area and gear categories and then again with the limited species categories. The results were not greatly influenced by this decision, with all species included resulting in only slightly higher discard estimates than the limited species data. The ARM subcommittee decided that the limited species represented the best data since it eliminated trips that were unlikely to encounter horseshoe crabs.

3.3.2.1.6 Horseshoe Crab Size and Maturity

During the 2019 benchmark, there was no consideration given to the size or maturity of horseshoe crabs discarded. For the ARM Revision, the biological sampling of kept and discarded horseshoe crabs in NEFOP was examined. Biological sampling of horseshoe crab length was limited to statistical area 621 (97%) and reported mostly without the sex of the crab. Despite these limitations, the prosomal width frequency was noticeably different between horseshoe crabs kept on observed trips and those discarded (Figure 10). Horseshoe crabs kept, on average, were larger than horseshoe crabs discarded. When a reason for discarding was provided, most fishermen indicated it was because the crabs were too small or regulations prohibit retention.

Discarded horseshoe crab lengths indicated that many of them were likely to be immature and therefore should not be included in the estimates used for the CMSA, which does not model immature crabs. To filter out immature crabs, length-weight relationships were used as developed during the 2019 assessment. Since many of the measured crabs were not sexed, a sex ratio was used (52% male and 48% female) based on commercial bait sampling data. For females the length-weight relationship used was:

$$\log_e(Wt) = \log_e(PW) * 2.8659 - 15.1802$$

and for male horseshoe crabs, the length-weight relationship used was:

$$\log_e(Wt) = \log_e(PW) * 2.4381 - 12.9439$$

where Wt=weight of the horseshoe crab in kg and PW=prosomal width in mm (ASMFC 2019). As determined by committee consensus, a length cutoff of 180 mm was used to differentiate mature from immature. The proportion at weight that corresponded to mature crabs in the

biological sampling was expanded to the discard estimates to eliminate immature crabs from the analysis for the CMSA. Again, while this analysis did estimate the number of immature horseshoe crabs captured and discarded, the immature stage was not modeled in the CMSA or revised ARM Framework. Only estimated mature horseshoe crabs were used in the analyses going forward. On average, 43% of the discarded horseshoe crabs were estimated to be mature for the years with biological sampling in the database, 2012-2019. For 2003-2011, the average proportion mature was used (Table 6).

3.3.2.2 Discard estimation methods

After examining the NEFOP and ACCSP data in finer detail as recommended by the 2019 peer review panel, the data used in the analysis were filtered to include six statistical areas, more specific gear categories which were then generalized into trawl, gill nets, and dredges, and limited species targeted and landed as described in above sections. Calculating discard ratios annually by gear, rather than by month or statistical area, resulted in the best discard estimates due to missing or limited data in the other configurations. Following data filtering, NEFOP observer data were used to develop annual ratios of observed discarded horseshoe crab to observed landings of all species by gill nets, bottom trawls, and dredges from the statistical areas within for 2004-2019. Ratios were then applied to reported gill net, bottom trawl, and dredge landings of all species from those areas for 2004-2019 as queried from the ACCSP warehouse to estimate total discards of horseshoe crab.

The annual ratios by major gear type were calculated as the ratio of the mean discards of horseshoe crab per observation (i.e., tow or net set), in pounds, to the mean landings of aggregated species per observation, also in pounds (Equation 1).

$$\text{Equation 1: } R = \frac{\bar{D}}{\bar{L}} = \frac{\sum_1^n D_i}{\sum_1^n L_i}$$

This ratio estimator includes all observations with observed landings of any species, including those where no horseshoe crab were discarded. The variance of the ratio estimator was calculated with Equation 2 (Pollock et al. 1994).

$$\text{Equation 2: } Var(R) = \frac{1}{n(n-1)\bar{L}^2} \left(\sum_1^n D_i^2 + R^2 \sum_1^n L_i^2 - 2R \sum_1^n D_i L_i \right)$$

It was assumed that discarding rates during observed trips were representative of overall discarding rates in these fisheries. Small sample sizes of positive observations precluded developing ratios at finer resolution (e.g., by state or season).

For trawls, annual mean weights were calculated as the total number counted from subsamples divided by the total subsample weight and were applied to the discard estimates in weight to derive discard estimates in numbers. In years with no observer data, averages of all the years combined were used. For gill nets and dredges, there was not sufficient biological sampling to

calculate the mean weight of horseshoe crabs caught as bycatch in the gear. A conversion factor of 1.5 pounds per horseshoe crab caught as bycatch in the dredge and gill net gears was used to convert from pounds to numbers.

A discard mortality rate of 5% was assumed for both dredge and trawl discards of horseshoe crab and a 12% mortality rate was applied to gill nets. These mortality rates were developed from stock assessment subcommittee, technical committee, and ARM subcommittee discussions. There is a lack of information about discard mortality rates from various gears for horseshoe crabs. A sex ratio of 48% female to 52% male was applied to split the discards by sex for the CMSA based on commercial bait sampling data in the region.

3.3.3 Discard Estimates

The ratio estimators varied by gear and year with the highest ratios of discarded horseshoe crabs to kept species occurring in the trawl fisheries (Table 7-Table 9). While trawl fisheries had higher ratios for discarded horseshoe crabs, the most discarded horseshoe crabs by number occurred in the dredge fisheries. Discards from dredges increased remarkably in 2014-2019 due to several observed trips with high discarded horseshoe crabs in those years. Trawls also showed the highest rates of discards in similar years, 2015-2017. Conversely, estimated discards from gill nets were the highest in 2011 and 2013 and decreased from 2014-2019. Estimated discards for all three gears combined showed an increase of discards throughout the time series, although those estimates were highly influenced by the dredge discard estimates.

The sex ratio, mortality rates by gear, and proportion mature values were applied to the discard estimates to get the final number of dead mature horseshoe crabs by sex in the region to use in the CMSA. The number of dead horseshoe crabs was high in 2016, 2017, and 2019 for both sexes, driven mainly by high discard estimates from dredges those years (Table 10; Figure 11).

4 HORSESHOE CRAB FISHERY INDEPENDENT DATA SOURCES

During the 2019 benchmark stock assessment, several fishery independent surveys in the Delaware Bay region were explored and many were used to develop indices of relative abundance to support modeling in the region. The following indices were used in the peer reviewed CMSA and were updated for this report with additional years of data. All indices were developed using the delta distribution for the mean and variance for each year of a survey to specifically take into account the number of zero catches (Pennington 1983).

4.1 New Jersey Ocean Trawl Survey

4.1.1 Survey Design and Methods

New Jersey's Ocean Trawl Survey has been operating since August of 1988 and collects samples during five survey cruises per year (30 samples in January, 39 samples each in April, June, August and October) in the nearshore ocean waters of New Jersey. It uses a three-in-one

design, two-seam trawl net with forward netting of 12 cm stretch mesh, rear netting of 8 cm, and a 6.4 mm bar mesh liner in the cod end. The survey incorporates a random stratified design with sampling sites selected within 15 strata (Figure 12) with longitudinal boundaries consisting of 5, 10 and 15 fathom isobaths. The latitudinal boundaries are identical with the NMFS groundfish survey except the extreme southern and northern ends of the sampling area. These strata are further divided into blocks which are 2.0 minutes longitude by 2.5 minutes latitude for the mid-shore and offshore strata, and 1.0 minutes longitude by 1.0 minutes latitude for the inshore strata. The standard duration of each sample is a 20-minute tow.

4.1.2 Biological and Environmental Sampling

Catches are sorted to species level whenever possible, enumerated, weighed (gross weight per species), and measured for length/width (cm) data. Certain species are sexed and horseshoe crabs have consistently been sexed since 1999. Environmental data include depth (m), surface and bottom water temperature (degrees Celsius), salinity (0/00), dissolved oxygen (mg/L), air temperature, wind direction and speed, weather conditions, wave height, and swell direction and height.

4.1.3 Evaluation of Survey Data

A spring/summer (April and August) index was developed from this survey for female adult (≥ 19 cm pw) and male adult (possessing male pedipalps) horseshoe crabs. The indices were developed for the years in which the crabs were consistently sexed (1999-2019), although only 2003-2018 are used in the CMSA. In 2019, the April cruise did not run and therefore the 2019 data point for the spring index only includes the August data and should not be used for modeling.

4.1.4 Abundance Index Trends

Both indices of female and male horseshoe crab abundance began as relatively high in 1999 and then declined over several years to the time series low in 2010 (Figure 13-Figure 14). The indices began to steadily increase until the time series high in 2013, after which horseshoe crabs declined in abundance again and then had variable abundance until a relatively high point in the terminal year, albeit a reduced survey that year due to the missing April cruise.

4.2 Delaware Fish and Wildlife Adult Trawl Survey

4.2.1 Survey Design and Methods

Delaware has conducted the Adult Trawl Survey in three discrete time spans: 1966 – 1971, 1979 – 1984, and continuously since 1990. This assessment used the data from the latest time period (1990 – 2017) and was updated through 2018 for the spring portion of the survey. The survey samples 9 fixed stations monthly from March through December for an annual total of 72

samples. This survey uses a 30 foot, 2-seam otter trawl with a 3 inch stretch mesh in the wings and body and a 2 inch stretch mesh in the cod end. The sampling area includes the Delaware waters of the Delaware Bay at depths ranging from 7 – 35 m (Figure 15). The standard duration for each sample is 20 minutes at a speed of 3 knots.

4.2.2 Biological and Environmental Sampling

Catch is sorted to species level, enumerated, and weighed (aggregate per species) and measured for length/width to the nearest 0.5 cm. Horseshoe crabs are sexed, enumerated, and measured (prosomal width). Environmental data include tide stage, water temperature (degrees Celsius), salinity (ppt), cloud cover, and depth (m).

4.2.3 Evaluation of Survey Data

This survey catches mainly adult horseshoe crabs and spring (April through July) indices were developed from this survey for male and female horseshoe crabs separately. Overall, the proportion positive tows varied little between the seasons with the spring showing slightly higher values than the fall (43.6% spring, 39.5% fall). The spring index was used in the peer-reviewed 2019 benchmark assessment in the modeling and therefore it was also used for this report.

4.2.4 Abundance Index Trends

For all adult female horseshoe crabs in the spring (Figure 16), abundance was highest in 1990 and 1991, and then a downward trend began from 1992 through 1995. It rebounded with an increase in 1996 before continuing the general trend downward through 2005. There was a moderate increase in 2006 and 2007 before dropping to low abundance levels from 2008 through 2013. Since 2014 there has been a generally upward trend. A similar pattern was seen for the spring indices of adult males (Figure 17).

4.3 Delaware Bay Horseshoe Crab Spawning Survey

4.3.1 Survey Design and Methods

The ASMFC's FMP for Horseshoe crab (ASMFC 1998) required that the states of Delaware, Maryland, and New Jersey implement pilot horseshoe crab spawning surveys based on "standardized and statistically robust methodologies." In January 1999, the ASMFC convened a workshop that established a framework for such surveys in the Mid-Atlantic region. The framework built upon existing horseshoe crab spawning survey efforts by Finn et al. (1991) and Maio (1998). The survey began in 1999 and has continued through the present. Approximately 25 beaches are sampled in the Delaware Estuary during nighttime high tides in May-June. The goals are to provide an index of spawning activity and distribution in the region, increase the understanding of environmental factors on spawning activity and distribution, and promote public awareness of the role crabs play in shorebird dynamics. The survey has been shown to

provide levels of spatial and temporal coverage essential for understanding trends in spawning activity (Smith and Michels 2006).

4.3.2 Biological and Environmental Sampling

The survey collects environmental data including water temperature, tidal height, wave height and biological data such as sex and spawning activity.

4.3.3 Evaluation of Survey Data

The ARM workgroup was primarily interested in this survey for the sex ratio data it provides in order to inform control rules in the Delaware Bay region. The ARM workgroup determined that this survey provides the most reliable data available for spawning beach sex ratios. For other data provided by this survey, the full annual reports are available at <https://www.delawarebayhscsurvey.org/surveyreports/>.

4.3.4 Sex Ratio Trends

Annual sex ratios from the spawning beach survey are available in Table 11. Current horseshoe crab harvest management strategies in the Delaware Bay area limit the harvest to predominantly male crabs. Concern was expressed that these strategies may cause spawning sex ratios (M:F) to drop and yet the sex ratio has increased in recent years. Annual sex ratios have varied over the course of the survey but has been above five male horseshoe crabs to one female horseshoe crab for the last three years.

4.4 Virginia Tech Horseshoe Crab Trawl Survey

4.4.1 Survey Design and Methods

The trawl survey conducted by Virginia Polytechnic Institute and State University (Virginia Tech) is the only survey available that is designed specifically to characterize the horseshoe crab population in coastal and lower Delaware Bay (Figure 18; Bi et al. 2020). The survey has operated from 2002-2011 and then again from 2016-present due to a lack of funding during the missing years. The survey area is stratified by distance from the shore and bottom topography. Tows are 15-minutes long and the survey only operates in the fall (mid-September-late October).

4.4.2 Biological and Environmental Sampling

All horseshoe crabs are counted and a subset are measured for prosomal width and identified by sex and maturity. Immature, newly mature, and mature crabs are differentiated in the data set.

4.4.3 Evaluation of Survey Data

This is the only survey specifically designed to catch and characterize the horseshoe crab population in its sampling region. The ARM workgroup decided to accept the indices as provided by Virginia Tech since they also used the delta distribution to model the mean and error of the annual catch.

4.4.4 Abundance Index Trends

The indices of abundance developed by sex and stage for horseshoe crabs in the Virginia Tech trawl survey can be found in Figure 19. Total abundance is estimated by extrapolating the mean catch per tow to the sampling universe illustrated in Figure 18 for the Delaware Bay Area. Abundance varied by stage and sex, although there is a slight increase in abundance across the stages throughout the time series until the terminal year of 2019 when all indices saw a decrease.

5 RED KNOT SURVEYS

5.1 Red Knot Mark-Resight Survey

5.1.1 Methods

Mark-recapture-resight data were used to estimate passage population size and parameters related to migration ecology (Nichols 1996). The Jolly-Seber mark-recapture model for open populations (Jolly 1965; Seber 1965) is appropriate for migration studies because a stopover area can be viewed as an open, “flow-through” system. Estimation focuses on the total number of individuals going through the system in a relatively short period of time.

Red knots have been individually marked at Delaware Bay and other locations with engraved leg flags since 2003. Each leg flag is engraved with a unique 3-character alphanumeric code (Clark et al. 2005). Mark-resight data (sight records of individually-marked birds and counts of marked and unmarked birds) were collected on the Delaware and New Jersey shores of Delaware Bay according to the methods for mark-resight investigations of Red Knots in Delaware Bay (Lyons 2016).

The spatial sampling plan was as follows. The study area is a collection of 22 sites (beaches or shoreline segments), 13 in Delaware and nine in New Jersey. To facilitate even sampling of all sites, the site boundaries were delineated on a map of the study area and defined with a written description. Observers thus know the area to be sampled on each visit to the site. It is not possible to sample all 22 sites at Delaware Bay in one day because the study area is too large. From previous work in the study area, it was estimated that three days would be required to complete a circuit of all sites for mark-resight sampling. Thus the mark-resight “sampling occasion” was defined as 3-day periods between 10 May and 6 June and all data for each 3-day

period are aggregated. That is, multiple observations of the same individual bird in each 3-day period are lumped into one observation (detected) for that 3-day period.

The temporal sampling plan defined two different aspects important for an effective study design to estimate population size. First, resighting surveys were conducted at all sites during each sampling occasion (e.g., 3-day period). Second, sampling periods were defined so that sampling begins when the first birds arrive and continue until the last birds depart the study area. This temporal coverage is essential to capture the entire passage population; if resighting surveys began after birds have arrived in the study area, the stopover population size estimate will not include any birds that arrived and left before sampling began.

On the same days as the resight surveys, observers also conducted scan samples of randomly selected flocks to determine the proportion of the population with marks (Lyons et al. 2016). For each randomly selected flock, observers checked a sample of birds for marks and recorded the number of individually marked birds and the number of birds checked for marks in each sample (Appendix A).

All flag resightings were validated each year with physical capture and banding data available in the data repository at <http://www.bandedbirds.org/>. Resightings without a corresponding record of physical capture and banding (i.e., “misread” errors) were not included in the analysis. However, banding data from Argentina are not available in bandedbirds.org; therefore, all resightings of orange engraved flags were included in the analysis without validation using banding data. Resightings of 21 flagged individuals whose flag codes were accidentally deployed in both New Jersey and South Carolina were omitted (A. Dey, *personal communication*) because it is not possible to confirm individual identity in this case.

To estimate stopover population size, the methods of Lyons et al. (2016; see section 5.1.1.1) were used to analyze 1) the mark-resight data (flag codes), and 2) data from the scan samples of the marked-ratio. In this “superpopulation” approach, passage population size is estimated using the Jolly-Seber model for open populations, which accounts for the flow-through nature of migration areas and probability of detection during surveys.

5.1.1.1 Statistical Methods to Estimate Red Knot Population Size Using Mark-Resight Data and Counts of Marked Birds

The observations of marked birds were converted into encounter histories, one for each bird, and encounter histories were analyzed with a Jolly-Seber (JS) model (Jolly 1965; Seber 1965; CroSBie and Manly 1985; Schwarz and Arnason 1996). The JS model includes parameters for recruitment (β), survival (ϕ), and capture (p) probabilities; in the context of a mark-resight study at a migration stopover site, these parameters are interpreted as probability of arrival to the study area, stopover persistence, and resighting, respectively. Stopover persistence is defined as the probability that a bird present at time t remains at the study area until time $t + 1$. The CroSBie and Manley (1985) and Schwarz and Arnason (1996) formulation of the JS model

also includes a parameter for superpopulation size, which in this approach to mark-resight inferences for stopover populations is an estimate of the marked (leg-flagged) population size.

Three-day periods were used rather than days as the sampling interval for the JS model given logistical constraints on complete sampling of the study area; multiple observations of the same individual in a given 3-day period were combined for analysis.

Inference was made from a fully-time dependent model; arrival, persistence, and resight probabilities were allowed to vary with sampling period $[\beta_t \varphi_t p_t]$. In this model, $p_1 = p_2$ and $p_{K-1} = p_K$ (where K is the number of samples) because not all parameters are estimable in the fully-time dependent model (Jolly 1965; Seber 1965; Crosbie and Manly 1985; Schwarz and Arnason 1996).

The methods of Royle and Dorazio (2008) and Kéry and Schaub (2012, Chapter 10) were followed to fit the JS model using the restricted occupancy formulation. Royle and Dorazio (2008) use a state-space formulation of the JS model with parameter-expanded data augmentation. For parameter-expanded data augmentation, the observed encounter histories were augmented with all-zero encounter histories (n = approximately 2000) representing potential recruits that were not detected (Royle and Dorazio 2012). Lyons et al. (2016) was followed to combine the JS model with a binomial model for the counts of marked and unmarked birds in an integrated Bayesian analysis. Briefly, the counts of marked birds (m_s) in the scan samples are modeled as a binomial random variable:

$$m_s \sim \text{Bin}(C_s, \pi), \quad (1)$$

where m_s is the number of marked birds in scan sample s , C_s is the number of birds checked for marks in scan sample s , and π is the proportion of the population that is marked. Total stopover population size $\hat{N}^*$ is estimated by

$$\hat{N}^* = \hat{M}^* / \hat{\pi} \quad (2)$$

where $\hat{M}^*$ is the estimate of marked birds from the J-S model and $\hat{\pi}$ is the proportion of the population that is marked (from Eq. 1). Estimates of marked subpopulation sizes at each resighting occasion t ($\hat{M}_t^*$) are available as derived parameters in the analysis. An estimate of population size was calculated at each mark-resight sampling occasion $\hat{N}_t^*$ using $\hat{M}_t^*$ and $\hat{\pi}$ as in equation 2.

To better account for the random nature of the arrival of marked birds and addition of new marks during the season, a time-specific model was used for proportion with marks in place of equation 1 above:

$$m_s \sim \text{Binomial}(C_{s,t}, \pi_{\text{occasion}(st)}) \quad (3)$$

for s in $1, \dots, n_{\text{samples}}$ and t in $1, \dots, n_{\text{occasions}}$

$$\text{logit}(\pi_t) = \alpha + \delta_t$$

$$\delta_t \sim \text{Normal}(0, \sigma_{occasions}^2)$$

where m_s is the number of marked birds in scan sample s , C_s is the number of birds checked for marks in scan sample s , δ_t is a random effect time of sample s , and π_t is the time-specific proportion of the population that is marked. Total stopover population size $\widehat{N}^*$ was estimated by summing time-specific arrivals of marked birds to the stopover (B_t) and expanding to include unmarked birds using estimates of the proportion marked:

$$\widehat{N}^* = \sum \widehat{B}_t / \pi_t$$

Time-specific arrivals of marked birds are estimated from the Jolly-Seber model using $\widehat{B}_t = \widehat{\beta}_t \widehat{M}^*$ where $\widehat{M}^*$ is the estimate of the number of marked birds and $\widehat{\beta}_t$ is the fraction of the population arriving at time t .

5.1.1.2 Assumptions of the Mark-Resight Jolly-Seber Model to Estimate Population Size

The mark-resight Jolly-Seber model to estimate Red Knot population size has six assumptions: rate parameters are homogeneous in all birds, marks are not lost or overlooked and are recorded correctly, sampling is instantaneous, emigration is permanent, fates are independent with respect to rate parameters, and marked ratio data are representative of the population. Here, a summary of these assumptions is provided and the bias that may result from violations of the assumptions is discussed.

The first assumption is the homogeneity of rate parameters. The rate parameters of the JS model are probability of arrival to the stopover, probability of stopover persistence, and probability of resighting. The assumption of homogeneity of rates implies that the same rate parameters govern the arrival, persistence, and resighting of all marked and unmarked individuals.

As noted above, the estimation of M^* is based on the resightings of marked birds encountered at each sampling occasion. Observations of unmarked birds are not used in this part of the inference process. Heterogeneity in resighting probability, in which different marked birds present during the sampling occasions have different probabilities of being resighted, can cause bias in parameter estimates (Williams et al. 2002). “Trap response” refers to the situation in which a bird’s previous detection history (usually whether it has been seen before or not) influences its subsequent probability of being resighted. If birds exhibit a “trap-happy” response, in which previously detected birds are resighted repeatedly, marked population size estimates will be negatively biased; if birds exhibit a “trap-shy” response, marked population size estimates will be positively biased (Williams et al. 2002). Trap response may seem unlikely in a mark-resight study because animals are not physically captured. However, uneven sampling of the study area may result in a form of heterogeneity and/or trap response of resighting probability. For example, if certain sites in the study area are visited more often than others,

the same birds may be resighted in a pattern that mimics either heterogeneity or a trap-happy response. Finally, the legibility of the alphanumeric code may be a function of how much ink remains in the engraving. Ink is lost from the engraved leg flags over time (years). Flags that were applied many years ago may not be as legible or readable as flags applied in recent years, creating heterogeneity in resighting probability. Flags that have become completely illegible were treated as unmarked. Birds with illegible flags do not appear in the resighting statistics, and therefore they are counted as unmarked when tallying the counts of marked and unmarked birds for estimation of π .

The above assumptions about detection probability apply to resightings of individual marked birds. The special counts used to estimate marked to unmarked ratios, π , are typically different than the surveys used to obtain detection histories of marked birds. These counts do not require individual identification information for marked birds and usually entail special counts during surveys designed to record marked bird identifications. Estimation of π requires the assumption that marked and unmarked birds have equal probabilities of being detected in these special counts. Trap response would occur if marked birds showed different detection probabilities than unmarked, but this sort of response seems unlikely in such counts. Finally, it should be noted that detection probabilities for marked birds in the two types of surveys, those used to estimate marked to unmarked ratios and those used to estimate M^* , need not be the same.

Effects of heterogeneity in stopover persistence on estimates of stopover duration and population size have not been thoroughly investigated (Williams et al. 2002). Heterogeneity in stopover persistence may result from population structure (e.g., different stopover dynamics for age classes or migratory subpopulations), and stopover-age effects, where stopover-age is measured by length of time at the stopover. In a simulation study of age-related variation in survival probability, Manly (1970) found that the JS model could be reliably used when there is small to moderate variation in survival (persistence) probability.

Some amount of heterogeneity in stopover persistence may result from aggregating data into sampling occasions for analysis, e.g., the 3-day sampling occasions used in Delaware Bay. For example, individual birds observed on day 3 of the sampling occasion may have a greater probability of remaining until the next sampling occasion than birds observed on day 1. However, because the average stopover duration of knots in Delaware Bay is much greater than 3 days, heterogeneity in stopover persistence resulting from data aggregation should be small. Hargrove and Borland (1994) found that effects of aggregating data for sampling occasions did not produce bias in population parameters when survival is high within the pooled periods.

Effects of heterogeneity of rate parameters resulting from age and population structure require additional research. The ARM workgroup plans to explore models that accommodate age-related variation in stopover persistence as part of the ongoing review of monitoring data for the Adaptive Resource Management Working Group for Delaware Bay. In addition, it may be possible to model stopover persistence as a function of boreal-wintering area of marked birds using observations away from Delaware Bay.

The second assumption is that marks are not lost or overlooked, and are recorded correctly. Birds are marked with a leg flag (Clark et al. 2005), which is attached using epoxy and is not expected to fall off over time. Furthermore, loss of flags is not expected to impact population size estimates because the JS model currently implemented at Delaware Bay is a single-season model (i.e., loss of flags during the approximately 15-day stopover may be minimal).

Incorrect recording of alphanumeric combinations, however, may impact parameter estimates. Using the centralized database of capture and banding data (bandedbirds.org), alphanumeric combinations that have not been deployed in the field are removed before analysis. Some errors of recording are thus handled as part of data management. However, it is not possible to identify instances in which alphanumeric codes are incorrectly recorded as codes that actually have been deployed (i.e., “false-positives”). The rate of false positive identifications and impacts on parameter estimates requires additional research.

A form of “flag loss” may result as the ink in engraved leg flags is lost over time or the alphanumeric code otherwise becomes unreadable; this type of flag loss may be an important consideration of multi-year studies of annual survival and other parameters but is not expected to impact passage population size estimates in single-season investigations if such flags are properly treated in analysis. Either birds with such flags should be counted as “unmarked” in the surveys for marked to unmarked ratios, or if this is too difficult (requires too much extra time), then the ratio of unreadable to readable flags in the detection history sampling can be used to adjust the marked to unmarked ratio.

The third assumption of the method is that sampling is instantaneous. This assumption is related to the assumption of homogeneous survival (persistence) probability. Strictly speaking, the assumption of instantaneous sampling is rarely met in practice. The interval between sampling occasions is typically long relative to the duration of the sampling occasion, however. In a simulation study of sampling occasions created from pooling data, Hargrove and Borland (1994) found that estimates of population sizes were acceptable because bias was small.

The fourth assumption is “permanent emigration”. Emigration from the study area is expected to be permanent. Temporary emigration will not bias estimates of passage population size if it is a completely random process (Kendall et al. 1997). That is, birds not available for detection (temporary emigrants) at one sampling occasion are no more or less likely to be available for detection at the next sampling occasion than birds that are currently available. Knots move from the bay shore to the Atlantic shore during the stopover season but these movements are considered random temporary emigration and therefore not a source of bias.

Fifth, independence of fates with respect to rate parameters was assumed. This assumption may be violated if birds migrate in pairs, family groups, or other associations that remove independence of fates with respect to arrival, persistence, and resighting. Thus far, there is no evidence that shorebirds migrate in groups that would result in a violation of this assumption. If this assumption is violated, variance estimates will be negatively biased resulting in confidence intervals that do not accurately reflect uncertainty in parameter estimates, but such a violation

will not create bias in population estimates. Variance estimates can be adjusted with quasi-likelihood methods to accurately reflect uncertainty in parameter estimates.

Finally, it was assumed that the marked ratio data collected with scan samples are representative of the population. Scan samples of flocks of birds are used to estimate the proportion of the population with marks; in each scan sample, the observer records the number of marked birds and the number of birds checked for marks. Care is taken to ensure that the samples are representative of the flocks under study and the population as a whole. A field protocol has been developed to randomly select birds to be scanned and avoid bias in the data collection. Sampling is maintained throughout the season to maintain a representative sample.

5.1.2 Results

The first mark-resight estimate of red knot passage population size at Delaware Bay was made in 2011 (Table 12). The passage population estimates were fairly stable between 2011 and 2020 at approximately 45,000 birds. In 2011, the passage population was estimated to be 43,570 (95% credible interval: 40,880 – 46,570). The passage population peaked in 2015 at 60,727 (55,568 – 68,732) and was lowest in 2020 (40,444 [33,627 – 49,966]).

5.2 Red Knot Delaware Bay Peak Count

5.2.1 Methods

Aerial surveys in the Delaware Bay are conducted annually. The survey covers approximately 80 km of beach in New Jersey and 80 km of beach in Delaware during northbound stopover of shorebird migrants in May and early June. Aerial surveys are conducted in a Cessna high-wing airplane, beginning on the New Jersey side of the bay at Cape May (38.97444948 latitude and -74.96220913 longitude) and ending on the Delaware side at Cape Henlopen (38.7831592730231 latitude and -75.121961041194 longitude; Clark et al. 1993). The survey route is divided into 81 segments defined by geographic features easily discerned from the air. Two observers count during each survey, one person records GPS location data. The plane is flown 25-30 m offshore at approximately 110km/hr, temporarily flushing for ease of counting and species identification. Surveys commence at Cape May approximately 1 to 2 hours after high tide and conclude at Cape Henlopen approximately 2 to 3 hours after high tide as birds are more concentrated and easier to count. From 1986 – 2008 surveys were conducted weekly through May and early June (5-6 counts) by the same observers (Kathleen Clark and Jim Dowdell); all migrant shorebird species were counted including red knot (REKN), ruddy turnstone (RUTU), sanderling (SAND), short-billed dowitcher (SBDO), dunlin (DUNL), and semipalmated sandpiper (SESA).

In 2009 observers and method for aerial counts changed. Counts were reduced to two flights during the peak of stopover (May 18 – 28). In 2009 a bay-wide ground and boat count (of inaccessible areas) was instituted to reduce uncertainty in aerial estimates especially in areas

with high densities of birds (Mispillion Harbor, DE; Egg Island, NJ). From 2009 – 2015 only REKN and RUTU were counted. In 2015-2019 surveyors changed; REKN and RUTU were consistently counted; SAND, SBDO, DUNL, SESA/Peep were inconsistently counted during this period. There were no aerial counts taken in 2020 due to the COVID-19 pandemic.

5.2.2 Results

Peak stopover abundance of red knots in Delaware Bay (aerial/ground counts) had been low and stable for much of the last decade, 2009 to 2021 (Figure 20). Peak abundance declined in 2017 (17,969); resightings of marked red knots (NY, MA) indicate some birds left the Bay early to seek food elsewhere due to low egg resources. This departure was seen in estimates of time-specific stopover population size by Lyons (2017). In 2018 and 2019, peak numbers of red knots were higher (32,930 and 30,880, respectively) as more birds remained in the bay to take advantage of surface eggs more widely available through the stopover period. In 2020, red knot peak abundance declined, (19,397 on May 24) and 2021 observed fewer than 7,000 red knots, the lowest count since surveys began in 1986 and well below the previous 1-year record low count of 12,375 birds in 2007. Aerial and ground surveys do not account for turnover; (the total number of knots moving through Delaware Bay stopover, May 1 to June 7).

6 HORSESHOE CRAB POPULATION MODEL

6.1 Catch Multiple Survey Model

6.1.1 Model Background

Initial attempts at modeling Delaware Bay horseshoe crab stock dynamics using a catch-survey analysis (CSA) began in 2008 (ASMFC 2009b) adhering largely to the methods described in Collie and Sissenwine (1983). The horseshoe crab's unique life history was well-suited to the two-stage modeling approach, as newly mature horseshoe crabs, termed primiparous, exhibit readily-identifiable secondary sexual characteristics, cease molting, and recruit into the spawning population in the ensuing year (Schuster and Sekiguchi 2003; Section 2.1.3). Horseshoe crabs that have spawned at least once, termed multiparous, bear identifiable, permanent, mating abrasions (Hata and Hallerman 2009). Relative abundances of primiparous and multiparous crabs are measured in the Virginia Tech Horseshoe Crab Trawl Survey in the fall directly outside of the population's major spawning grounds (Bi et al. 2020). Primiparous and multiparous females were used as indices of pre-recruits and full-recruits in the catch survey model.

While the initial CSA in 2008 provided a promising model for horseshoe crab, it was not fully developed at that time and was not used for management. Subsequently, a catch multiple survey analysis (CMSA) was developed and peer reviewed for the 2019 stock assessment and tailored to available horseshoe crab survey and harvest information in order to produce estimates of Delaware Bay adult female abundance and fishing mortality rates. The 2019 CMSA

was tested with an operating model and found that model fits were very close to simulated data (ASMFC 2019). Additionally, a retrospective analysis was done which showed minor error or bias from a data peel to 2009, and several sensitivity runs were conducted and the base model was shown to be highly robust. For the 2019 assessment, poor fit to survey indices prevented the development of male-only model. The peer review panel stated that the population estimates from the CMSA were the best available estimates of abundance and fishing mortality for female horseshoe crabs in the Delaware Bay region and that the estimates were suitable for input in the ARM model.

For this ARM Revision, the benchmark CMSA was extended to add additional years of data. The structure of the model, as described below, is generally unchanged. Inputs to the model were unchanged except in instances where the ARM subcommittee had an opportunity to address peer review comments from the assessment, for example, the discard estimates. During the 2019 benchmark assessment, the assessment team focused on the CMSA model development of female horseshoe crabs. While a male model was attempted at that time, there were initially some convergence issues and poor fit to the indices and further development was not attempted due to the timeline of the benchmark. For this ARM Revision, more time was dedicated to explore starting values and stability of the male model and a male model was successfully developed using the same data sources as the female model.

6.1.2 Model Description

The CMSA contains a similar, simplified model structure to the Chesapeake Bay Blue Crab sex-specific catch multiple survey analysis by Miller et al. (2011). The model tracks the dynamics between two horseshoe crab stages: i) primiparous (newly mature yet spawning-naive); and ii) multiparous (spawning-experienced). The broad assertion is that all primiparous females will participate in the proceeding spring spawning event, thus fully entering the multiparous stage within a single year (12-month period). Therefore, multiparous abundance in a given year is a direct function of the primiparous and multiparous abundance in the previous year minus harvest and natural mortality.

The catch multiple survey model is based on the first order difference equation:

$$N_{y+1} = \left((N_y + R_y)e^{-Mt} - C_y \right) e^{-M(1-t)} \quad (1)$$

which relates the fully-recruited abundance at the beginning of the year (N_{y+1}), to the fully-recruited abundance at the beginning of the previous year (N_y), plus pre-recruit abundance in the previous year (R_y), minus catch (C_y), all decremented by natural mortality, M , with t representing the fraction of the year corresponding to the harvest midpoint.

Minimum data requirements for the model include: i) annual indices of relative abundance for each size stage; ii) relative selectivities of size stages to the survey gear; iii) annual harvest; and iv) an estimate of instantaneous natural mortality rate.

Survey indices of abundance are assumed proportional to absolute stock sizes and are described by

$$r_{i,y} = s_i q_i R_y e_i^{\delta y} \quad (2)$$

and

$$n_{i,y} = q_i N_y e_i^{\eta y} \quad (3)$$

where r_i and n_i are the observed indices of pre-recruit and fully-recruited horseshoe crabs from survey i , q_i is the survey catchability coefficient, and $e^{\eta y}$ and $e^{\delta y}$ are lognormally distributed random variables, which represent survey measurement errors. The term s relates the pre-recruit catchability to the full-recruit catchability expressed as the ratio of q_r/q_n (Conser 1994).

$$s = q_r/q_n \quad (4)$$

Annual exploitation rates μ were calculated as

$$\mu_y = C_y / (R + N)_y \quad (5)$$

Instantaneous fishing mortality rates F were calculated from relationships between μ , instantaneous total mortality rate Z , and annual mortality rate A .

$$Z_{y+1} = \ln \left(\frac{(R_y + N_y)}{N_{y+1}} \right) \quad (6)$$

$$A_y = 1 - e^{-Z_y} \quad (7)$$

$$F_y = \mu_y \frac{Z_y}{A_y} \quad (8)$$

Parameters are estimated by minimizing the objective function, which is the sum of the likelihood components for each data source. Each likelihood component consists of

$$L_i = k_i + \frac{1}{2} \sum_{y \in i} \left((\ln O_{i,y} - \ln P_{i,y})^2 / cv_{i,y} \right) \quad (9)$$

where O and P are observed and predicted values of the indices of abundance for each survey i . Constants k were ignored to simplify the equations. Empirical survey cv (coefficient of variations) were used for each year of the index i,y . Likelihood weightings λ were employed to best use available horseshoe crab data sources.

6.1.3 Model Configuration

The unit stock being modeled in the CMSA was the Delaware Bay horseshoe crab population, and male and female horseshoe crabs were modeled separately. The region, for purposes of

defining the boundaries of this unit stock, included states from New Jersey to Virginia. All horseshoe crabs found in Delaware Bay and ocean waters of New Jersey and Delaware are considered part of the Delaware Bay stock. A significant proportion of horseshoe crabs found in ocean areas of Maryland and Virginia also belong to this unit stock. After a review of genetics and tagging work, the DBETC and ARM subcommittee concluded that 45% and 20% of horseshoe crabs found in the ocean areas of Maryland and Virginia are likely of Delaware Bay origin, as necessary to determine quota allocations across the region (ASMFC 2012). This assessment operated under this allocation arrangement for purposes of defining the unit stock and its harvest removals from within this region.

A one-year model time step based on the January to December calendar year was used. All model parameters were estimated in the log scale.

The CMSA model was implemented in ADMB version 12.0. Log-scale standard deviations of parameters and derived values were generated in ADMB as described in Fournier et al. (2012).

Three fishery-independent surveys provided information about Delaware Bay adult abundance: the Virginia Tech, Delaware Fish and Wildlife Adult Trawl, and New Jersey Ocean Trawl Surveys. Stage-specific, swept-area abundance estimates of primiparous and multiparous females and males from the Virginia Tech survey (Bi et al. 2020) were used as pre-recruit (R) and full-recruit (N) indices. Virginia Tech swept-area estimates were based on mean crab densities (assuming a lognormal delta-distribution) expanded to the Delaware Bay survey area, 5,127 km². The ratio s was set to unity, given no evidence to support differences in catchability between stages of similar size and, ostensibly, distribution. Since Virginia Tech collections occur in October, these indices were lagged forward to represent N and R at the start of the ensuing calendar year (January). The survey did not operate from 2012 to 2015 due to funding limitations leading to a gap in the middle of the time series. Therefore, two aggregate stage ($R+N$) indices were constructed from the Delaware and New Jersey trawl surveys, since mature animals were not specifically categorized as primiparous or multiparous in the field. Aggregate stage indices were based on spring trawl collections and were assumed to reflect abundance at the start of the model time-step. As was done in the peer-reviewed 2019 benchmark assessment, these two additional surveys were used for the full time series of the model as indices of relative horseshoe crab abundance, not just as “gap fillers” for the missing years of the VA Tech Trawl data. Empirical annual survey CVs were incorporated into the modeling framework.

Three sources of harvest were included in the CMSA model: i) commercial bait landings; ii) commercial dead discard estimates; and iii) biomedical mortalities. All harvest data were partitioned to only adult horseshoe crabs of Delaware Bay origin by sex. Discard data were unavailable for 2003, so it was assumed that discard mortalities equaled the 5-year average value estimated in 2004-2008. The biomedical data in this report represents the coastwide data for the purposes of model development since the regional data is confidential. Delaware Bay-specific biomedical data will be used in the ARM model to determine the harvest in the region if the model is approved for management use.

Instantaneous natural mortality rate (M) on adult females was assumed to be $M=0.3$ (Section 2.1.4), which was higher than the 2019 stock assessment where $M=0.274$. M was assumed constant across years and equal for primiparous and multiparous crabs since both stages will experience spawning-related mortality, the primary source of adult natural mortality. Both sexes used the same M , as differences in survival were not significant in the data for males and females.

In the 2019 model, the three surveys were weighted based on estimated process error variances. The peer review panel suggested that the survey weights be removed since the CVs for the surveys also weight the data and it was unclear whether uncertainties were double counted. Sensitivity analyses showed that the results were robust to the configuration of the weights. Following the recommendation of the peer review, the ARM subcommittee removed the survey weights for this model configuration.

All input values can be found in Table 13 for female horseshoe crabs and Table 14 for male horseshoe crabs. Twenty-one parameters were estimated: median primiparous abundance (1); primiparous abundance for each year (17); catchability coefficients (2) for the Delaware and New Jersey surveys; and multiparous abundance for the start of time series (1), summarized in Table 15.

6.1.4 Results

Base model predictions fit indices well for both female and male horseshoe crabs, with excellent agreement with the primiparous index and well-behaved fits through observed multiparous indices (Figure 21 - Figure 22).

Estimated female and male primiparous abundance was fairly stable through the time series with the exception of the missing years of the Virginia Tech trawl survey (2013-2016; Table 16 - Table 17, Figure 23- Figure 24). Rising multiparous abundance was evident in both sexes and reflects some of the large increases seen in the multiparous trawl indices in later years (Table 16 - Table 17, Figure 23- Figure 24). Fishing mortality rates are very low (average female $F=0.018$ and average male $F=0.024$), seemingly reflecting the current period of highly protective fishery restrictions and moratoria (Figure 25).

6.1.5 Sensitivity Runs

Numerous sensitivity runs were explored during the initial development of the CMSA model for horseshoe crabs (ASMFC 2019) to evaluate the effects of assumptions on natural mortality, harvest, survey weights, CVs, catchability (q), and starting values. The base model was highly robust to large variations in starting values of primiparous crabs, multiparous crabs, and q . Model convergence and parameter estimations were unchanged from changes in starting values ranging by more than an order of magnitude.

The configuration of the CMSA for this report remains the same as the 2019 peer-reviewed model with three changes: (1) the survey weights were removed, (2) discard estimates were re-estimated and different values of discard mortality by gear were considered, and (3) a different value of M was used. The survey weights and discard estimate changes were made to address comments made by the peer review panel. Natural mortality was re-estimated from the 2019 benchmark and the revised value was used for this ARM revision. The sensitivity to these changes in the model configuration were evaluated. Similar to the benchmark, the model was robust to the changes explored (Table 18 and Table 19).

6.2 Projection Model

6.2.1 Population Dynamics

The ARM model makes harvest recommendations based on the values of a number of components of the current state of the Delaware Bay ecosystem. Fundamental to the operation of the ARM algorithm and the choice of an optimal harvest policy is the ability to simulate the system state into the future. Because the state of the Delaware Bay system is represented in the ARM model via abundances of horseshoe crabs and red knots, population projection models are required for both species. This is true of both the previous and present ARM model versions.

The previous ARM model used a stage-based horseshoe crab projection model (ASMFC 2009a), which required knowledge of a number of parameters that are difficult to estimate and not regularly monitored. These included survival rates for eggs and juveniles, maturation rates for juveniles, and per capita fecundity (Figure 26). Because egg and juvenile abundances are not monitored, it is not straightforward to update the associated parameters: they are essentially latent.

In contrast, the horseshoe crab projection model used in the revised ARM model derives directly from the Catch Multiple Survey Analysis (CMSA; Section 6.1.2). It includes only two life stages, multiparous and primiparous adults, with the sexes distinguished within each. The resulting model is simpler (Figure 27), and all four population segments are monitored each year. Multiparous abundances in year $y + 1$ are given by

$$N_{y+1}^f = \left((R_y^f + N_y^f) \cdot e^{-M^f z} - H_y^f \right) \cdot e^{-M^f(1-z)} \quad (1)$$

for females (superscript f) and

$$N_{y+1}^m = \left((R_y^m + N_y^m) \cdot e^{-M^m z} - H_y^m \right) \cdot e^{-M^m(1-z)} \quad (2)$$

for males (superscript m), with R_y the abundance of primiparous crabs in year y , N_y number of multiparous crabs in year y , M the instantaneous mortality rate, and z the timing of harvest expressed as a proportion of the annual cycle (see Table 20 for parameter values). These expressions exactly mirror Equation 1 of Section 6.1.2, though the notation differs somewhat.

In place of a description of fecundity, survival of eggs, and survival and maturation of juveniles, a simplified recruitment process is used to generate primiparous adults of each sex, each year (Section 6.2.2).

6.2.1.1 Natural Mortality

Whereas the CMSA model uses only the point estimate of female and male horseshoe crab instantaneous natural mortality ($M^f = M^m = 0.3$; Section 6.1.3; D. Smith, USGS, unpublished data), the projection model incorporates uncertainty around that estimate as well. Annually, and separately for each sex, mortality values are drawn from a normal distribution:

$$M_y \sim \text{Norm}(\mu^M, \sigma^M) \quad (3)$$

with $\mu^M = 0.3$ and $\sigma^M = 0.0182799$ (Table 20).

6.2.1.2 Background Harvest

When the horseshoe crab projection model is used as part of the optimization algorithm, bait harvest is determined annually by a harvest model component that takes as input 1) the state of the system (female and male adult crab abundances; adult red knot abundance), and 2) the harvest policy. Two other kinds of harvest are accounted for in the horseshoe crab simulation model, however: 1) dead commercial discards (mortality from becoming bycatch; Section 3.3), and 2) biomedical mortality (Section 3.2).

For each sex, ranges were found of estimates for the number of crabs killed as commercial discards and by the biomedical fishery in years 2014-2018. The low values from each of the two ranges were then added together, as were the high, to find the range in background mortality from fishing activity not managed by the ASMFC. In the horseshoe crab projection model, this background harvest was drawn each year from a uniform distribution. Separately for each sex

$$H_y^{bg,f} \sim \text{Unif}(L_{bg}^f, U_{bg}^f) \quad (4)$$

$$H_y^{bg,m} \sim Unif(L_{bg}^m, U_{bg}^m) \quad (5)$$

with L_{bg} the minimum and U_{bg} the maximum observed background harvest value (see Table 20 for values). Total harvest H_t is then found by adding bait harvest to the background harvest.

In the runs of the horseshoe crab projection model described in this report, both as a standalone simulation and as part of the revised ARM model, coastwide estimates for biomedical mortality are used (Section 3.2.2). In generating the optimal harvest policy for final use by ASMFC in setting horseshoe crab harvest limits, confidential estimates specific to Delaware Bay would be used instead (Section 3.2.3).

6.2.2 Horseshoe Crab Recruitment

In the horseshoe crab projection model, primiparous crabs (R in Equations 1 and 2) are generated annually by a process that is parameterized directly from CMSA estimates of primiparous abundances. This represents an advance over the horseshoe crab model in the previous ARM version, since parameters of the recruitment process may be updated annually as new CMSA estimates are generated from trawl surveys.

For a given year, the recruitment process includes two main steps:

- 1) proposed abundances of female and male primiparous abundances are generated from a bivariate lognormal distribution;
- 2) the number of spawning females whose eggs were fertilized (N^e) in years $y-10$ and $y-9$ are checked: if N_{y-10}^e is lower than a threshold, the proposed number of female recruits is scaled downward; if N_{y-9}^e is lower than the threshold, the proposed number of male recruits is scaled downward.

These steps are explained in detail in the subsequent sections.

6.2.2.1 Proposed Primiparous Abundance

Each year proposed female and male primiparous abundances $\mathbf{d}_y = [d_y^f \quad d_y^m]$ are drawn from a bivariate lognormal distribution:

$$\ln(\mathbf{d}_y) \sim Norm(\boldsymbol{\mu}, \Sigma) \quad (6)$$

with $\mu = [\mu^f \quad \mu^m]$, the natural log of the mean abundances for females and males, and Σ the variance -covariance matrix:

$$\Sigma = \begin{bmatrix} \sigma_f^2 & \rho\sigma_f\sigma_m \\ \rho\sigma_f\sigma_m & \sigma_m^2 \end{bmatrix} \quad (7)$$

with σ^f and σ^m standard deviations and ρ the correlation between female and male primiparous abundances. An advantage to using a bivariate distribution, is that the observed correlation between female and male primiparous abundances can be preserved in the projection model. Parameters of this distribution were obtained directly from CMSA estimates, in the following way.

For the purpose of parameterizing the recruitment distribution described above, estimates of primiparous abundances beginning in 2013 were chosen. Visual inspection of the CMSA time series (Figure 23 and Figure 24) suggests a qualitative shift in the population trajectory beginning around 2013, and it was thought that including all years in the time series might lead to an underestimate of the potential for recruitment in the future. The latest CMSA estimates available for analyses in this report are from 2019.

The strategy for developing the recruitment distribution comprised these steps: 1) find the parameters of lognormal distributions corresponding to the point estimates and 95% confidence intervals of female and male primiparous abundances in each year in 2013-2019; 2) draw a large number of samples from each of these fourteen distributions (seven years by two sexes); 3) arrange the samples in a two-column matrix, one of female values, the other male, making sure each row is from the same year; 4) fit a bivariate lognormal distribution to the samples via maximum likelihood.

For each year in the period 2013-2019 and for each sex, a mean and standard deviation was required for each of 14 normal distributions describing logarithms of primiparous abundances. This was complicated significantly by the gap in the time series of the Virginia Tech trawl survey (Section 4.4), because the estimates of primiparous abundances during 2013-2016 are quite uncertain and unstable (top panels in Figure 23 and Figure 24). This instability is a consequence of the CMSA model structure, and of the fact that the Virginia Tech trawl is the only one of the three trawl surveys used in the CMSA that provides counts of primiparous crabs.

However, it was thought that when taken together, the average of the estimates of the mean primiparous abundance would be a reliable expression of the recruitment required to yield the adult abundances observed following the VA Tech gap, in 2017-2019. The justification for this position lay in the structure of the CMSA, and the fact that its estimates represent a balance between observed counts and the population dynamics codified in the CMSA. So, separately for females and males, the average of the point estimates of primiparous abundance was taken over 2013-2016 to represent the mean abundance for each of those years.

The confidence intervals for primiparous abundance over 2013-2016 were deemed unusable. To generate standard deviations over this period, the ARM workgroup reasoned that the coefficient of variation (CV) ought to remain fairly stable over the entire CMSA time series, 2003-2019. Therefore, the VA Tech gap years 2013-2016 were excluded and standard deviations for all remaining years were found; then the mean CV over those years was determined, separately for females and males. Then the average means described previously were used as well as the mean CVs to calculate a standard deviation to use in each year in 2013-2016. The method used to find standard deviations ‘directly’ for years 2003-2012 and 2017-2019 is described next.

To approximate standard deviations of normal distributions that when exponentiated would correspond to means and confidence intervals output by the CMSA, the natural logarithm of the mean and confidence limits was found. The confidence limits were treated as quantiles of a normal distribution. On the log scale, the appropriate standard deviation was found by taking the mean difference between each confidence limit and the mean, and dividing this value by the quantile of a standard normal distribution corresponding to a probability of 0.975 (approximately 1.96).

Having thus found means and standard deviations for the desired normal distributions (generating logarithms of primiparous abundances) - indirectly for years 2013-2016 and directly for 2017-2019 - 10,000 random deviates were drawn from each of them. These were arranged in a two-column matrix, with female values in one column and male in the other. Each row was drawn from distributions representing the same year, preserving any correlation present in the time series.

Then maximum likelihood was used to fit a bivariate normal distribution to the samples. The mean and variance of male primiparous abundances is estimated to be considerably higher than those of females; and the correlation is moderately positive (Table 20).

6.2.2.2 Stock-Recruitment Relationship

For a given year y , the primiparous abundances d_t generated by the recruitment distribution (Equation 6) are considered realistic provided that the number of fertilized eggs was sufficiently high in the year of the cohort hatched. As a proxy for the number of fertilized eggs, a value the ARM workgroup named the effective number of spawning females, N^e , was used. If N^e is below a threshold, the values d_y are scaled downward.

Because the time steps in the projection model do not correspond to calendar years, but rather begin October 1, both primiparous and multiparous crabs observed in year y will breed in year y . The effective number of spawning females in year y is the product of the number of adult females (that is, the number of primiparous plus the number of multiparous) and a fertility factor, f . If $S_y^f = R_y^f + N_y^f$ is the total number of spawning females and $S_y^m = R_y^m + N_y^m$ is the total number of spawning males, then

$$N_y^e = f_y S_y^f, \quad (8)$$

with fertility dependent on the sex ratio in year y :

$$f_y = \min \left(1, \frac{2S_y^m}{S_y^f + S_y^m} \right) \quad (9)$$

Expected maturation time to the primiparous stage is ten years for female crabs; nine years for males (Section 2.1.2). The scalars to be used in adjusting the number of recruits in year y are $s_y = [s_{y-10} \ s_{y-9}]$, with each element of the vector defined as

$$s_y = \begin{cases} 1, & \text{if } N_y^e \geq N^*, \\ N_y^e / N^*, & \text{if } N_y^e < N^*. \end{cases} \quad (10)$$

The threshold value N^* was chosen to be 3,750,000. This value was chosen as the point at which recruitment would decline because it was approximately the lowest number of total females estimated by the CMSA during the time series (3.9 million in 2006) and harvest restrictions had been in place for several years prior to this time. The scalars s_y thus follow a ‘broken-stick’ curve (Figure 28).

Finally, the proposed recruitment values d_y are scaled by s_y to obtain the number of recruits (i.e., primiparous crabs) $R_y = [R_y^f \ R_y^m]$:

$$R_y = d_y \circ s_y, \quad (11)$$

where ‘o’ indicates elementwise multiplication.

The recruitment process governing primiparous abundances in year y thus incorporates stock-recruitment information for two different cohorts, one from year $y-9$ (for males) and one from year $y-10$ (females). It is important to note, however, that although the males and females maturing to primiparous stage in year y were hatched in different years, they were subject to

the same conditions in subsequent years. The specification of a covariance in the bivariate recruitment distribution (Equations 6 and 7) accounts for this shared history.

However, it is also worth noting that some of the observed correlation in estimates of primiparous abundances produced by the CMSA may be due to annual variation in sampling efficiency. The survey methods and analysis approach currently in use do not allow estimation of and correction for detection probability (or availability). It is not currently possible, then, to determine how much of the observed correlation between male and female abundances is due to shared variation in annual survival probabilities, and how much is an artifact of annually varying detection probability or availability (see Research Recommendations, Section 10).

Although it will not address heterogeneity in detection probability, consistent monitoring via trawl surveys and estimation with the CMSA model will allow rapid learning about the recruitment process. At present, only seven years of CMSA estimates are used to inform recruitment, and four of those are quite uncertain because of the absence of the Virginia Tech trawl survey data in that period. Each additional year of data will add considerably to the understanding of horseshoe crab recruitment, provided the Virginia Tech trawl data are available. Without the Virginia Tech trawl and the ability to reliably estimate primiparous abundances, knowledge of the horseshoe crab recruitment process will not advance (see Research Recommendations, Section 10).

Finally, the ARM workgroup acknowledges that the transition from a more mechanistic horseshoe crab projection model in the previous ARM version, to one that does not attempt to explain changes in abundance in terms of precise demographic stages may seem counterintuitive. However, a more mechanistic model requires more data about more life stages; and the only stages that have been consistently monitored in Delaware Bay are primiparous and multiparous adults. Use of a model that relies only on those segments of the population that are regularly observed allows for constant refinement of its parameters at no additional cost.

6.2.3 Projection Model Results and Sensitivity

Summaries of a number of applications of the new horseshoe crab projection model are provided primarily in graphical form. For each scenario considered, 5,000 simulations of the model were run and the median and 2.5th and 97.5th quantiles were reported. First, the sensitivity of the model to different levels of harvest will be discussed, then to changes in parameters of the recruitment process.

6.2.3.1 Effect of harvest on long-run horseshoe crab abundance

A comparison of simulations with zero harvest (Figure 29), against a set that experiences background harvest levels (that is, mortality from biomedical use and bycatch) shows a modest reduction in the long-run equilibrium abundances (Figure 30): about 50,000 fewer females expected in year 100 (a 0.38% reduction); 80,000 fewer males (a 0.22% reduction).

The maximum harvest allowed under the previous ARM Framework was 210,000 females per year and 500,000 males (ASMFC 2009a). The expected long-run equilibrium abundance under this maximum harvest scenario (Figure 31) is somewhat lower than the background harvest scenario (Figure 30): 0.74 million (5.6%) fewer females, 1.8 million (5.1%) fewer males. Even under this maximum harvest scenario, however, the population is still predicted to increase and then stabilize after about ten years from the present.

Under a much higher harvest scenario of 2 million females and 2 million males annually (Figure 32), the population trajectory is considerably more affected over the projection period, showing reductions from recent abundances almost immediately. The expected female abundance in projection year 100 is reduced relative to the maximum ARM harvest (Figure 31) by 7.08 million (57%); expected male abundance is reduced by 8.13 million (24%).

6.2.3.2 Sensitivity to recruitment parameters

Because relatively few years of CMSA estimates inform the recruitment process in the horseshoe crab projection model, the possibility that the mean primiparous abundances estimated from this period are too high was considered and that the estimates will be reduced as more years of CMSA estimates become available. To understand the sensitivity of the projection model to reduced values of the female ($\exp(\mu^f) = 3.11 \times 10^6$) and male ($\exp(\mu^m) = 6.90 \times 10^6$) nominal means μ used in the recruitment distribution (which generates the logarithm of primiparous abundances; Equation 6), the workgroup ran 5,000 simulations at each of a number of reduced values of μ . The expected HSC abundances 100 years in the future (Figure 33) appear quite sensitive to changes in the median of the lognormal recruitment distribution, $\exp(\mu)$. Both sexes show a similar pattern, with a generally linear reduction in the long-run abundance with reduced values of $\exp(\mu)$, but then a steep dropoff to zero beginning at some threshold value between 35-40% of the nominal value of $\exp(\mu)$.

6.2.3.3 Sensitivity to recruitment and harvest

If recruitment is indeed lower than the estimates made here or estimates become lower as more years of CMSA become available, the effect of harvest on horseshoe crab abundance could in turn be affected. To assess this possibility, the projection model was run across a range of harvest values, at three levels of mean recruitment values, $\exp(\mu)$:

1) its nominal value (Table 20),

$\exp(\mu) = \exp([\mu^f \mu^m]) = \exp([14.95 \ 15.75]) = [3.11 \ 6.90] \times 10^6$ (Figure 34 and Figure 35);

2) a 5% reduction, $\exp(\mu) \times 0.95 = [2.95 \ 6.55] \times 10^6$ (Figure 36 and Figure 37);

3) a 10% reduction, $\exp(\mu) \times 0.90 = [2.80 \ 6.21] \times 10^6$ (Figure 38 and Figure 39).

Looking across expected long-run female abundances (Figure 34, Figure 36, Figure 38) reduction in expected recruitment can be seen to induce increased sensitivity of the population

to harvest; the same pattern is apparent for males (Figure 35, Figure 37, Figure 39). The complex pattern to the right side of the male abundance plots results from the effect of the sex ratio, through the fertility factor (Equation 9).

7 RED KNOT POPULATION MODEL

7.1 Multi-State Framework

7.1.1 Model Background and Description

This section describes this Revision's attempt to replicate the analyses of ASMFC (2009a) and McGowan et al. (2011a). The approach of ASMFC (2009a) and McGowan et al. (2011a) was followed to develop mark-recapture models in a multistate open robust design and to address the ARM revision's TORs.

The purpose of these models is to estimate annual survival of red knots that stop at Delaware Bay based on their body mass at departure and to estimate the probability of gaining weight during stopover. Because of the hypothesized relationship between female horseshoe crab abundance and mass gain of red knots (Niles et al. 2008), the survival modeling provides a direct link between red knot population dynamics and female horseshoe crab abundance. The approach used here expanded on existing methods of open robust design (Kendall et al. 1997; Kendall and Bjorkland 2001) and multistate survival analyses (Nichols and Kendall 1995) and incorporated both mark-recapture data and mark-resighting data to estimate mass-specific survival probabilities and the probability of gaining weight during stopover. The resighting data do not have any information on an individual's body mass at the time of observation; however, this assessment developed models to take advantage of the substantial resighting dataset, which greatly improves precision of survival estimates. This analysis represents an effort to quantify the relationship between red knot demography (annual survival) to horseshoe crab abundance through weight gain at Delaware Bay.

Two body mass classes (states) were established for knots at the bay: < 180 g and ≥ 180 g. The stopover season was divided into three secondary periods for the robust design: 1–19 May, 20–25 May, and 26 May–5 June (Figure 40), the same time windows used in the original analysis. Most of the information required by the state transition analysis (e.g., weight gain) is provided by individuals that were caught and weighed more than once. Birds that were weighed in two different secondary periods within a single season were especially useful in informing the models of state transition dynamics. The secondary periods for the robust design were created to maximize the number of within season recaptures to improve precision of parameter estimates. Approximately one third of all captures between 1997 and 2019 occurred in each of the three sampling periods.

In the analysis, birds could enter or depart the study area (Delaware Bay) during any of the three periods in either mass state. Once at Delaware Bay, the birds could transition between periods from either mass state to the other mass state or remain in the same mass state. In

each period, birds could be 1) physically captured, weighed, and assigned to a mass state, 2) observed in the field, in which case its mass state is unknown, or 3) both physically captured and observed in the field in the same period. For each secondary period in the stopover season, there were two pieces of data that were represented in the individual encounter histories: captured or not (with mass state for captures) and observed in the field or not (Figure 41).

Example encounter histories for four years of data collection are provided in Figure 41. The data are grouped into three doublets in each year to represent the three secondary encounter periods. In each encounter history (row), “A” indicates that the bird was captured below the 180 g threshold (light), “B” indicates that the bird was captured above the 180 g threshold (heavy), and “1” indicates that a bird was observed in the field. A “0” in the first column of a doublet for any secondary period indicates the bird was not captured whereas a “0” in the second column of a doublet indicates that the bird was not observed in the field.

With these data and the multistate open robust design analysis, several parameters were estimated that were associated with the ecological and sampling processes that generated the data (Figure 40): arrival probability (β), departure probability (δ), capture probability (p), resight probability (r), transition probability (ψ), and annual survival probability (S). Survival probability was assumed to approach 1 during the stopover period but otherwise possible state-dependence, period-dependence, and/or year-dependence for all other parameters had potential to be evaluated. Time-specific environmental covariates (e.g., annual snow cover in the arctic) were also used to examine relationships between the environment and red knot demography.

Following ASMFC (2009a) and McGowan et al. (2011a), the ARM workgroup developed a set of candidate models and evaluated their support from the data using an information-theoretic approach (Burnham and Anderson 2002). The candidate model set included models that described the potential relationships between horseshoe crab populations, red knot mass increase during stopover, and red knot annual survival. The candidate models focused on evaluating three research hypotheses: 1) heavy birds have a higher probability of annual survival than light birds, 2) arctic weather conditions upon arrival influence red knot annual survival, with lower survival rates predicted for years of high snow cover, and 3) horseshoe crab spawning abundance positively affects red knot mass transition probabilities during the stopover at Delaware Bay.

To develop the set of candidate models, a sequential approach to model building was used. Initially, the best model structure was determined for parameters associated with the sampling process (capture and resighting probabilities) and ecological parameters not under direct investigation (arrival and departure probabilities). Various combinations of state-, time-, and period-dependency for these parameters were compared while keeping other parameters as general as possible (year-specific survival probabilities and period-specific mass transition probabilities constant across years). This initial phase of model building indicated that the best model for capture probabilities was mass state and year dependent (i.e., capture probabilities varied across years and between mass states independently [year $\times$ state]). Adding period

dependency (additive or interaction) to the capture probabilities produced models that appeared to fit the data well, but that produced unrealistic parameter estimates in many cases. The best model structure for resight probabilities included year, state, and period interactions (year $\times$ state $\times$ period). Resighting probabilities before 2003 were set to zero since field-readable bands were not used prior to that season. Having identified the best model structure for the parameters associated with the sampling process, multiple models about the ecological parameters of interest were then evaluated, each with the same structure for the sampling process parameters.

To investigate the research hypotheses regarding adult annual survival, models were included that allowed survival to vary with mass state and snow cover (additive and interaction terms), as well as models with no structure on survival (null models). Morrison (2006) and Morrison et al. (2007) reported that the arrival condition in the arctic was a key predictor of survival of European red knots (subspecies *islandica*) breeding on Ellesmere Island, Canada. They concluded that birds leaving the stopover sites in Iceland at low weights had higher mortality after arriving on the breeding grounds if there was extensive snow cover on the ground. Those same effects may hold true for *rufa* red knots that stop at Delaware Bay. It was hypothesized here that the effects of poor departure condition would be exacerbated by snow cover on the breeding grounds and expected to see low survival of light birds in years of high snow cover. Any relationship between survival of heavy birds and Arctic snow cover were not expected. Arctic snow cover was estimated following the methods described by MacDonald (2020). In brief, daily mean snow cover data from 1997-2019 at 32-km resolution were obtained from the National Centers for Environmental Protection's North American Regional Reanalysis (NARR) dataset (Mesinger et al. 2006). The data were filtered to only the area considered to be the preferred red knot breeding habitat (MacDonald 2020; Smith and Rausch 2013) during 15-30 June of each year (considered peak nest initiation period; MacDonald 2020; Niles et al. 2008). For each year, the overall mean percent snow cover in each grid cell was calculated.

To examine the research hypothesis regarding state transition probabilities, these transitions were modeled as a function of female horseshoe crab abundance and stopover period (additive and interaction terms), as well as with null models (no covariates or temporal structure). Horseshoe crab population estimates from the Catch Multiple Survey Model (Section 6.1) and estimates from the spawning survey of the proportion of the horseshoe crab population spawning in May each year (Section 4.3) were used. Four models were created with these two predictors: two models using each of the predictors as main effects alone, one with an additive combination, and one with the interaction (horseshoe crab abundance $\times$ proportion spawning in May). Models were also compared that restricted the covariate structure on transitions from heavy to light because the dataset included very few within-season transitions from heavy to light mass state; similarly, there were few "transitions" from heavy to heavy. Because of this paucity of data, heavy to light transitions as a function of horseshoe crab abundance were not modeled.

The models of adult annual survival and mass state transitions describe above were compiled in a candidate model set and an AIC information theoretic approach was used to compare the fit of candidate models to the data from 1997–2019 (Burnham and Anderson 2002).

7.1.2 Results and Discussion

The model with the most support based on AIC (Table 21, Model 1) was one in which annual survival was a function of mass state and year (additive main effects); transitions between mass states (both light-to-heavy and heavy-to-light transitions) were a function of horseshoe crab abundance, proportion spawning in May, and stopover period (three-way interactions; Table 21).

Model 2 was similar: annual survival was again a function of mass state and year (Table 21). With respect to the transition probabilities, however, the effects of horseshoe crab abundance and May spawning proportion were additive in Model 2, rather than interactive as in Model 1. Furthermore, the strength of these additive effects was not the same in each stopover period, as indicated by the interaction with period (Table 21). Model 3 was similar to Model 1 except that transitions from heavy-to-light state were a function of only stopover period, unrelated to horseshoe crab abundance. Models 2 and 3 were not competitive with Model 1, however. Model 2 was 80.9 AIC units from Model 1 (Table 21).

The measure of Arctic snow cover used was not a good predictor of annual survival in this analysis. A model with additive effects of snow cover and mass state ($S[\text{state} + \text{snow}]$) was 729 AIC units below the most-supported model. Models that allowed annual survival to vary as a function of snow cover alone ($S[\text{snow}]$) received even less support from the data; models with this structure were at least 941 AIC units below model 1.

As noted above, Models 2 and 3 were not competitive and therefore the ARM workgroup focused on the parameter estimates of Model 1 (Table 21). Furthermore, the parameter estimates for the transitions between light and heavy states in this model were focused on given the importance of hypotheses related to mass gain during stopover for decision making and harvest management constrained by red knot conservation at Delaware Bay. In model 1, the transitions between mass states varied with horseshoe crab abundance and proportion of the population spawning in May and the interaction of these predictors.

The parameter estimates for the transitions between stopover (secondary) periods are shown in Table 22. Transition 1 occurs between 19 and 20 May, whereas transition 2 occurs between 25 and 26 May. For transition 1, the parameter estimates in the interaction model indicate little relationship between the probability of gaining weight and horseshoe crab abundance and the proportion spawning in May. For transition 2, the parameter estimates indicate an inverse relationship between the probability of gaining weight and horseshoe crab abundance and the proportion spawning in May (Table 22).

These counterintuitive results are not consistent with the ARM workgroup's hypotheses and predictions about the effects of horseshoe crab abundance on refueling performance of red

knots during stopover at Delaware Bay. Furthermore, these results are inconsistent with the results of ASMFC (2009a) and McGowan et al. (2011a). McGowan et al. (2011a) found that the light-to-heavy transition probability between periods 2 and 3 (i.e., transition 2) had a strong positive relationship with the number of horseshoe crabs that spawned in May. These results show the opposite; as the number of horseshoe crabs spawning in May increased, the probability of transition from light to heavy decreased (Table 22). In addition, there was a large discrepancy in the magnitude of the estimated probability of gaining weight during stopover (ψ^{LH}) of McGowan et al. (2011a) and these results. McGowan et al. (2011a) showed that the probability of gaining weight (ψ^{LH}) was ≥ 0.75 at transition 1 and ranged from approximately 0.35 to 0.65 at transition 2, depending on horseshoe crab abundance. The estimates in this report of the probability of gaining weight (ψ^{LH}) were never > 0.3 and in most cases were < 0.2 , which is not consistent with empirical observations.

Despite following the modeling and estimation framework of McGowan et al. (2011a) and having more data available for this analysis, the attempt to essentially replicate the previous approach and update the understanding of the relationships between red knots and horseshoe crabs at Delaware Bay was not successful. The results were not only counter-intuitive but also inconsistent with McGowan et al. (2011a) and the ARM workgroup's predictions. Furthermore, there was evidence that the analysis was relatively unstable and sensitive to the starting values provided. Whereas the multistate open robust design has many advantages for modeling and estimation at stopover areas, it may be that some aspects of this framework were problematic. For example, the 180 g threshold to distinguish light and heavy birds does not provide the flexibility to model the effects of horseshoe crab abundance on body mass as a continuous variable. McGowan et al. (2011a) chose the 180 g threshold based on the results of Baker et al. (2004) and Niles et al. (2008). It may be that a different mass threshold, or multiple thresholds resulting in multiple mass classes, may provide more flexibility and more reliable results. Similarly, the delineations of the secondary periods for the robust design are another type of inflexible threshold that may have complicated the modeling and estimation. The secondary periods are somewhat arbitrary and of unequal duration (e.g., 1–19 vs. 20–25 May) for reasons described above. In the open robust design used here, these date thresholds are used across years and do not allow for annual variation in migration timing, which may limit the usefulness of the multistate robust design in this case. Given the counterintuitive nature of these results, the parameter estimates are not useful for revisions to the adaptive harvest management framework for horseshoe crabs and red knot conservation at Delaware Bay. Therefore, the ARM workgroup chose to replace the multistate open robust design framework with an integrated population modeling framework.

7.2 Integrated Population Model (IPM)

7.2.1 Background

Integrated population models (IPMs) are a statistical method for combining multiple data sources for a fuller picture of population dynamics (Besbeas et al. 2002; Schaub and Abadi 2011). IPMs lend themselves to full annual cycle applications because they are anchored on a

description of the life cycle of the species, usually via a population matrix model (Caswell 2001). A key benefit of IPMs is the ability to estimate latent demographic rates, i.e., parameters of interest for which little or no data exists (Abadi et al. 2010; Schaub and Abadi 2011). For red knot in Delaware Bay, there is little information about annual recruitment rate of new adults into the breeding population. This demographic rate is difficult to estimate due to challenges of monitoring breeding success in the Arctic as well as juvenile survival during the nonbreeding season. By combining an analysis of the mark-recapture data to inform adult survival estimates with an analysis of count data to inform changes in population size, recruitment rate for this population can be inferred.

Migratory stopover sites play a critical role in the annual cycle of long-distance migrants (Alerstam 2011; Newton 2004) and are the focus of many monitoring programs. However, analysis of mark-recapture data from stopover sites is complicated by the highly mobile nature of the population, with individuals passing through the site at rates that can vary among individuals, throughout the season, or among years (Tucker et al. 2021). An IPM was developed for this assessment that accounts for interannual variation using an open robust design mark-recapture model (Kendall and Bjorkland 2001; Kendall et al. 2019), which simultaneously estimates annual variation in survival and dynamics of site use. This modeling framework uses monitoring data from a single site to infer full annual cycle population dynamics.

7.2.2 Model Description

The IPM consists of three submodels analyzed simultaneously. The mark-recapture data were analyzed using an open robust design model (Tucker et al. 2021) to estimate apparent annual survival probability as well as parameters related to the within-season processes of arrival and persistence at the site (described in detail below). The count data were analyzed using a state space model to estimate the change in population size between years while accounting for counting error. The matrix projection model links these two analyses by describing the underlying processes of survival and recruitment that contribute to the changes in population size among years. A conceptual diagram of the IPM is provided in Figure 42.

7.2.2.1 Matrix Projection Model

The life cycle model was based on a two-stage matrix model in which the number of juveniles (superscript J) and adults (superscript A) alive in the spring of year $y+1$ depends on the number of individuals of each age class in the previous year (N_y^J and N_y^A), the annual survival for each age class (ϕ_y^J and ϕ_y^A), and fecundity (f_y). This model was developed to consider a spring stopover site (i.e., a pre-breeding census), and therefore the fecundity parameter is the product of the average number of offspring produced per breeding adult and winter survival of first-year birds.

$$\begin{bmatrix} N_{y+1}^J \\ N_{y+1}^A \end{bmatrix} = \begin{bmatrix} 0 & f_y \\ \phi_y^J & \phi_y^A \end{bmatrix} * \begin{bmatrix} N_y^J \\ N_y^A \end{bmatrix}$$

For red knot, individuals do not reproduce or undergo spring migration until their second spring, and therefore only animals in the adult age class are observable. A recruitment parameter ρ_y was estimated as the product of fecundity and juvenile survival:

$$\rho_y = f_y * \phi_{y+1}^J$$

For a system in which juveniles migrate in their first year and are distinguishable from adults, juvenile survival and fecundity could be estimated separately. This recruitment rate operates on a two-year lag; the expected number of new recruits in year y (i.e., individuals migrating north to breed for the first time, denoted with superscript R) is equal to the total number of adults in the population in year $y-2$ times the recruitment rate from that year ($N_y = N_y^A + N_y^R, N_y^R = N_{y-2} \rho_{y-2}$). The expected number of returning adults in year y is equal to the total number of adults in year $y-1$ multiplied by the annual survival probability ($N_y^A = N_{y-1} \phi_{y-1}$). To account for demographic stochasticity and other unmeasured variation in realized survival and recruitment, the true number of new recruits was drawn from a Poisson distribution around the expected value. To constrain the number of new recruits within reasonable bounds, a maximum possible number of recruits ($maxR_y$) was calculated and this value was used to truncate the Poisson distribution.

$$N_y^R \sim \text{Poisson}(N_{y-2} * \rho_{y-2}) T(0, maxR_y)$$

$$maxR_y = N_{y-2} * 2$$

The use of this maximum value is based on the assumption that recruitment is due solely to the birth of new birds, not immigration to the flyway population, and observations that the maximum clutch size for red knot is four eggs (Baker et al. 2001). If all adults in the population paired and produced a four-egg clutch, all four eggs hatched, and all four chicks survived their first winter and first full year, the number of new recruits would be equal to $maxR_y$. Given the threats to breeding success, chick survival, and first-year survival, this maximum value is unlikely to be realized and therefore the ARM workgroup thought it is reasonable and not overly constraining. It is useful for ensuring that estimates for recruitment stay within reasonable bounds.

The true number of surviving adults was drawn from a binomial distribution with number of trials set as the number of individuals alive at year $y-1$ and the probability equal to the adult annual survival probability.

$$N_y^A \sim \text{Binomial}(N_{y-1}, \phi_{y-1})$$

7.2.2.2 Open Robust Design Model for Mark-Recapture Data

During migratory stopover, there is a high rate of turnover of individuals and it cannot be assumed that the entire passage population is present on any given day. Additionally, temporary emigration (skipping the stopover site) could make some individuals unavailable in

some years. To account for these dynamics, temporary emigration and the entry and departure of individuals from the stopover site within a year was explicitly modeled using an open robust design model (ORD). This model is described in detail by Tucker et al. (2021). Under this model, primary sampling occasions (years, denoted y) are divided into secondary sampling occasions (3-day periods, denoted t). It was assumed that individuals can arrive and depart only once within a year, but that those arrivals and departures can occur during any secondary sampling occasion.

The ORD model consists of three likelihoods. The first (L1) describes the process of re-encountering individuals across years, which is conditioned on the number of individuals released in each year and depends on the annual probabilities of survival (ϕ_y), temporary emigration (γ^{II} and γ^{OI}), and detection (p_y^*). Two temporary emigration parameters were estimated: γ^{II} is the probability of being present at the site in year y if present in year $y-1$ and γ^{OI} is the probability of presence if absent in year $y-1$. The second likelihood (L2) describes the process of encountering individuals for the first time in secondary period t of year j . It also conditions on the total number of individuals seen in each year and depends on the probabilities of arrival ($\delta_{y,t}$), persistence ($\psi_{y,t}$), detection ($p_{y,t}$), and transience (τ). The probability of remaining at the site for at least two sampling occasions in a given year (τ) was estimated using the age class method described by Giavi et al. (2014) and Rushing et al. (2017). The third likelihood (L3) describes the process of re-encountering individuals during secondary occasions of each year. It conditions on the total number of individuals encountered in occasion t of year y and depends on the year- and period-specific probabilities of persistence ($\psi_{y,t}$), detection ($p_{y,t}$), and transience (τ). A previous analysis of the mark-resight data indicated very little annual variation in temporary emigration or transience (Tucker et al. 2021), so to reduce the total number of parameters in the IPM those probabilities were estimated as constant across time. All within-season parameters (arrival, persistence, detection) could vary among periods and years.

For the primary period likelihood (L1), capture histories of birds first captured and marked in Delaware and all subsequent resightings were pooled; the first capture in these cases was physical capture and all subsequent encounters were resightings in the field. To estimate within-year processes (secondary period likelihoods L2 and L3), only resightings of individuals after the year of first capture were used, since birds are unobservable via resighting before first capture (before they are marked with a field-readable tag). Therefore, within-year dynamics were not estimable for the first year of monitoring (2005).

For most years of the monitoring program, only one color of plastic leg flag was used to mark red knot (lime green with black characters), but beginning in 2014 a new type of flag was deployed: dark green with white characters (Figure 43). Anecdotal reports from field observers suggested that the dark green flags might be more difficult to resight than lime flags. To account for potential differences in detection probability between birds marked with these two colors, observations were split based on flag color and summarized in two separate m-arrays for years 2015-2018. Different detection probabilities were allowed for each set of observations to estimate the effect of flag color on resighting probability.

$$\text{logit}(p_{y,t}) = \mu^p + \beta_G * DG + \varepsilon_{y,t}^p$$

$$\varepsilon_{y,t}^p \sim \text{Normal}(0, \sigma_p^2)$$

Here, μ^p is the average resighting probability for lime flags, β_G is the effect of dark green flag color on resighting probability, $DG = 1$ for dark green flags and 0 for lime flags, and $\varepsilon_{y,t}^p$ is the random year- and period-specific variation in resighting probability.

From the parameters described above, an estimate of the flyway population-wide probability of being present at the stopover site in each secondary occasion of each year was derived. Here, the flyway-wide population is all red knot that used Delaware Bay at least once. This parameter depends on the temporary emigration probabilities (γ^{II} and γ^{OI}), transience probability (τ), year- and period-specific entry probabilities ($\delta_{y,t}$), and year- and period-specific stopover persistence probabilities ($\psi_{y,t}$). The probability of being present in secondary period t given that an individual is available and using the site to refuel (i.e., a “resident”) in year y is denoted $a_{y,t}$ and is a function of the probabilities of entry and persistence in that year. This value is calculated by summing the arrival and persistence probabilities across the stopover period to determine the cumulative probability of either arriving just before a given period, or arriving previously and remaining in the study area.

$$a_{y,t} = \begin{cases} t = 1 & \delta_{y,1} \\ t > 1 & \delta_{y,t} + a_{y,t-1}\psi_{y,t-1} \end{cases}$$

To account for transients that do not remain after the first occasion, the stopover residency probability is included for each period before the current period t . The probability of being present in occasion t for individuals using the site in year y is therefore calculated as:

$$z_{y,t} = \tau(a_{y,t} - \delta_{y,t}) + \delta_{y,t}$$

In each year, the probability of being available in year y is the sum of the probabilities of being present given that an individual was unavailable (γ^{OI}) or available (γ^{II}) in the previous year. The probability of being present in secondary occasion t of year y for all birds in the flyway population is therefore:

$$\pi_{y,t} = \gamma^{II} z_{y,t} + \gamma^{OI} z_{y,t}$$

Only data from birds first captured and marked in Delaware Bay were included in this analysis, for a total 179,785 resightings of 12,134 individual birds.

7.2.2.3 State Space Model for Counts

Each year aerial surveys are conducted in Delaware Bay to count the number of each species of shorebird present (see Section 5.2). Surveys typically occur in late May to capture the peak of spring migration, but timing varies among years due to weather conditions and other logistical

constraints. In 2009 the survey flight path was expanded to include some areas not previously sampled (Dey et al. 2011). For this analysis, the peak count from each year was used to estimate an index of the population size. In most years this count was from the aerial survey, but in three years (2009, 2012, 2013) the peak count was from the ground count conducted concurrently with the aerial survey.

The number of birds available to be counted during a given occasion in a given year depends on both the proportion of population present in Delaware Bay at that time and, of those using Delaware Bay, the proportion present on beaches included in the survey. The proportion of the flyway population estimated to be present in Delaware Bay is the parameter $\pi_{y,t}$ from the mark-recapture submodel. An additional parameter, $\omega_{y,t}$, was included to estimate the proportion of the birds present that were available for counting on surveyed beaches. Prior distributions for $\omega_{y,t}$ were developed by comparing aerial counts to the estimated period-specific population size from the superpopulation model of mark-recapture data (Lyons et al. 2016). The superpopulation model uses the mark-resight data to estimate the number of birds present in the Bay during each sampling period in each year. Assuming that the superpopulation model estimates reflect the true number of birds present, the ratio of counts to model estimates provides a heuristic for the proportion of the population that was counted.

$$Count_{y,t} = N_{y,t}^{super} * \omega_{y,t}$$

$$\hat{\omega}_{y,t} = \frac{Count_{y,t}}{N_{y,t}^{super}}$$

The parameter $\hat{\omega}_{y,t}$ was calculated for all years for which both superpopulation estimates and counts were available, 2011-2018. There were two years in which the aerial count exceeded the period-specific superpopulation estimate (2017 and 2018); in those years it was assumed that $\omega_{y,t}$ is 1, i.e., that all of the birds present were available to be counted with error, where overcounting is possible. The distributions of $\hat{\omega}_{y,t}$ were visually examined and the prior distribution of $\omega_{y,t} \sim Beta(6, 2)$ was set for 2009-2018. For 2005-2008, it was assumed that $\omega_{y,t}$ would be lower since fewer beaches were included in the aerial survey. For those years, a prior distribution of $\omega_{y,t} \sim Beta(4, 3)$ was used. The effects of the choice of priors on the model results was explored using a sensitivity analysis, described in a following section. For each year, the count was modeled as follows:

$$N_{y,t}^{avail} = N_y * \pi_{y,t} * \omega_{y,t}$$

$$\log(C_{y,t}) \sim Normal(\log(N_{y,t}^{avail}), \sigma_{obs}^2)$$

where σ_{obs}^2 is the counting error. Prior distributions for all model parameters are provided in Table 24.

7.2.2.4 Effects of Environmental Variables on Red Knot Demographics

The effects of horseshoe crab abundance and the timing of spawn on both apparent survival probability and recruitment rate were estimated. Horseshoe crab abundance (HSC_y) was estimated for each year using the CMSA (see Section 6.1). Due to the large range of estimated abundances and to reduce the effect of extreme values, HSC_y was $\log_{10}$ -transformed and used as a predictor in the analysis. The proportion of spawning activity that occurred in May ($MaySpawnPct_y$) was used as an estimate of the relative amount of spawning that coincided with red knot stopover, which typically peaks in late May. The proportion of spawn occurring in May was estimated from spawning surveys by finding the cumulative female spawning density that occurred by the end of May and dividing by the total female density for that year (see Section 4.3). An interaction between horseshoe crab abundance and timing was estimated, which posited that the effect of the overall abundance of horseshoe crabs depended on the timing of spawn in a given year. Previous analyses have also indicated that Arctic snow cover during the breeding season is associated with apparent survival probability, so an effect of mean Arctic snow cover ($snow_y$) on survival was also estimated. Arctic snow cover was estimated following the methods described by MacDonald (2020). In brief, daily mean snow cover data from 2005-2017 at 32-km resolution was obtained from the National Centers for Environmental Protection's North American Regional Reanalysis (NARR) dataset (Mesinger et al. 2006). The data were filtered to only the area considered to be the preferred red knot breeding habitat (MacDonald 2020; Smith and Rausch 2013) during 15-30 June of each year (considered peak nest initiation period; MacDonald 2020; Niles et al. 2008). For each year, the overall mean percent snow cover in each grid cell was calculated. Both $MaySpawnPct_y$ and $snow_y$ were centered for analysis by subtracting the mean, to aid model convergence (average $MaySpawnPct = 0.599$, average $snow = 0.568$). For each year, apparent annual survival probability (ϕ_y) was estimated as:

$$\begin{aligned} \text{logit}(\phi_y) &= \mu^\phi + \beta_1 * HSC_y + \beta_2 * MaySpawnPct_y + \beta_3 * HSC_y * MaySpawnPct_y + \beta_4 \\ &\quad * snow_y + \varepsilon_y^\phi \\ \varepsilon_y^\phi &\sim \text{Normal}(0, \sigma_\phi^2) \end{aligned}$$

where μ^ϕ is the intercept and ε_y^ϕ is a random error term.

The ARM workgroup was also interested in evaluating the effect of horseshoe crab abundance on recruitment rate. Since recruitment rate is a latent parameter in this analysis (i.e., not directly informed by data), the ARM workgroup thought it would be an overparameterization to try to estimate the full interactive effects described above. Timing of spawn is related to water temperature and is therefore not controllable, and horseshoe crab abundance is the more relevant metric to the harvest optimization (see Section 8); therefore, only a relationship between recruitment rate and horseshoe crab abundance was estimated:

$$\log(\rho_y) = \mu^\rho + \beta_5 * HSC_y + \varepsilon_y^\rho$$

$$\varepsilon_y^\rho \sim \text{Normal}(0, \sigma_\rho^2)$$

where μ^ρ is the intercept and ε_y^ρ is a random error term.

7.2.3 Model Configuration

7.2.3.1 Informative Priors

Informative priors were used on some model parameters to aid convergence and MCMC sampling efficiency (Table 24). Priors for temporary emigration probabilities (γ^{II} and γ^{OI}) and stopover residency probability (τ) were based on a previous analysis of the mark-resight data collected in Delaware from 2005-2018 (Tucker et al. 2021). A vaguely informative prior for the intercept for recruitment rate, μ^ρ , was also provided. This parameter was drawn from a Uniform distribution with a mean of 0 and maximum of 0.5. A recruitment rate of 0.5 would be realized if every pair produced one offspring that survived its first two winters.

7.2.3.2 MCMC Estimation and Model Fit

The IPM was specified and fit using JAGS, jagsUI, and R version 4.0.5 (Plummer 2003; Kellner 2015; R Core Team 2019). Three MCMC chains of 5,500,000 iterations each were sampled, 500,000 were discarded as burn-in values, with an adaptive phase of 50,000 iterations, and every 100th sample was kept. This resulted in a total of 50,000 draws from the posterior distribution, which was sufficient to ensure convergence of all parameters ($\hat{R} < 1.1$ and confirmed with visual inspection of traceplots). All model estimates are presented as posterior means and 95% credible intervals.

Unified goodness-of-fit tests have not been developed for IPMs, so the model fit for each submodel was assessed independently using posterior predictive checks (Kéry and Schaub 2012), which involves simulating expected data sets and comparing the deviation of expected and observed data from model predictions. The open robust design sub-model was assessed using the Freeman-Tukey diagnostic and the state-space model was assessed using χ^2 . Posterior predictive checks indicated adequate fit of the state-space model with a Bayesian p-value of 0.44 ($p = 0.5$ indicates no evidence of systematic difference in lack of fit statistics between the observed and simulated data sets). There was some evidence of overdispersion in the open robust design model (Bayesian p-value = 0.9) which could arise due to unmodeled individual heterogeneity or the grouping of observations into 3-day sampling periods.

7.2.4 Results

7.2.4.1 Demographic Rate Estimates

Estimates of adult apparent survival probability were consistently high, with an average of 0.93 (95% CRI: 0.90, 0.96, Table 25, Figure 44). Estimates of recruitment rate showed little year-to-

year variation (Figure 44), with an average recruitment rate of 0.075 (95% CRI: 0.011, 0.15, Table 25). Despite this low average recruitment rate, estimates of population growth rate (λ) indicate that the red knot population was most likely stable to increasing from 2005-2018, with an average population growth rate (λ) over this period of 1.04 (95% CRI: 1.00, 1.06). A population growth rate of 1 indicates a stable population; annual estimates of population growth rate varied with the posterior mean < 1 for some years (Figure 44), but the overall trend over this 14-year period was positive.

The estimates of apparent annual survival probability are similar to those from the initial ARM modeling efforts (McGowan et al. 2011a) and from red knot wintering in Florida (Schwarzer et al. 2012). These estimates of survival ~ 0.9 are greater than previous estimates, which were closer to ~ 0.8 (Atkinson et al. 2001; Baker et al. 2004), as well as unpublished estimates based on resighting data from southbound migration (L. Niles, *personal communication*). There are a few potential explanations for the difference. First, it is possible that more recent estimates are positively biased. Tucker et al. (2019) showed that individual misidentification due to incorrect reading or transcription of flag alphanumeric codes could result in positively biased survival estimates if error rates are greater than $\sim 5\%$. Importantly, this bias is greatest for the estimates from the earliest years and decreases over time, resulting in a spurious negative trend in survival over time. In that same analysis, the authors estimated the misidentification error rate of red knot resightings in Delaware as between 0.31% and 6.6%. The analysis presented here used resightings of flags originally deployed in Delaware Bay and screened the data for potential misreads by removing all flags that did not have a banding record or were recorded as resighted before they were deployed. Furthermore, the previous studies that resulted similarly high survival estimates showed no evidence of the characteristic negative trend that is produced by misreads. Therefore, the ARM workgroup thinks it unlikely that these estimates are positively biased.

A second possible explanation is that older estimates are negatively biased. The only other published estimates of red knot survival from Delaware Bay are from shorter studies (4-5 years) and using physical recaptures of birds only, not field resightings (Atkinson et al. 2001; Baker et al. 2004). The probability of recapturing a marked red knot is significantly lower than the probability of resighting; McGowan et al (2011b) estimated an average recapture probability of between 0.02 and 0.07, depending on mass state, compared to average resighting probability of ~ 0.4 . A short study period combined with low detection probability can result in negatively biased estimates of survival probability (Williams et al. 2002). Additionally, earlier estimates of apparent survival probability did not account for nonrandom temporary emigration (i.e., birds preferentially skipping or returning to Delaware Bay). The estimates from this IPM and those by Tucker et al. (2021) indicate that temporary emigration is nonrandom, with the probability of using the Bay following a year of use ($\gamma^{II} = 0.82$) greater than the probability of using the Bay after a year of non-use ($\gamma^{OI} = 0.084$). This nonrandom temporary emigration can also lead to negatively biased survival estimates if not accounted for in the model (Peñaloza et al. 2014). Although the analysis by McGowan et al (2011b) does not explicitly account for temporary emigration, it is possible that the mass state transition probabilities between the end of year t and beginning of year $t+1$ absorb some of this unmodeled variation in return rates. The analysis

by Schwarzer et al (2012) does account for emigration. With the short study periods, low detection probability, and unmodeled nonrandom temporary emigration, it is likely that previous estimates of survival were negatively biased to some extent.

A third possible explanation is based on an ecological hypothesis about the segregation of birds by wintering area. Red knot stopping in Delaware Bay overwinter as far north as the southeast U.S. and as far south as Argentina. It has been proposed that southern-wintering birds that have a longer migration have lower annual survival probabilities than northern-wintering birds. Declines in the number of red knot overwintering in Argentina (Niles et al. 2008) suggest a decline in the southern-wintering subpopulation and therefore that in more recent years a greater proportion of the Delaware Bay stopover population may be northern-wintering birds. If earlier estimates of survival were from a stopover population containing a higher proportion of southern-wintering birds than more recent estimates, this could explain why earlier estimates were lower. Discerning the wintering locations of birds using Delaware Bay and potential differences in survival probability is the focus of ongoing work involving stable isotope analysis. At the time of this report, there is little evidence to support or refute this hypothesis. This is a key area for future research (Section 10).

In the IPM, estimates of population growth rate and recruitment rate are based on an analysis of the count data. These estimates could be more precise with more information about counting error. Such information could come from survey-specific covariates (e.g., observer ID, tide state, weather conditions), the integration of simultaneous ground count data, or future implementation of a double-observer counting method. At the time of this analysis, such information was not available.

7.2.4.2 Effects of environmental variables on red knot demographics

A positive relationship between horseshoe crab abundance and adult apparent survival probability was estimated (Table 26, Figure 45 - Figure 47), but the magnitude of this effect was small ($\beta_1 = 0.38$, 95% CRI: 0.13, 0.67). The estimates indicate no evidence of survival probability responsive to either the timing of spawn or the interaction between spawn timing and abundance (Table 26, Figure 45 and Figure 46). A weakly negative relationship was estimated between mean Arctic snow cover and adult survival probability (Table 26, Figure 45), but again the magnitude of this effect was small ($\beta_4 = -1.06$, 95% CRI: -3.76, 1.74). Evidence of a relationship between horseshoe crab abundance and recruitment rate was not found (Table 26, Figure 47).

7.2.5 Sensitivity Runs

Several iterations of the IPM were run to test the sensitivity of model outputs and fit to the choice of prior distributions for the count availability ($\omega_{y,t}$), intercept for the recruitment rate (μ^p), and annual variation in the random error term for recruitment (σ_p). For each model version (Table 27, Figure 48), convergence ($\hat{R}$), model fit (posterior predictive checks), and parameter estimates were compared. Without strong information about availability in 2017

and 2018 (either by fixing $\omega_{2017-2018} = 1$ or using a strongly informative prior), model estimates indicated increased recruitment and population growth in later years. However, the ARM workgroup believes that such results are an artifact of the fact that a greater proportion of birds seems to have been counted in those years than in previous years (based on the correspondence between superpopulation model estimates and counts). In all versions in which this information was included in the model, little difference was found among prior parameterizations in the estimates of demographic rates. Additionally, the choice of priors had little effect on the ability of the MCMC sampler to reach convergence or metrics of model fit.

Unsurprisingly, posterior estimates of recruitment rate were sensitive to the choice of prior distributions for the intercept (μ^ρ) and annual variance (σ_ρ). The posterior means were largely unaffected by the choice of priors, but the uncertainty in these estimates increased when less informative priors were used. Because this parameter is estimated without additional data, the influence of the prior will naturally be stronger than for other model parameters. Ultimately, prior distributions that were slightly more informative were chosen, based on the ARM workgroup's knowledge of the species.

8 REVISED ADAPTIVE RESOURCE MANAGEMENT FRAMEWORK

The previous ARM Framework (ASMFC 2009a; Figure 49) differs in several ways from the revised version described here (Figure 50). Changes include new forms to the estimation and projection models used for each species, a new reward function and utility components, and a different approach to optimization using only a subset of the state variables used previously. These updates are detailed in the following sections.

8.1 Revised Estimation and Projection Models

Both the estimation (shown in yellow in Figure 49 and Figure 50) and projection models (in blue) have changed, for horseshoe crabs and red knots. For both species, the projection model now derives directly from the estimation model so that data collected annually to inform estimates of the system state (i.e., the species' abundances) and therefore harvest recommendations can also be used to update projection model parameters. Reliance on literature-based demographic rates has been eliminated ("Life history parameters" in Figure 49 are absent in Figure 50). The red knot model was also changed from a female-only model to one that considers both sexes.

Changes to the horseshoe crab projection model in the revised ARM Framework were described in Section 6.2.

The revised red knot projection model mirrors the structure of the integrated population model (IPM) exactly. Stochastic processes governing population dynamics are just as shown in Section 7.2.2.1. Linear predictors for recruitment rate (ρ) and adult survival (ϕ) are identical to those discussed in Section 7.2.2.4, including the same covariates and random effects. Indeed, because the projection and estimation models had the same structure, and because the IPM was fit in a

Bayesian framework using MCMC sampling, the MCMC samples were used from the jointly-estimated posterior distributions of the model parameters directly. By so doing, an important kind of information was preserved which would have been lost had each parameter's posterior distribution been summarized separately, each with its own parametric distribution; and then drew samples from each parameter's distribution separately in the projection model. That is, any unmodeled correlation between model parameters was preserved. In practice this meant, for a given year in a simulation instance, all the parameter values were obtained by simply selecting a row of the MCMC output matrix at random.

Red knot adults were predicted by the IPM to have high survival, and uncertainty about recruitment resulted in some simulated populations reaching unreasonably high abundances. Employing basic expectations of population function, and based on red knot abundance estimates from past decades, a simple density dependence mechanism was added to the projection model, so that abundances would largely stay within ranges that have been observed in Delaware Bay: 150,000 birds was chosen as the threshold above which recruitment would be reduced to zero (Morris and Doak 2002). To implement this in the model, recruitment (ρ) was multiplied by a scalar that followed a 'broken stick' curve: the scalar was equal to one when knot abundance was below 80% of the 150,000 threshold; above that value it was reduced linearly down to zero when abundance was at or above the threshold.

The previous ARM Framework made use of three competing models of red knot population dynamics, which differed mainly in the influence of horseshoe crabs they specified (ASMFC 2009). The models were assigned weights, and all three were employed in simulating red knot populations with predicted abundances representing a weighted average of the three models' predictions. In a 'passive' approach to adaptive management, these model weights would be periodically updated using monitoring data. However, model weight updating was never pursued.

In place of the use of competing models of population dynamics, the revised ARM version uses a single red knot model chosen to reflect previous findings regarding important effects on red knot survival (McGowan 2011b); parameter uncertainty regarding fixed covariate effects and accompanying annual random effects are now the targets for periodic updating. It is hoped that increased harmony between estimation and projection models—for both horseshoe crabs and red knots—will encourage more frequent model updating than was carried out under the previous ARM Framework.

The ability to simulate the focal ecological system is fundamental to adaptive management; this was true of both the previous and revised ARM Frameworks. The simulation models are used in different ways in the two versions, however, because the approach to optimization differs. These differences are described in the following section.

8.2 Changes to the Optimization Approach

The original ARM Framework made use of an optimization approach called dynamic programming to provide harvest recommendations given observed abundances of horseshoe crabs and red knots in Delaware Bay (ASMFC 2009a). There are many approaches to dynamic programming, and a number of software implementations are available. The software used to solve the original ARM model was named ASDP (for Adaptive Stochastic Dynamic Programming; Lubow 1995, 2001). Two major developments precluded its continued use in the revised ARM version, one connected to the software itself and another to the particular approach to dynamic programming it employs.

The ASDP software is no longer actively maintained by its author or any other entity (B.C. Lubow, *personal communication*), and indeed does not run in any modern operating system (Windows XP is the latest platform with which it is compatible). This fact alone has and will make its continued use by the ARM subcommittee onerous.

However, another detail of the revised horseshoe crab projection model makes the use of stochastic dynamic programming, as implemented by ASDP, unworkable. Instead of a stage-based model that can be updated each time step based entirely on the state of the population in the previous time step (a first-order Markov process), the revised horseshoe crab model uses a stock-recruitment relationship (Section 6.2.2) which requires reference to the population state nine and ten years previously, to update to the next time step. Under conventional dynamic programming, abundances in all years $\{y-10, y-9, \dots, y-1\}$ would become state variables over which the optimization would operate (the notion of a state variable is discussed further in Section 8.4). Problem definition in conventional dynamic programming relies on keeping the number of state variables very small, to ensure that the problem is tractable. Inclusion of such a large number of additional state variables would have made obtaining solutions under conventional dynamic programming approaches, even using modern software such as MDPSolve (Fackler 2011), either impossible or too time-consuming to be useful (Moxnes 2015).

Therefore, an optimization approach was chosen based on replicated forward simulations of the system, called Approximate Dynamic Programming (ADP; Powell 2007; Springborn and Faig 2019). In contrast to conventional dynamic programming, the system is simulated many times, over some sufficiently long time period, beginning with the present day. Many varieties of ADP exist; the one selected here, policy approximation (Krakenes and Moxnes 2005; Moxnes 2005; Powell 2007; Moxnes 2015) allows all information about each of these ‘time paths’ to be retained for reference by the population models. It was therefore trivial under ADP to implement the horseshoe crab stock-recruitment model, as well as the red knot recruitment model, which requires referencing adult abundance in year $y-2$.

8.3 Approximate Dynamic Programming in the ARM Framework

Dynamic programming (Bellman 1957), in the context of adaptive management, seeks to maximize an objective function over some future time period up to a time horizon, T . In the case of the ARM, that objective function takes the form of a reward, r , that is determined

annually. Horseshoe crab harvest is a component of the reward function, as is information about red knot abundance (specifics of the reward functions used in the previous and revised ARM versions are addressed in Section 8.5). The reward obtained in a given year y depends upon the state of the system (the abundances of horseshoe crabs and red knots in year y ; horseshoe crab abundances in years $y-10$ and $y-9$; red knot abundance in $y-2$; see Section 8.4.2) as well as the harvest policy. The decision to be made each year is how many female and male horseshoe crabs to harvest, given the state of the system, and this is determined by a harvest policy h . A solution to the dynamic programming problem constitutes a particular harvest policy: the one that will, given the simulation model of the system, return the highest possible value given the present state of the system.

Over the time horizon, the value V of a time path (a particular simulated instance of the system) is simply the expected value of the sum of the annual products of the reward and a discount factor $\delta \in (0,1]$:

$$V = E\left[\sum_{y=1}^T \delta^{y-1} r_y\right]. \quad (1)$$

The discount factor allows higher value to be placed on rewards obtained sooner than later. In the previous ARM Framework, the discount factor was set to 1.0; that precedent was retained here, and δ is dropped from subsequent equations.

Under the policy approximation approach this Revision took to ADP (Krakenes and Moxnes 2005; Moxnes 2005; Moxnes 2015), the harvest function has a well-defined functional form and takes a small number of parameters θ . The reward in year y is thus a function of the system state S_y and θ (both vectors in this case). For a given value of θ , then, the value is

$$V^\theta(S_1) = \sum_{y=1}^T r_y(S_y, \theta), \quad (2)$$

where S_1 is the state of the system at the beginning of the time period.

The simulation models for horseshoe crabs and red knots are stochastic, and it is unlikely that any two time paths begun in state S_1 would follow the same trajectories; they may also yield different values V^θ . To accommodate the variation in value V^θ that can occur among time paths given a particular harvest policy, a large number of iterations K were run at each particular value of θ . That variation was then summarized by taking a mean over the simulated time paths

$$g(\theta) = \frac{1}{K} \sum_{k=1}^K V^{\theta}(S_1). \quad (3)$$

$K = 10,000$ iterations were used for each value of θ . The function $g(\theta)$ could thus be maximized, and the values θ^* at the maximum value of g corresponded to the best harvest policy $h(S, \theta^*)$. Unlike with exact approaches to dynamic programming, true optimality is not guaranteed under this approach (as pointed out previously, methods returning truly optimal solutions were not applicable to this problem); but Moxnes (2015) was followed and $h(S, \theta^*)$ was referred to as the optimal harvest policy.

8.4 Harvest Policy Functions

Mainly as a result of the change to the optimization algorithm used by the ARM Framework, the harvest function has undergone significant changes.

8.4.1 Change from Discrete Harvest Packages to Continuous Harvest Recommendations

The harvest policy function in the previous ARM model was constrained by the limitations imposed by the ASDP software. It was discrete, taking values in $\{1, 2, \dots, 5\}$; each number specified a harvest package (ASMFC 2009a; Table 28). However, such a small number of packages was chosen only to make obtaining a solution feasible and not for any biological or management reasons.

This ARM Revision chose not to make use of the harvest packages two reasons. First, the form of the harvest function receives special attention under this approach to ADP. Its parameters θ are those over which maximization occurs (Equation 3) and as such the optimization is facilitated by limiting their number and ensuring their effect on the policy h is smooth and monotonic. A discrete-valued harvest policy function can be accommodated, but one that returns continuous harvest recommendations is simpler.

Second, because there are so few harvest packages, they link male and female harvest in an artificial way. It can be seen, for instance, that increasing male harvest from 420,000 to 500,000 necessarily reduces female harvest from 210,000 to 0 (Table 28). There is no ecological reasoning attached to this constraint. The ARM workgroup decided instead to allow male harvest to depend only upon male horseshoe crab abundance; and to let female harvest depend on female horseshoe crab abundance and red knot abundance.

However, one feature from the packages used in the original ARM version was retained: the maximum harvest for females was set to 210,000 and for males 500,000. Although harvest is treated as continuous in the new ARM Framework, it may be that harvest limits in practice should be rounded to some fixed values. This would in effect achieve a benefit of the harvest packages of the original ARM Framework: year-to-year stability in harvest limits. This possibility is discussed further in Section 8.7.1.

8.4.2 State Variables

In a dynamic programming problem, the state variables are used to represent the state of the system; they serve two functions: 1) their values in year y are necessary to predict the system state in year $y+1$, and 2) they serve as the decision variables, that is their values are used as input to the policy function (in the ARM Framework, the harvest function is the policy function). The state variables do not need to be observable; but if they are not monitored, they must be predicted each year in order to make a decision (in this case, about harvest).

The previous ARM model made use of six state variables, each of which represented an abundance of a particular population segment (ASMFC 2009a): 1) juvenile horseshoe crabs, 2) primiparous horseshoe crabs, 3) multiparous female horseshoe crabs, 4) multiparous male horseshoe crabs, 5) juvenile female red knots, and 6) adult female red knots. The possible range of each of these variables was then discretized by dividing it into a set of intervals; taken together, the discretized variables formed a grid in system state space. The harvest policy function returned a harvest package for each possible point on the state space grid: both the input and output of the harvest function were discrete.

In contrast, use of ADP in the revised ARM model allows both the input and output of the harvest function to be continuous; in fact, this simplifies specification of the model (Table 29). It also bypasses a step in the previous ARM model that could have affected the optimization process: deciding how to discretize the state variables.

Because the new simulation models for horseshoe crabs and red knots do not consider juvenile life stages, but rather base horseshoe crab and red knot recruitment on past abundance values, the state variables (i.e., those required to predict abundances in year $y+1$) were: 1) adult female horseshoe crabs (primiparous plus multiparous) in year y , 2) adult male horseshoe crabs (primiparous plus multiparous) in year y , and 3) adult red knots in year y ; along with 4) adult female horseshoe crabs (primiparous plus multiparous) in year $y-9$ and 5) in year $y-8$, and 6) adult red knot abundance in year $y-1$. Only a subset of the state variables, numbers 1-3 above, were used as the decision variables; that is, as inputs to the harvest policy function. Because each of the population segments used as decision variables is monitored each year, estimates can be plugged directly into the harvest function to obtain recommended harvest limits; there is no need to predict the values of unobserved population segments.

8.4.3 Form of the Harvest Policy Function

To facilitate maximization of the $g(\theta)$ function (Equation 3), logistic curves were used within the harvest function to map state variables into harvest recommendations. These curves being smooth and asymptotic to their range limits, it was thought they would lead $g(\theta)$ to be smoother and easier to optimize.

The revised harvest function returns a vector H of length two,

$$h(S, \theta) = \mathbf{H} = [H^f \ H^m], \quad (4)$$

with each element H^f and H^m continuous and ranging from 0 to the maximum harvest for each (210,000 for females, 500,000 for males). Male and female harvest are determined independently; male harvest depends only upon male horseshoe crab abundance, female harvest on both female horseshoe crab and red knot abundance.

For each state variable, a logistic curve is defined, via a parameterization that specifies the inflection point and the slope at the inflection point. The value returned from this function is called a harvest factor, $\eta \in [0,1]$. For each of male horseshoe crab (s^m), female horseshoe crab (s^f) and red knot (s^k) abundances, a corresponding harvest factor (η^f, η^m, η^k) is calculated according to

$$\eta(s) = \frac{1}{1+e^{\alpha(\beta-s)}}, \quad (5)$$

with α giving the slope and β the location of the inflection point. Example curves are shown in Figure 51.

The harvest factors are then used to produce the harvest recommendations $\mathbf{H}$. For males, this is very simple because male harvest depends only on male horseshoe crab abundance and the maximum allowable male harvest, H_{max}^m :

$$H^m = \eta^m H_{max}^m. \quad (6)$$

Producing H^f is more complex because the harvest factors for both female horseshoe crab and red knot must be used:

$$H^f = H_{max}^f \times (\eta^f + \eta^k - \eta^f \eta^k). \quad (7)$$

The expression $\eta^f + \eta^k - \eta^f \eta^k$ is itself always in $[0, 1]$, and balances the influence of s^f and s^r on H^f when they both take similar values relative to their respective inflection points, β^f and β^k . The effect of this balance can be seen in contour plots of the female harvest recommendations in Section 8.7.

The parameters governing the harvest policy then, are $\theta = [\alpha^f \ \beta^f \ \alpha^m \ \beta^m \ \alpha^k \ \beta^k]$; these are the variables that are optimized in the ARM algorithm. And the decision variables acting as inputs to the harvest function are $S_y = [s_y^f \ s_y^m \ s_y^k] = [R_y^f + N_y^f \ R_y^m + N_y^m \ N_y^k]$.

8.5 Reward Function

Unlike in the original ARM model, female horseshoe crab abundance does not directly inform male harvest in the harvest policy function, nor vice versa. However, both sexes do appear in the reward function. Also in contrast to the original ARM model, where red knot abundance acted as a constraint in the reward, here red knots are assigned a separate utility and their abundance contributes directly to the reward. The ARM workgroup felt that this way of accommodating red knot abundance – via direct contribution to the reward, rather than as constraint – better recognized the values reflected in the ARM project’s objective statement (Section 1.6).

The annual reward is given by

$$r_y = u_y^h + u_y^k + u_y^h u_y^k, \quad (8)$$

where the horseshoe crab and red knot utilities u^h and u^k , each take values in $[0, 1]$. This formulation promotes balance between horseshoe crab and red knot utilities, because although some reward can be obtained when the abundance of one or the other species is low, higher reward values are only possible when both species have high abundances.

The horseshoe crab utility depends upon the number of female and male horseshoe crabs harvested in year t , and reflects a precedent established in the original ARM model, that the monetary value of harvested female horseshoe crabs is twice that of males:

$$u_y^h = \frac{2H_y^f + H_y^m}{2H_{max}^f + H_{max}^m}. \quad (9)$$

The horseshoe crab utility thus reflects the ratio of the total monetary value of the bait harvest in year y , to the highest possible monetary value attainable from bait harvest.

The red knot utility function employs a threshold representing an estimate of historic red knot abundance in Delaware Bay. The ARM Subcommittee and DBETC considered two utility functions for red knots that bookend the options:

$$u_y^k = \begin{cases} 1, & \text{if } s_y^k \geq N_k^*, \\ \frac{s_y^k}{N_k^*}, & \text{if } s_y^k < N_k^*. \end{cases} \quad (10a)$$

$$u_y^k = \begin{cases} 1, & \text{if } s_y^k \geq N_k^*, \\ \frac{s_y^k}{(1-p)N_k^*} - \frac{p}{1-p}, & \text{if } 0.9 \cdot N_k^* \geq s_y^k < N_k^*, \\ 0, & \text{if } s_y^k < 0.9 \cdot N_k^* \end{cases} \quad (10b)$$

For equation 10a, utility rises linearly from zero to one as red knot abundance s_t^k increases from zero to the threshold $N_k^* = 81,900$. This utility function recognizes that higher red knot abundances are always preferred to lower ones, until red knots reach a satisfactory threshold level determined by stakeholder input during the original ARM Framework development.

For equation 10b, utility remains at zero until the red knot abundance s_y^k reaches $p = 90\%$ of the threshold $N_k^* = 81,900$. Then it increases from zero to one as s_y^k moves from 90% to 100% of N_k^* .

There was some committee disagreement about which of the two utility function to use, but ultimately the committees decided to use equation 10b as the utility function for red knots in the optimization because it was the closest to the previously used red knot utility function (ASMFC 2009a). While this was the closest to the previously used utility function of the two options explored, neither operate as a constraint like it did in the previous ARM Framework. In the current decision making case, there is a greater desire to take the chance of having higher red knot abundance and increase the total reward coming from red knot abundance.

Use of the threshold N_k^* is an effort to address new language in the ARM project's objective statement, which now includes an intention to "ensure that the abundance of horseshoe crabs is not limiting the red knot stopover population or slowing recovery." Although not a formal recovery target, the threshold value of 81,900 red knots does represent an established historical abundance that is considerably higher than recently estimated stopover population sizes.

8.6 Model Coding and Optimization

Approximate Dynamic Programming, although it is used to solve dynamic decision problems, is advantageous because it does not require the use of dynamic optimization techniques: the ADP framework removes time from the optimization problem. Once all the components of the function $g(\theta)$ (Equation 3) are specified and parameterized, it can be maximized using a static optimization algorithms. This is relatively straightforward because all elements of θ are continuous.

The revised ARM model and accompanying initialization steps were coded in program R (R Core Team 2021), which required only the following add-on packages: {abind} (Plate and Heiberger

2016), {bivariate} (Spurdle 2021) and {extraDistr} (Wolodsko 2020). Then, an optimization technique called the genetic algorithm was used, as implemented in the R package {GA} (Scrucca 2013; Scrucca 2017). The genetic algorithm uses a number of candidate solutions that then ‘evolve’ in a manner that is analogous to biological evolution, with solutions ‘mutating’ over time and converging on the extremum. Genetic algorithms, though slower than some methods, are effective at avoiding local extrema (Haupt and Haupt 2004). Parameter values relevant to the optimization are shown in Table 30. On a computer configured for the analysis of complex models, the genetic algorithm took approximately 2 hours to converge on a solution, where the criterion for convergence was no change to the solution for 200 iterations. Using the canonical model version (Section 8.7), 325 total iterations were performed, with one iteration taking on average 24.6 seconds.

Not all R packages are maintained indefinitely; some are inevitably abandoned over time. In the interest of code durability, the use of add-on packages was limited. Those used provide convenience functions for fairly common operations: they could be replaced if necessary with hand-written routines; or, if they are deprecated, will likely be replaced with similar packages.

8.7 Output from Canonical Model Version

The outcome from the revised ARM algorithm is discussed here, with maximum harvest set to $H_{max} = [H_{max}^f \ H_{max}^m] = [2.1 \ 5] \times 10^5$ and optimization parameters as in Table 30. The ARM model with these maximum harvest limits is referred to as the canonical version. Based on sensitivity runs of the standalone horseshoe crab projection model, these maximum harvest limits are expected to have little effect on long-run equilibrium abundances of horseshoe crabs (Section 6.2.3.1). However, this fact does not necessarily give much insight into the exact form of the optimal harvest policy.

Optimal values of θ , the parameters of the harvest function h , are given in Table 31. The slope of the female harvest factor curve, α^f , is shallower than that for male horseshoe crab or red knot (Figure 52). And interestingly, the inflection point for the red knot harvest factor, β^k , is somewhat higher than the threshold abundance used in the red knot utility function, 81,900.

The optimal harvest policy function for males (Figure 53) shows that bait harvest limits near the maximum of 500,000 crabs are recommended for abundances above about 15 million. Male abundances ($R^m + N^m$) are above 15 million in 10 of the 17 years for which CMSA estimates are available (Table 17); all mean abundances in the past 6 years exceed that value, however.

The optimal female harvest function shows a rather conservative approach to female bait harvest overall, with harvest increasing gradually and not nearing its maximum until above any female horseshoe crab abundance estimated by the CMSA in 2003-2019 (Table 16), with red knot abundances at contemporary levels (Figure 54 - Figure 57). However, in contrast to the original ARM model, this harvest function does not recommend zero levels of female harvest at contemporary female horseshoe crab abundances (Table 32). Equilibrium abundances for male

and female horseshoe crabs and red knots are predicted to be high, but red knot abundances in particular are very uncertain throughout the simulation time period (Figure 58 - Figure 59).

8.7.1 Rounding of Continuous Output from the Harvest Function

One potential benefit of the harvest packages used in the original ARM Framework is the resistance they may provide to annual changes in harvest recommendations. Although the revised ARM model provides continuous harvest recommendations, the application of some system of rounding could provide a simple means of achieving the same effect: for instance, by choosing a regular interval of multiples of 50,000, and rounding female and male horseshoe crab harvest recommendations to the nearest of these values (Figure 60 and Figure 61). Alternatively, each continuous harvest recommendations could be always rounded down to the nearest discrete value it exceeds (Figure 62 and Figure 63).

Each of these approaches alters the de facto maximum female harvest to 200,000; some rule should perhaps be devised to snap some values to 210,000, for instance those that exceed 200,000.

It is also evident that the rounding down approach forces the male harvest recommendations to reach exactly 500,000 before the rounded recommendation would also be 500,000 (Figure 63). This may be an undesirable property.

8.8 Sensitivity Runs for the Revised ARM Model

8.8.1 Sensitivity to Harvest Limits

As shown in Section 6.2.3.1, the horseshoe crab projection model is not especially sensitive to changes in harvest in the range of the maximum harvest used in the canonical revised ARM model ($H_{\max}^f = 210,000$, $H_{\max}^m = 500,000$). Increasing harvest to these levels from zero (i.e., full moratorium) decreased equilibrium abundances by only 5-6%. Here, therefore only optimization results based on a scenario with significantly larger maximum harvest: $H_{\max}^f = 2$ million and $H_{\max}^m = 2$ million are presented.

Interestingly, the harvest policies resulting from this model are quite aggressive (Figure 64 - Figure 66) despite the higher maximum harvest limits. The qualitatively different shape of the contour plot in Figure 64 compared to that in Figure 54, may be partly due to the effect of setting $H_{\max}^f = H_{\max}^m$, in combination with the fertility factor which penalizes sex ratios that are too skewed toward females.

As expected, such aggressive harvest reduces male and female abundances considerably (Figure 67). Although the abundance of red knots at year 100 is reduced, as is survival (Figure 68), the effect is modest. This is due to the small magnitude of the effect of horseshoe crab abundance in the red knot IPM.

8.8.2 Sensitivity to Variation in Expected Recruitment

As discussed in Section 6.2.3.2, the horseshoe crab projection model is sensitive to changes in median recruitment. To assess the effect such sensitivity might have upon the optimization outcome, random variation in the median recruitment was introduced in the following way.

A proportion v was specified and the standard deviation was found for a normal distribution around zero with 2.5th and 97.5th quantiles equal to $\{-v, v\}$. Then n_{iter} random deviates were drawn from this distribution and the natural logarithm of these was added to each of the n_{iter} values of μ , the vector of female and male means for the bivariate normal distribution used to generate the logarithm of primiparous horseshoe crab abundances. In this way, the median abundances $\exp(\mu)$ varied over iterations, mostly within the interval $[\exp(-v), \exp(v)]$.

Allowing variation in the median recruitment value across simulations results in a generally more conservative harvest policy. When median recruitment varied $\pm 5\%$ (Figure 69), the policy differed from the canonical one primarily through an increased inflection point along both the female horseshoe crab and red knot axes (upward and rightward shifts in Figure 69, relative to Figure 54). When recruitment varied $\pm 10\%$ (Figure 70), however, the slopes along the female horseshoe crab and red knot axes were primarily affected: they are much shallower than without any variation in expected recruitment.

Expected recruitment is based on a relatively short time period (Section 6.2.3), and it is possible that the current estimate is not very close to the true value. Allowing random variation in these parameters could act as a safeguard against basing decisions on incorrect values. Results presented here demonstrate that the effect on the harvest policy of introducing this kind of variation is somewhat ambivalent: a small amount of variation in median recruitment leads to more conservative harvest; larger variation to more moderate harvest at high abundances, but also higher harvest at low abundances of female horseshoe crabs and red knots.

8.9 Review of Anticipated ARM Framework Workflow

There are two main tasks for which the ARM model or its components will be regularly used.

A) The first is to set harvest limits in a given year. This requires four pieces of information:

- 1) the definition of the harvest function h (Section 8.4.2),
- 2) the values of the latest optimal parameters of the harvest function, θ^* ,
- 3) the year's CMSA estimates of multiparous and primiparous horseshoe crab abundances for both sexes (Section 6), and
- 4) the year's Delaware Bay red knot abundance estimate (Section 5).

Calculating the recommended harvest limits involves only plugging in abundances and parameters into the harvest function.

B) The second task is updating parameters of the revised ARM model. This could be conducted annually; two datasets would require updating, beyond those already required for task A above: 1) the proportion of female horseshoe crabs spawning in May, and 2) the estimate of snow cover in the *rufa* red knot breeding grounds (Section 7.2.2.4).

Updating the ARM model involves three steps:

- 1) re-run red knot IPM with updated mark-recapture/resight and count data and covariate values,
- 2) obtain new estimates for the horseshoe crab recruitment process (means, standard deviations, correlation; Section 6.2.2)
- 3) re-run optimization of the ARM model with updated IPM output from #1 and updated recruitment parameters from #2, as well as updated IPM covariate values, CMSA estimates and red knot abundance estimates.

Steps #1 and #3 require some computing time. Optimization runs of the ARM model conducted for this report generally took 2 hours or less. Obtaining converged estimates with the IPM may take considerably longer.

9 STOCK STATUS AND CONCLUSIONS

There have been no overfishing or overfished definitions adopted by the Management Board for horseshoe crabs in the Delaware Bay. The 2019 benchmark stock assessment (ASMFC 2019) characterized the status of the Delaware Bay area as “neutral”. This status determination was based on fits of autoregressive integrated moving average models (ARIMA) and the probability that the terminal year of fishery independent surveys was below a 1998 index-based reference point. In the Delaware Bay area, two out of five surveys examined were below this reference point, thus giving the area a “neutral” status. However, three out of the five surveys showed an increasing trend over the most recent ten-year period and none showed a decrease.

The purpose of this ARM effort in the Delaware Bay was not to determine stock status in the traditional sense of commercial fishery management (e.g., overfished and/or overfishing). Rather, the purpose was to determine the optimal harvest strategy given the states (i.e., abundance) of horseshoe crabs and red knots. The total “reward” from the system was a function of both horseshoe crab harvest and abundance of red knots, and the optimization routine employed here determined the amount of horseshoe crab harvest that maximized that reward. Results from the optimization show the sex-specific harvest of horseshoe crabs that maximize the total reward given the state of horseshoe crab and red knot populations. For example, if abundance of both species is low, the corresponding optimal harvest should be low, and if the abundance of both species is high, the corresponding optimal harvest can also be high (within constraints of maximum allowable harvest). Also, relatively high optimal harvest of horseshoe crabs can result from a situation where the abundance of horseshoe crabs is high

relative to red knots. As Figure 53 shows, there is a nonlinear relationship between optimal harvest and the abundance of both species.

Optimal harvest recommendations are dependent on the underlying population dynamics models for both species. Although the population dynamics models were parameterized with empirical data from the Delaware Bay system, these data are still limited. Sensitivity analyses of the horseshoe crab projection model demonstrated that future abundance of horseshoe crabs was most sensitive to the mean recruitment parameter and this parameter had a much greater effect on future horseshoe crab abundance than did harvest within the limits of Addendum VII (ASMFC 2012; maximum female harvest of 210,00; maximum male harvest of 500,00). For red knots, posterior estimates of recruitment rates were sensitive to the prior used in estimating recruitment rates. Recruitment parameters in any population model are notoriously uncertain, but continued monitoring of the system should help refine these parameters for both species.

As a final comparison of outputs between the previous ARM Framework and the revised Framework in this report, optimal harvest recommendations were compared between the two using abundance data from 2017 – 2019 (Table 32). Under the previous ARM Framework, abundances of male and female horseshoe crabs came from the VA Tech trawl swept area population estimates decremented by half a year's worth of natural mortality, while CMSA estimates of abundance were used under the revised Framework. Red knot abundance estimates came from Delaware Bay stopover super-population estimates in both cases. Optimal harvest recommendations under the previous ARM Framework were for harvest package #3 (0 females, 500,000 males) in all years. However, if the revised ARM Framework were applied to abundance estimates from 2017 – 2019, female harvest would have been recommended. Male harvest was still near the 500,000 maximum under addendum VII, but female harvest would have been somewhat less than the maximum of 210,000.

It also should be noted that this ARM Revision was developed using coastwide biomedical data so as to avoid data confidentiality issues. The population estimates for horseshoe crabs from the CMSA therefore represent an overestimate. If this Revision is accepted for management use, the Delaware Bay-specific biomedical data will be used to determine the harvest package and the model will be run by someone (e.g., ASMFC staff) with confidential data access. Therefore, the final harvest recommendations are likely to be marginally lower than those reported in Table 32 when the Delaware Bay-specific values are used. No other model inputs were affected by data confidentiality.

Harvest recommendations under the revised ARM Framework are based on a continuous scale rather than discrete harvest packages as in the previous Framework. Also, the harvest of females is decoupled from the harvest of males in this revision. The previous ARM Framework needed discrete harvest packages due to capacity limitations of the antiquated ASDP software, and other than the upper limits on harvest of each sex, these packages were defined rather arbitrarily. The revised ARM Framework has an advantage in that harvest can be recommended on a continuous scale for each sex and ideally makes more intuitive sense to stakeholders. Actual implementation of the recommended continuous harvest could be discretized by

management each year. For example, a recommended harvest level could be rounded or truncated to the nearest 50 or 100 thousand. Discretizing annual recommendations would likely add stability to harvest recommendations across years.

This revision of the ARM Framework represents several advancements in not only the knowledge of the population dynamics of horseshoe crabs and red knots, but also how to efficiently model them. The population dynamics models for both species are now parameterized with empirical data from the Delaware Bay rather than based on literature values for life history parameters coming from elsewhere. Because they are based on empirical data from the Delaware Bay, model updating will be more efficient and transparent as new data for both species is collected through routine monitoring efforts.

10 RESEARCH RECOMMENDATIONS

The ARM subcommittee identified several recommendations that would benefit the adaptive management of horseshoe crabs and red knots in the Delaware Bay area. These have been characterized as future research, data collection, and data analysis and modeling. The ARM subcommittee recommends that the model parameters for both species be updated in at most five years (although annual updates with the most recent data are desirable) and another benchmark assessment and model evaluation be considered in ten years. The ARM and DBETC recommend that during the years between this assessment and the next, members remain proactive about maintaining surveys and research programs and continue to initiate or participate in activities that accomplish some of the research recommendations listed below.

10.1 Future Research

- Evaluate the effect of climate change on horseshoe crabs and red knots. This includes the effects of warming temperatures, sea level rise, and storm frequency and intensity on the timing and duration of spawning, movement of crabs into and out of Delaware Bay, and effects on spawning habitat. For red knots, this includes effects of climate change on breeding conditions in the arctic and resulting recruitment of red knots.
- Incorporate potential climate change effects into the optimization (e.g., predicted trends in arctic snow cover).
- Evaluate the relationship between horseshoe crab egg density on spawning beaches and abundance of horseshoe crabs in the bay-wide spawning survey and total population estimates derived from the catch multiple survey analysis.
- Improve the understanding of horseshoe crab recruitment for the purpose of updating the stock-recruitment relationship.
- Continue evaluation of catchability and factors influencing catchability of the Virginia Tech horseshoe crab trawl survey.

- Address the issue of gear saturation for spawning beach surveys and/or explore analyses that would be less sensitive to gear saturation. Explore the methodology and data collection of spawning beach surveys and the ability of these surveys to track spawning abundance.
- Quantify the amount of contemporary suitable horseshoe crab spawning habitat in the Delaware Bay.
- Further explore the multi-state mark-recapture analysis of red knot tagging data to estimate the probability of gaining weight and survival as a function of horseshoe crab abundance. Examine the effects of tagging biases, time periods of stopover, short-versus long-distance migrants, and selection of states (i.e., weight thresholds).
- Evaluate the proportion of New York bait landings that could be comprised of Delaware Bay-origin crabs and the movement between the two regions.
- If possible, include other sources of horseshoe crab removals (e.g., illegal take, poaching) in the CMSA. Other sources of removals are currently unknown, but can be added in the future if quantified.

10.2 Data Collection

- Continue funding and support for the annual Virginia Tech horseshoe crab trawl survey. Consider increasing the sampling effort within the Delaware Bay region or expanding the survey along the Atlantic coast if future funding allows.
- Better characterize horseshoe crab discards in other commercial fisheries and refine estimates of discard mortality.
- Continue to collect horseshoe crab sex and stage (primi- and multiparous stages) information from the Delaware Bay Adult Trawl Survey and the New Jersey Ocean Trawl Survey.
- Continue to evaluate biomedically bled crabs' mortality rates and effects on spawning behavior. Consider a tagging study of biomedically bled horseshoe crabs to obtain relative survival and collaborations between researchers and biomedical facilities that would result in peer-reviewed mortality estimates.
- Maintain consistent data collection and survey designs for spawning beach surveys each year.
- Increase effort for tagging resights for horseshoe crabs.
- Improve estimates of counting error during red knot aerial surveys by recording and maintaining records of additional information such as observer ID, tide state, and

weather conditions. The integration of simultaneous ground count data or a double-observer method could also be used to improve this component of the IPM.

10.3 Data analysis and modeling

- Update horseshoe crab stock-recruitment relationships as more data become available and refine methodologies to characterize uncertainty.
- Update parameters describing the influence of horseshoe crabs on red knot survival and recruitment through re-fitting the red knot integrated population model to new data.
- Integrate red knot “proportion marked” data into the IPM so that analyses conducted to determine the state of the system can be used to update model parameters with no additional effort.
- Investigate alternative utility functions for red knots with additional stakeholder input.
- Continue to evaluate horseshoe crab tagging data by fitting capture-recapture models that include a short-term (1 year) bleeding effect, account for spatial distribution of harvest pressure, account for capture methodology, and account for disposition of recaptured tagged individuals. Potential methodological approaches include use of time-varying individual covariates to indicate which crabs are 1 year from bleeding and use of hierarchical models to estimate interannual variation in survival within time periods defined by major regulatory changes.
- Explore the possibility of modeling stopover persistence as a function of boreal-wintering area of marked birds using observations away from Delaware Bay.

11 MINORITY OPINIONS

11.1 Niles Minority Opinion

Larry Niles PhD. ARM Subcommittee Member, Wildlife Restoration Partnerships

11.1.1 Introduction

In 2011 the Atlantic States Marine Fishery Commission disbanded their Shorebird Committee after the group recommended a complete moratorium on horseshoe crab harvests until better information is available to guide both the bait and blood harvests. Shortly afterward, the Adaptive Resource Modeling committee began work to create a statistical model aimed at estimating a harvest package that would "provide adequate stopover habitat for migratory shorebirds" (ASMFC 2009a). The author believes the ARM model does not provide sufficient horseshoe crabs for shorebirds, especially the federally listed red knot. Moreover, I believe the ARM model management does not provide for the coming challenges presented by the growing threat of climate change.

The horseshoe crab population of Delaware Bay is the last remaining spawning population, from Maine to Florida, large enough to produce surface eggs for migrating shorebirds. A singular food resource, crab eggs historically allowed red knots to rapidly double bodyweight, increasing adult survival and productivity (Baker et al. 2004; Duijns et al. 2017). A rapidly developing unmanaged harvest in the 1990s cut the population and reduced surface egg densities to less than one-fifth of pre-harvest numbers, from an average of more than 50,000 eggs/square meter to less than 10,000 eggs/square meter in 2021 (Smith et al. *in review*, provided as supplemental material). The overharvest of horseshoe crabs, and reduced egg resources were causal factors in red knot population decline leading to listing as "threatened" by the US Fish and Wildlife Service (USFWS 2014, pg. 248-9).

In response, the Atlantic States Fisheries Commission (ASFC) and the USFWS first developed the Interstate Fishery Management Plan (FMP) for Horseshoe Crabs (ASFC 1998). However, uncertainty in setting a baseline number for horseshoe crab populations has been a limiting factor in the management plan. In 2000, the Stock Assessment Subcommittee (SAS) and Peer Review Panel (PRP) concluded there was "inadequate information for a coastwide stock assessment, to establish reference points, fishing mortality rates, recruitment estimates, and recommended a conservative risk-averse approach because of localized population decline, increased catch and effort, slow maturation, susceptibility of spawning crabs to harvest, population resiliency and the need for a superabundance of horseshoe crab eggs in the Delaware Bay" (ASFC 2000b, pg. 2). In other words, the ASFC, the SAS, and PRP concluded that the trawl, dredge, and other surveys being used at the time, were unsuitable for determining horseshoe crab population numbers and eggs were not only a vital resource but a superabundance of eggs was important to the Delaware Bay shorebird stopover. Addendum III (2004, pg. 4) reiterates statements from the Peer Review Panel that "horseshoe crab eggs are only profitable to shorebirds if they occur in high surface density" (USFWS 2003). In 2000, the ASFC initiated a new benthic trawl survey designed to sample horseshoe crabs, conducted by Virginia Tech and led by David Hata and Eric Hallerman. Addendum III (2004) put forward a monitoring program including horseshoe crab surface egg densities, an indicator of foraging conditions for red knots and shorebirds.

Ten years of harvest restrictions (1998-2009) produced little improvement in crab numbers, and the ASFC initiated the Adaptive Resource Management (ARM) Framework (ASFC 2009a). The ARM Model, implemented in 2013, added a more structured approach and multispecies management objective: "Manage the harvest of horseshoe crabs in the Delaware Bay to maximize harvest but also maintain ecosystem integrity and provide adequate stopover habitat for migrating shorebirds." To date, the ARM model has not produced a substantive increase in female crabs, as documented by the Virginia Tech trawl survey, or adequate stopover habitat for shorebirds (i.e., surface eggs).

In 2013, the Horseshoe Crab Technical Committee inexplicably ended horseshoe crab egg surveys without recommendations or replacement. NJDEP and other groups continued egg surveys; however, horseshoe crab surface eggs were not supported as a metric in the 2021

ARM Model revision. In contrast, trawl and dredge surveys, previously disregarded as unsuitable but no longer suggesting decline, were added into the ARM Model revision.

11.1.2 Enumerated Concerns

The current ARM Model underwent revision to include data collected over the last ten-plus years. Although the ARM framework deserves praise for its statistical innovations and a multispecies approach, I believe it no longer serves the interests of either red knots or shorebirds. The new ARM Model, like the old model, does not provide "adequate stopover habitat", a superabundance of eggs, or the restoration of horseshoe crabs for these reasons:

1. The 1998 Management Plan specifically listed existing trawl, spawning, and egg surveys stating, "while useful for general trends within specific areas, each is complicated by factors that may bias data, such as sampling error, inappropriate equipment or incomplete sampling effort" (ASPMC 1998, pg. 22). The Plan recommended a standardized monitoring program (ASPMC 1998, pg. 22-24) formalized in Addendum III (ASPMC 2004).
2. To overcome concerns over data bias, the Atlantic Coast Benthic Trawl Survey, conducted by Virginia Polytechnic Institute and specifically designed to sample horseshoe crabs, was initiated in 2000 in the Mid-Atlantic Region (NJ to VA). Nearly two decades later, the Virginia Tech Survey has not shown a sustained increase in the number of mature female crabs over the time series (2001 to 2019) (Bi et al. 2019).
3. The 1998 plan also resulted in a bay-wide horseshoe crab egg survey, developed by Dr. Dave Smith (US Geological Survey, Leetown WV) and implemented in 2005 in NJ and DE. Egg surveys were already conducted in NJ, the first in 1986 and 1987, a second in 1990 and 1991, and continuously since 2001 (Smith et al. *in review*). The Horseshoe Crab Technical Committee disenfranchised the egg survey from the FMP in 2013 based on critiques of the technique citing a lack of correspondence between egg clusters and surfaces eggs and criticisms of enumeration methods used in DE and NJ, but offered no recommendations or alternatives. Thereafter, Delaware discontinued participation in the egg survey, and New Jersey continued egg surveys to the present.
4. In 2015, New Jersey updated survey methods focused on increasing samples sizes and altering the count methodology conducting randomized sampling throughout the entire intertidal area to reduce variability and error margins. Side-by-side comparisons of old and new methods showed the new methods statistically robust. The current surveys being conducted collect data for two important metrics, egg clusters show horseshoe crab spawning activity, and surface egg samples show food availability for red knots and other shorebirds (Smith et al. *in review*). Eggs are the critical link in the management model that would determine whether there is an "adequate stopover habitat for migrating shorebirds" (Figure 1). To date, the survey has shown no sustained increase in surface eggs over the time series (2005 to 2021), and eggs remain below historic

abundances (1985-1991: $\bar{x}$ = 144,609 eggs/sq. meter; 1990-1991: $\bar{x}$ = 47,971 eggs/sq. meter; 2015-2021: $\bar{x}$ = 11,565 eggs/sq. meter; (Smith et al. *in review*)).

5. The ASMFC created the Adaptive Resource Management (ARM) Subcommittee to develop a mechanism for deciding horseshoe crab bait harvest quotas based on the management objective: "[. . .] to maximize harvest but also to maintain ecosystem integrity and provide adequate stopover habitat for migrating shorebirds." Since implementation, ARM management has recommended male-only bait harvest (see ASMFC FMP Reviews <http://www.asmfc.org/species/horseshoe-crab>). The ARM Subcommittee has made nine annual recommendations despite no improvement in horseshoe crab populations in the Virginia Tech Trawl or the NJ horseshoe crab egg surveys.
6. The newly revised ARM model, presented to the ARM Subcommittee in August 2021, uses data from the Virginia Tech Benthic Trawl as well as the NJ Dredge and Ocean Trawl, and the DE 30-foot trawl in a new catch-survey model despite the ASMFC's stated concern over data bias; (See item #1 above). Added to the ASMFC's original misgivings over the survey, New Jersey's moratorium on horseshoe crab harvest adds additional uncertainty – does the newly added survey measure the results of NJ moratorium or Delaware Bay's ARM management? Greater uncertainty arises from the model's use of only five years of data, a short time series that could easily bias results. Although this relies on the Agency's use of "best available data," it also defies the long-held advice of technical and peer review committees to avoid making conclusions about populations based on a short time series of data. In contrast, surface eggs and clusters were excluded from the ARM revision because the committee judged the seven-year time series (2015-2021) too short.
7. The growing concern over ARM population estimates for horseshoe crab comes from the conclusions that the population has increased and reached an equilibrium despite the lack of evidence of an increase in both the Virginia Tech Trawl and egg counts. This prompted repeated concerns from the authors of these studies.
8. These concerns were presented by Dr. Larry Niles at the February 2021 ARM workshop, including the reservations about using data from trawl and dredge surveys not directed at horseshoe crabs, the lack of improvement in the Virginia Tech survey, and the lack of improvement in NJ's egg survey (see Figure 3). The ARM Subcommittee largely disregarded these concerns.
9. The ARM Model's emphasis on modeled horseshoe crab numbers and narrowly defined harvest packages satisfies commercial harvest interests, but crab eggs are the primary concern for red knots and other shorebirds for whom eggs are the primary (or sole) food source for successful spring migration and productivity (Baker et al. 2004; Duijns et al., 2017). The two interests are related, but crabs maintained at levels sufficient to supply bait, and biomedical use are not necessarily abundant enough to saturate spawning beaches with a high density of surface eggs. Indeed, these diminished egg densities

clearly cannot accommodate the inevitable changes wrought by Climate Change including increasingly adverse wind and wave conditions. Egg data reveals that current management does not provide enough egg clusters and surface eggs when conditions are ideal. But in less-than-ideal conditions, like cold water or bad weather years, surface eggs plummet, leaving shorebirds without any resources until after they leave for Arctic breeding areas. This occurred in 2019. This circumstance is far different than the eggs encountered by shorebirds in 1986-87 and 1990-91. These data not only show egg densities greater than five times the current densities and a longer period of robust densities in cold or warm water years

10. ARM members have suggested that a lack of suitable spawning habitat, or climate change impacts to habitat, is responsible for crab population "stability" at the current level. I conclude this is incorrect for several reasons.
 - a. First, this ignores the estimated deaths of over 1 million crabs each year from legal bait and biomedical harvests, unaccounted discards, and other unmanaged mortality that may equal legal harvests, indirect impacts on survival through bleeding and harvesting anomalies. For example, genetic samples indicate nearly 44 percent of NY legal bait harvest, which includes both sexes, is of Delaware Bay Origin crabs (E. Hallerman, *personal communication*, April 2021). Similarly, ASMFC estimated mortality of horseshoe crabs from the bleeding by biomedical companies which was half of peer reviewed and published studies.
 - b. Second, suggestions that habitat is limited without any supporting data also represent a lack of understanding of horseshoe crab breeding biology. If habitat were limited and female crabs were abundant enough to saturate spawning beaches with egg clusters, then suitable habitats would have high surface egg densities through May. Data on egg clusters (2015-2021) and surface eggs (2000-2021) do not reflect this condition.

Lastly, NJ has restored horseshoe crab breeding habitat to the optimal condition since Hurricane Sandy (2013), with projects totaling over \$10 million and over 3 miles of horseshoe crab habitat restored. Although restored beaches contain greater egg densities than unrestored beaches (Smith et al. 2019), densities remain about one-fifth of that seen prior to the 1990's overharvest. If habitat were limited, all suitable habitats would be saturated with eggs. (Smith et al. *in review* 2021).

11.1.3 Conclusions

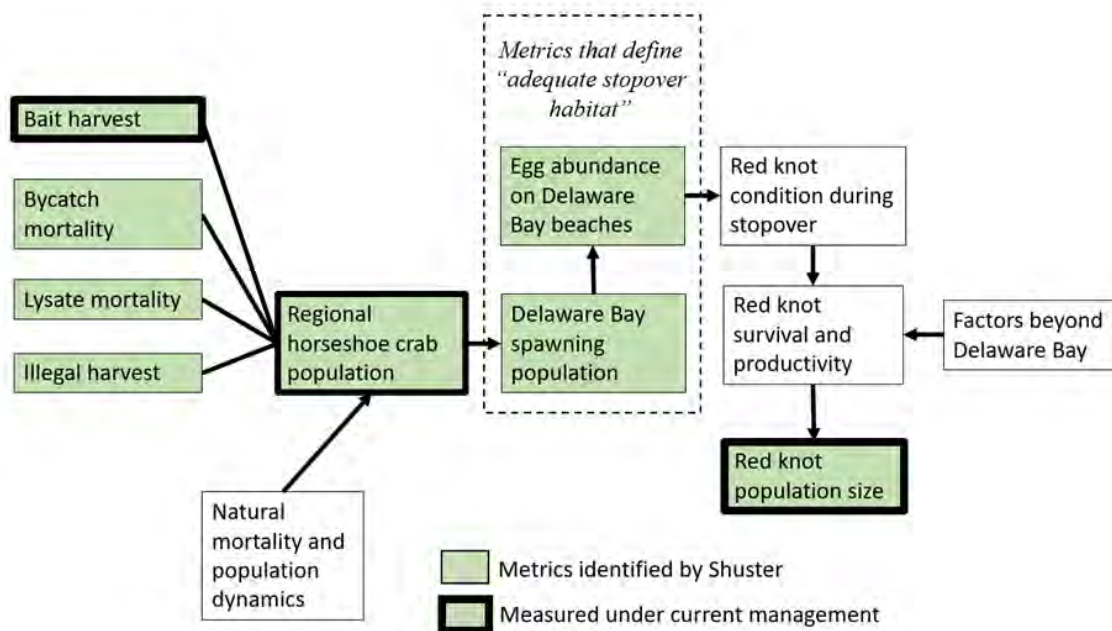
Horseshoe crab eggs and red knot populations have not increased during the 23 years of ASFMC management, including nine years of ARM Model management (Lyons 2020). The lack of sustained increase in female crabs, insufficient egg clusters on spawning beaches, and insufficient surface eggs for shorebirds leave the Bay in a destabilized condition subject to reduced, delayed, or interrupted crab spawning even under fair weather conditions. Insufficient

numbers of mature females keep egg densities far below those found in the 1980s and 1990s, and this diminished egg resource will all but disappear if weather and water temperatures are not calm and warm, respectively. Where abundant egg resources once buffered the red knot population against stochastic events (population "Resiliency and Redundancy", USFWS 2021, pg. 5, paragraph 3; pg. 6, paragraph 1), red knots are now left vulnerable to any perturbation within and outside of Delaware Bay. At the start of the model, the technical groups refused fisheries survey data collected which showed horseshoe crab decline (ASMFC 2000b pg. 2) then reinstated the same data when it showed increase. This reduces the scientific credibility of the model and suggests the need for horseshoe crab harvest is greater than the continued existence and recovery of red knots.

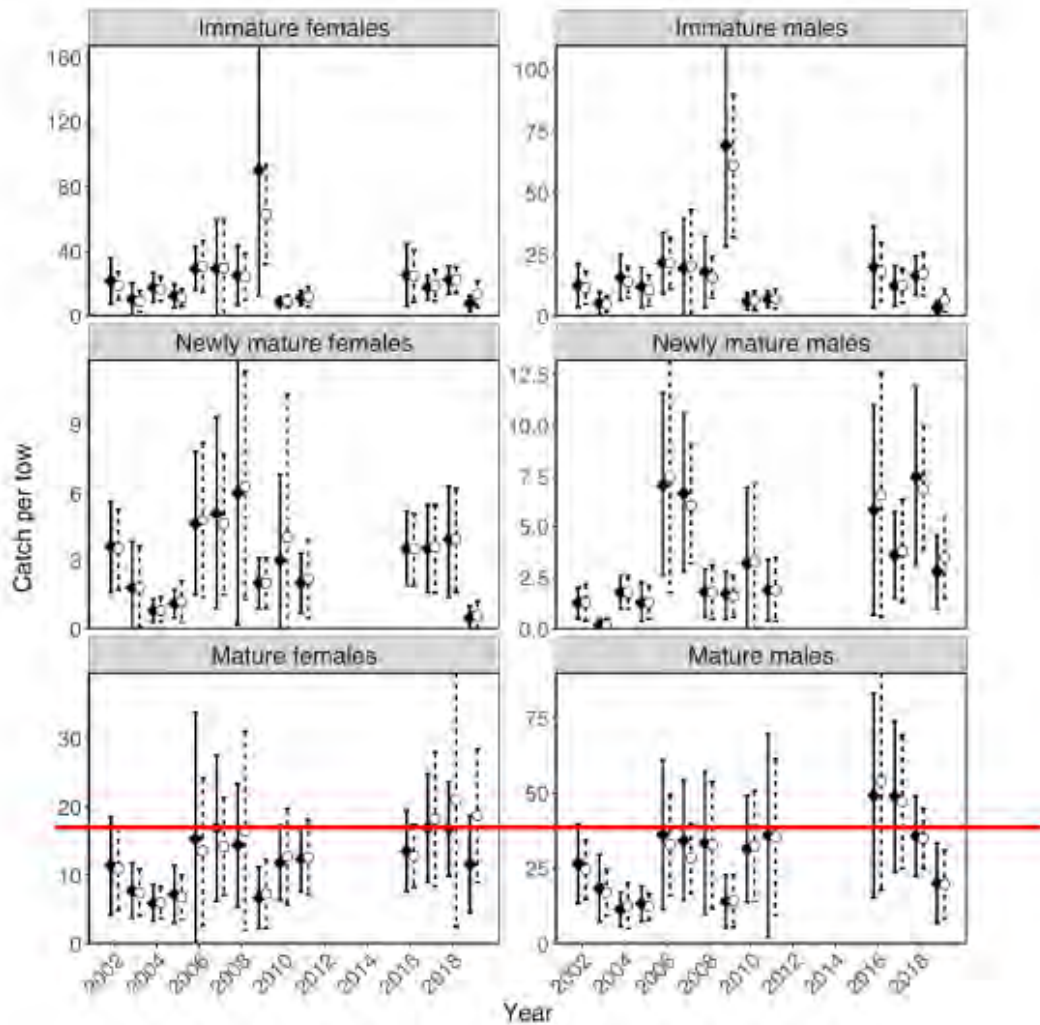
Therefore, I believe the management of horseshoe crabs on Delaware Bay, after nine years of ARM Model implementation with concurrent monitoring, does not satisfy the management objectives set forth in the 1998 Fishery Management Plan and 2009 ARM Model Framework - to maintain ecosystem integrity and provide adequate surface eggs for shorebirds. Additionally, I believe the USFWS assumption that: "as long as the ARM is in place and functioning as intended, ongoing horseshoe crab bait harvests should not be a threat to the red knot" (79 Fed. Reg. at 73,709) cannot be legitimately supported. I request the USFWS reverse or at least reconsider this assumption and "provide recommendations and technical assistance to ensure that future harvests of horseshoe crabs do not result in the take of red knots under section 9 of the [Endangered Species] Act." (79 Fed. Reg. at 73,710).

Additionally, I believe the current management cannot create the resiliency necessary to weather the impact of Climate Change. Managing horseshoe crab populations for the sake of harvesters does not provide for a robust population of horseshoe crabs necessary to weather increased threats of storm frequency and intensity during the spawning period. Increasing Climate Change impacts create an even more pressing need for new management measures to restore a robust population of horseshoe crabs and the associated superabundance of horseshoe crab eggs that previously characterized spawning conditions in the Delaware Bay.

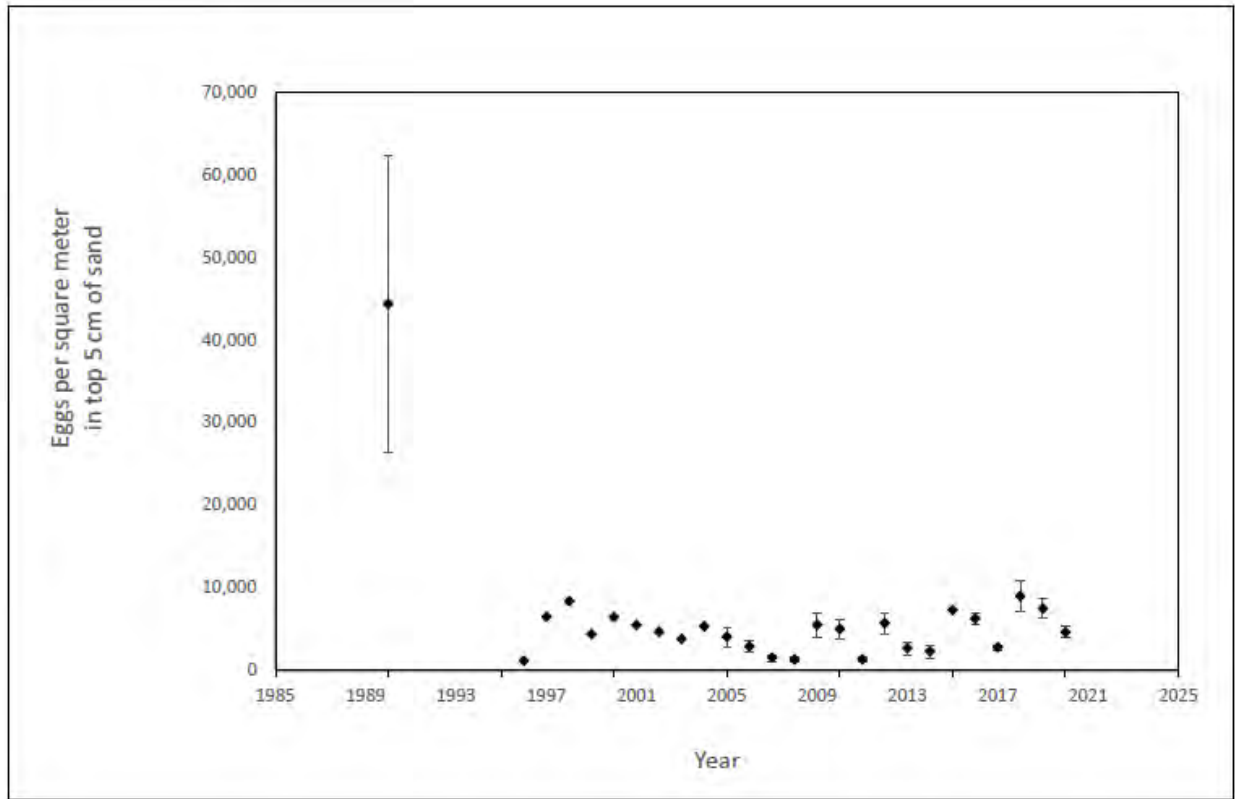
11.1.4 Tables and Figures



Niles Figure 1. The two metrics missing from the current ARM management framework are intended to describe conditions on spawning beaches. Omission of these beach-based measurements are a lost opportunity because they offer unique insights into management effectiveness. Conditions on spawning beaches serve as a critical link in a management logic model that would determine whether there is “adequate stopover habitat for migrating shorebirds.”



Niles Figure 2. Plots of stratified mean catches per 15-minute tow of horseshoe crabs in the coastal Delaware Bay Area survey by demographic group. Vertical lines indicate 95% confidence limits. Solid symbols and lines indicate the Delta distribution model. Open symbols and dashed lines indicate the Normal distribution model. Note difference in y-axis scales. Source: Figure 2 in Bi et al. 2020.



Niles Figure 3. Surface egg densities on NJ beaches: Historic 1990-1991 (Botton et al. 1994), unpublished report to NJDEP 1996-1999 (Botton and Loveland), NJDFW unpublished data 2000-2021 (NJ Division of Fish & Wildlife).

Niles Table 1. Indices of bay-wide male and female horseshoe crab spawning activity (ISA), number of beaches surveyed, standard deviation (SD), coefficient of variation (CV), 90% confidence intervals (CI) and sex ratio for the Delaware Bay from 1999 to 2017 (Source: DE DFW).

Year	Beaches Surveyed	Male				Female				Annual Sex Ratio (M:F)
		ISA	90% CI	SD	CV (%)	ISA	90% CI	SD	CV (%)	
1999	17	2.5	1.86, 3.37	0.45	18	0.77	0.62, 0.97	0.1	13	3.2
2000	22	2.96	2.31, 3.80	0.45	15	0.91	0.74, 1.13	0.12	13	3.2
2001	22	2.37	1.91, 2.95	0.31	13	0.75	0.63, 0.90	0.08	10	3.1
2002	23	2.86	2.45, 3.34	0.27	9	0.91	0.79, 1.04	0.07	8	3.1
2003	23	2.89	2.50, 3.33	0.25	9	0.8	0.71, 0.91	0.06	8	3.6
2004	24	2.93	2.55, 3.36	0.24	8	0.77	0.68, 0.87	0.06	7	3.8
2005	23	3.23	2.79, 3.74	0.29	9	0.82	0.72, 0.93	0.07	9	3.9
2006	24	3.99	3.49, 4.56	0.33	8	0.99	0.89, 1.10	0.07	7	4
2007	24	4.22	3.63, 4.90	0.38	9	0.89	0.78, 1.01	0.07	8	4.7
2008	25	2.3	1.83, 2.90	0.32	14	0.68	0.59, 0.78	0.06	9	3.4
2009	26	4.67	4.11, 5.29	0.36	8	1	0.89, 1.11	0.06	6	4.7
2010	25	3.39	2.93, 3.94	0.31	9	0.8	0.70, 0.92	0.07	8	4.2
2011	25	3.31	2.83, 3.87	0.31	10	0.64	0.57, 0.72	0.05	7	5.2
2012	25	2.44	1.97, 3.01	0.31	13	0.56	0.47, 0.67	0.06	10	4.4
2013	25	3.2	2.98, 3.44	0.14	4	0.85	0.80, 0.91	0.03	4	3.8
2014	25	2.28	2.09, 2.48	0.12	5	0.54	0.50, 0.59	0.03	5	4.2
2015	23	2.75	2.59, 2.92	0.1	4	0.66	0.62, 0.70	0.02	4	4.2
2016	25	4.1	3.86, 4.36	0.2	4	0.9	0.85, 0.95	0.03	3	4.6
2017	25	3.68	3.37, 4.02	0.2	5	0.71	0.65, 0.78	0.04	6	5.2

Niles Table 2. Superpopulation estimate (mark-resighting method). Source: Lyons 2019, Table 4, Memorandum to the Delaware Bay Adaptive Resource Model (ARM) Working Group. September 30, 2020.

Table 4. Stopover (passage) population estimate using mark-resight methods compared to peak-count index using aerial- or ground-survey methods. The mark-resight estimate of stopover (passage) population accounts for population turnover during migration; peak-count index, a single count on a single day, does not account for turnover.

Year	Stopover population ^a (mark-resight N^*)	95% CI Stopover pop- ulation N^*	Peak-count index [aerial (A) or ground (G)]
2011	43,570	(40,880 – 46,570)	12,804 (A) ^b
2012	44,100	(41,860 – 46,790)	25,458 (G) ^c
2013	48,955	(39,119 – 63,130)	25,596 (A) ^d
2014	44,010	(41,900 – 46,310)	24,980 (A) ^c
2015	60,727	(55,568 – 68,732)	24,890 (A) ^c
2016	47,254	(44,873 – 50,574)	21,128 (A) ^b
2017	49,405 ^e	(46,368 – 53,109)	17,969 (A) ^f
2018	45,221	(42,568 – 49,508)	32,930 (A) ^b
2019	45,133	(42,269 – 48,393)	30,880 (A) ^g
2020	40,444	(33,627 – 49,966)	19,397 (G) ^c

^a passage population estimate for entire season, including population turnover

^b 23 May

^c 24 May

^d 28 May

^e Data management procedures to reduce bias from recording errors in the field; data from observers with greater than average misread rate were not included in the analysis

^f 26 May

^g 22 May

1998, FMP for Horseshoe Crab.

Pg 22. Summary of Monitoring Programs

While each of the above-mentioned monitoring programs are useful in identifying general trends within specific areas, each is complicated by factors that may bias the data, such as sampling error, inappropriate equipment, or incomplete sampling effort. The independent monitoring programs also lack a comprehensive data collection goal. The goal of a comprehensive horseshoe crab monitoring program should be to produce data necessary to develop a stock assessment for the Atlantic Coast horseshoe crab populations that can be used in future management decisions.

Numerous state and federal agencies, universities, and private organizations are involved in data-collection efforts to ascertain horseshoe crab population status. Monitoring and evaluation efforts specific for horseshoe crabs include egg counts in Delaware Bay (New Jersey and Delaware) by Dr. Robert Loveland of Rutgers University and Dr. Mark Botton of Fordham University, egg counts by Dr. Richard Weber of the University of Delaware, spawning surveys in Delaware Bay (New Jersey and Delaware) by Limuli Laboratories, spawning surveys in New Hampshire by Great Bay National Estuarine Research Reserve, and spawning surveys in Maryland's Chesapeake and coastal bays by Maryland Department of Natural Resources. Trawl surveys are conducted along the New Jersey Atlantic Coast by New Jersey Division of Fish, Game and Wildlife and within the Delaware Bay by the Delaware Division of Fish and Wildlife. Trawl surveys have been conducted along Maryland's Atlantic Coast bays by Maryland Department of Natural Resources, and in Peconic Bay, New York by New York State Department of Environmental Conservation. The NMFS Northeast Fishery Center, the State of Massachusetts, and the Connecticut Department of Environmental Protection also conduct trawl surveys. South Carolina Department of Natural Resource's Crustacean Management Section conducts trawl surveys in five estuaries in South Carolina. The National Oceanic and Atmospheric Administration / SEAMAP conducts shallow water trawl surveys between South Carolina and Florida. Limuli Laboratories and Maryland Department of Natural Resources also conduct tagging studies. Concurrently, several shorebird monitoring efforts are being conducted, including aerial surveys, diet / weight-gain studies, and banding studies by state and educational research institutions.

11.2 Majority Response to Niles and Justification for Why Opinion Not Adopted

The ARM workgroup is charged with making annual recommendations on the harvest of horseshoe crabs from the Delaware Bay area for the commercial bait industry. This revision to the ARM Framework links the population dynamics of horseshoe crabs and red knots within an optimization routine to make those recommendations. The minority opinion provided by Niles was not adopted in this revision to the ARM Framework because it lacked any proposed means or models for which to base annual harvest recommendations. Instead, the minority opinion focuses on a misrepresentation of the ecology and management of horseshoe crabs, an apparent lack of positive trend in egg density data from spawning beaches, and a lack of positive trend in the relative abundance of horseshoe crabs in the VA Tech Trawl Survey. Observation of trends without additional modeling does little to provide scientifically based harvest recommendations on an annual basis. Also, the minority opinion fails to provide any specific critiques of, or recommendations to improve, the population dynamics modeling of horseshoe crabs and red knots or the optimization techniques used in the majority report.

The opening paragraphs of the minority report materially misrepresent the ecology and management of horseshoe crabs. In the first paragraph, the author misstates the rationale for current ASMFC committee structure for horseshoe crab management in the Delaware Bay. In 2010, the ASMFC conceived of a committee structure to formalize the multiple species aspects of horseshoe crab management in Delaware Bay. Before the reorganization, the inclusion of shorebirds in horseshoe crab management was ad hoc. As part of the restructuring, the shorebird stakeholders were given formal positions in the newly created Delaware Bay Ecosystem Technical Committee (DBETC) and the Shorebird Advisory Committee. The reorganization placed the Adaptive Resource Management Work Group (ARM) under the DBETC because the focus of the ARM is on the Delaware Bay population. In the second paragraph, the minority report falsely implies that horseshoe crab populations from Maine to Florida had been large enough in the past to produce sufficient eggs for migrating shorebirds. Ecologists have long recognized that Delaware Bay is unique in its capacity to support the horseshoe crab and shorebird relationship (Shuster and Botton 1985; Myers 1986; Botton et al. 2003). In the third paragraph, the minority report misrepresents the ASMFC governance structure. The ASMFC developed the FMP in collaboration with Atlantic coastal states, USFWS, and NOAA. The minority report implies an incorrect role for USFWS in what is a collaborative process.

The use of egg density data within the ARM Framework was removed from consideration in the early stages of the adaptive management process and prior to the original peer-review of the ARM Framework in 2009. Egg density data are highly variable and when egg density surveys were conducted by both Delaware and New Jersey, there were large differences between the states in estimated densities due to differences in sample processing (ASMFC 2009a). As stated in ASMFC (2009a) “Even though the eggs are the food source for the birds and are the actual link between these species, our decision analysis (model state variables, management actions, utility functions/objective statements) is focused on abundance of these two species.” Including egg density data into this decision analysis would require restructuring of the population

dynamics models for each species. The relationship between horseshoe crab abundances generated by the CMSA and egg densities observed on the beaches would need to be quantified. Then the relationship between egg densities and red knot survival and recruitment would need to be quantified. To date, such an analysis has not been conducted, but it is one of several research recommendations listed in Section 10 of this report. This analysis was not done in ASMFC 2009a because the data were so temporally and spatially variable that useable metrics could not be identified in the survival analyses. Instead, the number of spawning females was used in 2009a and in this Revision, which is a more useful metric because it is more consistently measured, and, it is the system attribute that is directly managed through harvest. Additionally, the results of such analyses would likely yield little resolution in decision making because a direct link between female horseshoe crab abundance and red knot survival was established not only in the previous ARM Framework (ASMFC 2009a) but again in this Revision.

The other primary focus of the Niles minority opinion was trends in the VA Tech Trawl Survey. The ARM Framework has never used the relative abundance estimates (catch-per-tow) from the VA Tech Trawl Survey in making harvest recommendations. The previous ARM Framework used the catch-per-tow data expanded to a swept area population estimate in making harvest recommendations. This revision of the ARM Framework uses the population estimates generated by the CMSA, which are dependent on the VA Tech swept area population estimates (Figure 19) plus relative abundance indices from the NJ Ocean Trawl Survey (Figure 13-Figure 14) and the DE Adult Trawl Survey (Figure 16-Figure 17). There is precedence for the additional surveys' inclusions in the ARM, as both the NJ Ocean Trawl and DE Adult Trawl Surveys were used by the ARM Subcommittee to determine horseshoe crab abundance for the model in years when the VA Tech Trawl was not funded (2012-2015). The CMSA was peer reviewed in 2019 and the peer review panel stated, "The Panel recommends CMSA results when abundance and fishing mortality estimates are required, such as in the Adaptive Resource Management (ARM) model used by managers." Figure 23 of this report shows the female abundance estimates from the CMSA. Primiparous females have been highly variable over the time series, reflecting natural variation in year class strength, but multiparous females have increased. Average CMSA estimates of multiparous females were on average 3.77 million from 2003 – 2013, but increased to an average of 7.81 million from 2014 – 2019. Thus, it is erroneous to conclude that there has been no increase in female horseshoe crabs given the CMSA-based population estimates which were endorsed by the previous peer-review panel. The increase in multiparous females observed from 2014 -2019 makes sense given the curtailment of high harvest in early 2000s and the long time to maturity for horseshoe crabs.

11.2.1 Response to Numbered Items

The Niles minority opinion listed 10 specific points of criticism on the majority report. The following are point-by-point responses to each of those:

1. Numerous fishery-independent surveys have been evaluated and reconsidered since the implementation of the first Fishery Management Plan (FMP) in 1998 through the latest benchmark stock assessment in 2019 and this ARM Revision in 2021. The surveys used

in this report have statistical sampling designs, operate in a time and place that reliably capture horseshoe crabs, and have consistent methodology throughout the years used in the model. The NJ Ocean Trawl and DE Adult Trawl were approved for use in both the 2009 and 2019 stock assessments and in the ARM Framework for the years when the VT Trawl Survey was not funded.

The Niles minority opinion uses a quote from the 2000 ASMFC FMP Review (“...inadequate information for a coastwide stock assessment, to establish reference points, fishing mortality rates, recruitment estimates...”) as evidence that the NJ Ocean Trawl and DE Adult Trawl were previously deemed inadequate for assessing horseshoe crabs in the Delaware Bay area. The conclusions in the FMP Review referred to the inadequacy of the available data in 1998 (ASMFC 2002) but they did not categorize all existing surveys as being unsuitable for collecting necessary data. In the FMP’s section 3.5 Summary of Monitoring Programs, Component B recommended the continuation of existing state benthic sampling programs, including those in Delaware and New Jersey, and to record weight, number, and prosomal width by sex (ASMFC 1998). Though Delaware’s Adult Trawl Survey already collected all this information, New Jersey’s Ocean Trawl Survey did not record sex while collecting the other data. Subsequently, in 1999, New Jersey added sex data to their sampling protocol for horseshoe crabs. Additionally, in section 6.0 Management Research Needs, the FMP recommended the formulation of a “benthic sampling program for horseshoe crabs using standardized and statistically robust methodologies ...” (ASMFC 1998). To meet this recommendation, the ASMFC supported the implementation of a trawl survey focused specifically on horseshoe crabs in the Delaware Bay region to be conducted by VA Tech after successfully performing a pilot survey in 2001 (ASMFC 2002). While ASMFC’s support of this survey was unwavering, it also supported the continuation of existing surveys as stated explicitly in Addendum III, within the Monitoring Program Recommendations’ Component B2 (ASMFC 2004).

2. The VA Tech Trawl Report for the 2019 survey year states in its key findings, “Mean catch-per-tow of mature males and females in the coastal Delaware Bay area have been variable throughout the time-series, but show increasing trends since 2002.” These results are supported by increasing trends also seen in the Delaware and New Jersey trawl surveys. Regardless, the VA Tech Trawl Survey is variable from year-to-year and was not in operation for several years. Thus, this ARM Revision proposes the use of the CMSA to estimate horseshoe crab abundance since it can incorporate several indices of abundance and accounts for all quantifiable sources of removals (bait, biomedical, and discard mortality). The 2019 coast-wide benchmark assessment peer-review panel endorsed the use of the CMSA for this purpose. Additionally, the population estimates of multiparous horseshoe crabs varies less from year-to-year than the survey estimates alone.
3. During the development of the original ARM Framework (2009a), the committees discussed the substantial differences in methodology between New Jersey and

Delaware's egg density surveys and the impacts that had on the survey results. There was high variability both within and between sites, sampling issues, and unresolved uncertainty in the surveys and the DBETC could not reach consensus on how to use this data. Ultimately, the committees decided to link red knot population dynamics directly to horseshoe crab abundance rather than through eggs and data analyses support this relationship (McGowan et al 2011). Therefore, in 2012, Delaware requested a review of the state's egg survey since the survey was not being used to inform management and took personnel and money to maintain. Horseshoe crab technical committees were asked to review the survey and determine if it could be improved or if it should be discontinued. The DBETC determined in a 2013 memo that Delaware does not need to continue the survey because "egg density is not predictive of future stock recruitment... thus, egg density is not used to assess the horseshoe crab population" and "the ARM Framework relies on annual estimates of abundance for red knot and horseshoe crab populations." Finally, they concluded that "the DBETC recommends that the egg survey be discontinued as a compliance element for the states of New Jersey and Delaware. The DBETC added a note that individual states might want to continue the egg survey (for example, NJ requires it as part of their State's regulations) and the TC is willing to provide guidance and expertise to help improve the survey to detect trends for their needs." This was not disenfranchising the Delaware egg density survey but an acknowledgement that this survey was not being used for management and that states have limited staff and resources.

4. The trend in egg density from 1999 to 2021 (Figure 2 in Smith et al., unpublished data, supplemental to the Niles) appears to match the pattern in the trawl survey results over the same period. If so, the egg density data presented in Smith et al. (unpublished data) would support rather than refute the findings of the recent stock assessment and revised ARM.

The direct comparison of the Botton et al. (1994) egg densities to recently estimated egg densities is questionable because of confounding differences in spatial and temporal sampling design. Egg densities vary across the beach width, along the beach length, and over the spawning season (Weber and Carter 2009). A failure to account for all these sources of variation can confound egg density comparisons. For example, Botton et al. (1994) sampled only 2 cross-beach transects at 3 dates corresponding to peak locations and times. In contrast, Smith et al. (unpublished data) sampled 5 to 10 cross-beach transects once per week for 6 weeks. Whereas Botton et al. (1994) averaged over "peak" locations and times, recent egg sampling averaged over locations and times that included the peaks and the tails of the data distributions. Although the sampling design used in recent egg sampling results in a representative statistical sample, the results are not directly comparable to a study designed to sample only the spatial and temporal peaks.

Smith et al. (unpublished data) fails to adequately rule out the competing hypothesis that loss of spawning habitat explains changes in egg densities. A recently published

paper by Botton et al. (in press) reveals significant habitat loss along the eastern (NJ) shoreline in Delaware Bay and concludes that loss of quality spawning habitat is the main threat to horseshoe crabs. The habitat loss that Botton et al. (in press) documents took place from the 1980s to present time, which confounds egg-density comparisons over the same time presented by Smith et al. (unpublished data). A prediction that higher egg densities would result from crowding into reduced habitat fails to account for spatial shifts in habitat use throughout the bay. Horseshoe crabs do not exhibit fidelity to a spawning beach. Rather their habitat use is in response to the geomorphological dynamics of estuarine beaches. Spawning beaches form, erode, and migrate within an estuary. Anthropomorphic interventions, such as shoreline armoring, protect buildings and onshore property, but degrade spawning habitat by truncating the beach width and exposing peat deposits. Horseshoe crabs tend to avoid rather than crowd onto eroded beaches. Beach nourishment must be conducted on a scale and frequency to maintain sandy beaches in spite of erosive processes. The state of Delaware discontinued shoreline armoring (e.g., bulkheads and revetments) in the 1980's, whereas NJ continued to rely on hard structures to protect estuarine property. This highlights a fundamental flaw in the Smith et al. study caused by selecting sites to monitor based on past high abundance (Fournier et al. 2019) even though the habitat to support high abundance has changed. Horseshoe crabs can shift their habitat use spatially throughout the bay.

Smith et al. (unpublished data) attempt to infer population changes from a spatially constrained sample. The ASMFC stock assessments and ARM Framework combines multiple, cross-jurisdictional data sets to achieve the spatial and temporal coverage necessary to infer population status. But the data in Smith et al. (unpublished data) are restricted to a stretch of NJ shoreline that has experienced habitat loss (Botton et al., in press) and is not representative of the baywide habitat available to horseshoe crab population or shorebirds. The relevant question that is not answered or even asked by Smith et al. (unpublished data) is whether adequate eggs are available to shorebirds in the Delaware Bay.

5. Since the implementation of the ARM in 2012, the harvest package selected has consistently been 500,000 male-only horseshoe crabs in the Delaware Bay region. This is because for the duration of the ARM (2013-2022 fishing years), both horseshoe crabs (as estimated by VA Tech swept area population estimates) and red knots (stopover superpopulation estimates) have been below their thresholds of 11.2 million female horseshoe crabs and 81,900 red knots, respectively. Below these thresholds, the harvest of female horseshoe crabs has zero utility in the previous ARM optimization routine. The presence of these threshold constraints in the utility function was criticized during this revision for not being consistent with adaptive management and optimization procedures and therefore they were removed from the utility functions. The threshold functions were also criticized during the peer review of the original ARM Framework (ASMFC 2009a), specifically the knife-edge threshold. Estimates of horseshoe crab abundance from the CMSA, which have been adopted as the best estimates of

horseshoe crab population size, show that the population has increased. Currently, the ARM does not consider the NJ horseshoe crab egg surveys nor were the raw data, methods, or estimated values and associated error provided for this ARM Revision for consideration by the committee.

6. As stated in the response to item #1, the NJ Ocean and DE Adult Trawls have been reevaluated by technical committees and the stock assessment subcommittee and included in both the ARM Framework for when the VA Tech Trawl was not funded (2012-2015) and in two peer-reviewed benchmark assessments (ASMFC 2009b, 2019) as reliable indices of horseshoe crab abundance. There is no NJ dredge survey used as input to the CMSA or ARM framework. Both the NJ Ocean and DE Adult Trawls have consistent survey methods and reliably catch horseshoe crabs. Additionally, NJ Ocean Trawl has also started staging horseshoe crabs (primiparous and multiparous stages) to support the CMSA modeling in the future. The CMSA model uses both these surveys for the full time series (2003-2019), which is much longer than five years. While a short time series, such as the 2015-2021 NJ egg survey, would be challenging for modeling, it is not impossible but this data was not provided for consideration during model development.

The relative effects of NJ's moratorium versus ARM management are indistinguishable within a survey. The survey indexes the population which is influenced by overall harvest pressure on the population. Both the NJ moratorium and ARM management have reduced harvest compared to what it was prior to implementation of the horseshoe crab management plan in 1998. The uncertainty mentioned here could be applicable to the VA Tech survey results as well. These surveys provide abundance data regardless of the reasons for any increase/decrease/status quo trends seen in their data.

7. While outside the years of this report, the 2020 estimates from the VT Trawl Survey used in the ARM Framework was 9.5 million female horseshoe crabs (10.5 million females at the time of the survey in the fall of 2020 reduced by half a year's natural mortality to coincide with what would be available during the time of shorebird stopover in the spring of 2021). This value is approaching the 2009 ARM threshold of 80% carrying capacity, or 11.2 million females. While carrying capacity is not used in the ARM Revision, the long-term simulated equilibrium of female horseshoe crabs is estimated at 13.2 million females under the assumption of no female harvest from any source (Figure 29). The 2019 female horseshoe crab population estimated from the CMSA is 9.8 million (Table 16). This female population estimate from the CMSA represents an overestimate, as it is calculated using coastwide biomedical data and not the confidential Delaware-Bay only data. Regardless, both methods and estimates have the female horseshoe crab population approaching the former threshold (80% carrying capacity or 11.2 million females) or predicted equilibrium (13.24 million females). The egg counts have not, nor have they been since the ARM was implemented, a benchmark used by the ARM Framework due to multiple issues with the survey(s).

8. The ARM Subcommittee did not disregard these concerns, rather the two surveys (NJ Ocean Trawl and DE Adult Trawl) have demonstrated through two stock assessment peer reviews and vetting through the ARM Subcommittee that they are tracking the regional population. Both are multispecies trawls used in several species' stock assessments. Neither the NJ Ocean Trawl nor the DE Adult Trawl are dredge surveys, although that gear would be considered if there was a reliable survey that met the criteria. (Note: A NJ surf clam dredge was once used as an index in the assessment of horseshoe crabs, but this survey has not been considered since 2012 when sampling methodology changed.) All the surveys (VA Tech Trawl Survey, NJ Ocean Trawl, DE Adult Trawl) used in the ARM Revision were provided for consideration by the Subcommittee, including methods, raw data, and any state or university-calculated indices with estimated error. No data or comprehensive methods were ever provided for the NJ egg density survey. Following the February 2021 objections by Larry Niles, ASMFC staff participated in a call with Joseph Smith in March 2021 to discuss the NJ egg density survey but the raw data and methods were still not provided for consideration following that call. The unpublished draft manuscript by Smith et al. submitted with the minority report was the first time the ARM Subcommittee saw details on the current NJ egg density survey.
9. As previously stated, to incorporate the linkage between female horseshoe crab abundance, egg density on beaches, and red knot survival would require additional analysis to quantify these relationships for use in projection modeling and optimization. A direct link between female horseshoe crab abundance and survival has been established in this report as well as the previous ARM report (ASMFC 2009a) and in the literature (McGowan et al. 2011; Tucker et al. 2019, 2021). Again, one of the research recommendations from the ARM Subcommittee is continued analysis of egg density data and the relationship to horseshoe crab abundance estimates from the CMSA. Diminished egg densities wrought by climate change and increasing adverse wind and wave conditions is a possible hypothesis that would require additional research and analysis, and this is also another research recommendation specified in the report. Without actually fulfilling these research needs and conducting the appropriate analysis of those data, one is left with only speculation about the effects of these factors on the population dynamics of these two species. It is unknown if conditions in 2019 caused a decrease in red knot survival or recruitment because these data were beyond the years available at the time of the analysis contained within this report (i.e., the IPM development), therefore, to conclude weather conditions in 2019 had a deleterious effect on red knots is premature.
10. It is accurate to say that over 1 million horseshoe crabs die annually coastwide from legal bait and biomedical harvest. Reported coastwide bait landings in 2019 (the most recent available FMP Review) were 1,022,909 horseshoe crabs, below the coastwide quota of 1,587,274 horseshoe crabs. However, total Delaware Bay origin removals (bait, biomedical, and dead discards) used in the CMSA averaged 68,818 females and 267,297 males per year from 2008 – 2018 (Tables 13 and 14), and these are overestimates

because they assume coastwide biomedical mortality occurred solely in Delaware Bay. This number is significantly less than 1 million crabs each year. The ASMFC-estimated biomedical mortality of 15% was in fact derived exclusively from peer-reviewed and published studies (ASMFC 2019), comprised of estimates both lower and higher than 15% depending on the study and its methods. The current use of the CMSA meets the first term of reference in this report by including “unaccounted discards” and biomedical harvests. These were sources of mortality ignored in the previous ARM Framework. If “other unmanaged mortality” and “harvesting anomalies” can be quantified and those data are available, it would be an easy task to also include them in the total removals used in the CMSA.

It is true that 44% of the NY bait harvest of horseshoe crabs in the Long Island sound area have genotypes indicating that they originated from the Delaware Bay as noted by Dr. Eric Hallerman (personal communication). This is not surprising given potential large coastal movements observed through tagging studies of horseshoe crabs. However, a lower percentage of horseshoe crabs from the northeast area (which would include Long Island Sound) comprised commercial catches in the vicinity of Delaware Bay (e.g., Ocean City MD, Chincoteague and Assateague Islands, VA), thus indicating greater movement out of the Delaware Bay area than into the Delaware Bay area. Tagging data also suggest a greater movement rate out of Delaware Bay to NY than from NY into Delaware Bay (ASMFC 2019). Thus, harvest in NY waters is expected to have little impact on the Delaware Bay population because individuals originating from Delaware Bay and caught in NY likely represent permanent emigration from the Delaware Bay.

Finally, this ARM Revision makes no statements about horseshoe crab habitat other than as a research recommendation to evaluate the effects of climate change on horseshoe crabs and red knots, including the effects on spawning habitat and spawning timing.

11.2.2 Response to Niles Conclusions

Niles argues that the ARM Framework no longer meets the assumption by the USFWS that “as long as the ARM is in place and functioning as intended, ongoing horseshoe crab bait harvests should not be a threat to the red knot” (79 Fed. Reg. at 73,709). However, during the time that the ARM has been instituted, horseshoe crab abundance has increased (Figures 23 and 24) and red knot stopover population size has remained stable (Table 12). Further, this is not the appropriate forum to make a request to the USFWS.

Finally in his conclusion, Niles argues that considerations of climate change are not taken into account. This is false. Climate change considerations were taken into account by including arctic snow cover as a covariate in the IPM model for red knots. Snow cover was found to have a negative but not significant influence on red knot survival and no effect on recruitment, but this covariate remains in the model and as more data are collected, perhaps an influence of this covariate will become apparent and future modeling could incorporate predictions for how

snow cover may change into the future. Also, the effects of climate change were included in future research recommendations.

11.3 Walsh Minority Opinion

Wendy Walsh, ARM Subcommittee member, U.S. Fish and Wildlife Service (USFWS)

11.3.1 Introduction

I appreciate the opportunity to review the draft report entitled *Revision to the Framework for Adaptive Management of Horseshoe Crab Harvest in the Delaware Bay Inclusive of Red Knot Conservation*. The draft report represents a tremendous amount of work, knowledge, and technical expertise aimed at updating and improving the Adaptive Resource Management (ARM) framework that has guided the Atlantic States Marine Fisheries Commission's (ASMFC) horseshoe crab bait harvest policy since 2013. Pages 20-21 of the draft report list seven major changes from the current to the proposed ARM framework, with which I generally concur. Among the most positive changes are the replacement of literature values with empirical values for certain key horseshoe crab and red knot demographic parameters, and the explicit accounting for biomedical harvest and discard ("bycatch") as sources of anthropogenic crab mortality. Another major advance involves moving away from discretized parameters (e.g., a single, universal weight threshold for all red knots; three uneven time windows for birds to transition from "light" to "heavy;" a small number of harvest packages that linked male and female harvest levels) toward more continuous inputs and outputs that may allow the framework to more effectively "learn" and adapt absent those artificial constructs. However, I do have some concerns and objections, which are the focus of this minority report.

11.3.2 Simulation Models

The proposed changes to the ARM framework include complete replacement, not just updating, of the simulation models that are used to project horseshoe crab and red knot populations into the future. I have expressed concern that by replacing, instead of updating, these projection models, we risk losing some of the benefits of iterative learning that are supposed to accrue from the double-loop model of adaptive management (Figure 1). However, given the problems that were encountered upon updating the previous Multistate red knot model (draft report Section 7.1.2), I do concur that replacing it with the proposed Integrated Population Model (IPM) is the best path forward and represents best available science. Similarly, given the conclusion of a previous ASMFC peer review panel that the Catch Multiple Survey Analysis (CMSA) represents the best available horseshoe crab abundance estimates (draft report p. 18), I do likewise concur that CMSA should replace the previous State-based population simulation model for horseshoe crabs.

However, I request that the ARM Subcommittee revisit the possibility of weighting the Virginia Polytechnic Institute (Virginia Tech) data more heavily than the other data sets in the CMSA model, which is used in the proposed new ARM framework both to estimate current horseshoe

crab abundance as well as projecting those estimates into the future. It is significant that the Virginia Tech trawl is the only survey that is purpose-designed to estimate horseshoe crab abundance in the Delaware Bay region. And it is concerning that, without such weighting, the CMSA estimates for 2016 to 2019 were 1.1 to 5.3 million higher than the Virginia Tech estimates for total adult females (primiparous + multiparous), and 7.7 to 13.7 million higher for total adult males over that same time period (draft report Tables 16 and 17; Hallerman and Jiao, Table 6). This result was predictable from the sensitivity runs conducted for the 2019 stock assessment, which noted: *“An equal weight ... model produced considerably higher terminal stock size estimates since greater emphasis on the VT survey was no longer specified, allowing the model to more closely fit the sharply rising DE and NJ trawl indices.”* (ASMFC 2019, p. 77).

Rather than the equal weights assigned in the draft report, I recommend weighting the three data inputs to CMSA as per the 2019 stock assessment (0.59 Virginia Tech trawl, 0.16 Delaware adult trawl, 0.25 New Jersey ocean trawl) based on: (1) the technical rigor and deliberate design of the Virginia Tech trawl survey for the purpose of estimating crab abundance; (2) the high level of confidence that stakeholders have expressed in the Virginia Tech survey; (3) the previous support among many Delaware Bay Ecosystem Technical Committee members for weighting the Virginia Tech survey more heavily than the other surveys; and (4) the real-world consequences of a change in methodology that—had it been in place—would have changed harvest recommendations from 0 to 140,000 female crabs in 2 of the 4 recent years for which data are available. Regarding this last point about the resumption of female harvest, numerous concerns around risk and uncertainty are discussed in detail below.

11.3.3 Red Knot Utility Function

There is one other change proposed in the draft report to which I object and wish to express considerable concerns. Section 8 of the draft report describes a new red knot utility function that was developed for this update and that is proposed to guide harvest policy going forward. In a major break with the existing ARM framework, the proposed new utility function would allow for the immediate resumption of female crab harvest, potentially at levels approaching the maximum harvest limit. I have both procedural and substantive concerns with this proposed change, and respectfully request that this section of the report be reconsidered.

11.3.3.1 Procedural Concerns

As adopted by the ASMFC Horseshoe Crab Management Board, the existing ARM framework is underpinned by the concepts and principals of formalized adaptive management (ASMFC 2009a, p. iii). Adaptive management is a special case of structured decision making (SDM) for decisions that recur and for which uncertainty is an impediment.¹ In turn, SDM is a formal and transparent approach to decision making that incorporates views of all stakeholders and utilizes

¹ <https://nctc.fws.gov/courses/programs/decision-analysis/structured-decision-making-overview.html>

predictive modeling to assess the potential consequences of alternative actions (ASMFC 2009, p. 1). One of the key advances brought about by SDM in the arena of natural resource management is a great emphasis on complete elicitation of objectives and management actions from a full range of stakeholders (ASMFC 2009a, p. 1). Addendum VII, which formally adopted the ARM framework to guide harvest policy, states: *A goal of the ARM Framework is to transparently incorporate the views of stakeholders along with predictive modeling to assess the potential consequences of multiple, alternative management actions in the Delaware Bay Region* (ASMFC 2012, p. 2).

The SDM paradigm breaks the decision-making process into a number of discrete steps. As shown in Figure 2, an early step in SDM is developing explicit expressions of inherently value-laden objectives, reflecting individual, institutional, and societal preferences, weights, and risk attitudes. Accordingly, this step is typically undertaken with input from a broad group of stakeholders, helping to ensure stakeholder engagement in the process and ultimately stakeholder buy-in in the decision. Key to successful SDM is faithfully carrying forward and accurately interpreting those value-laden stakeholder inputs through the remaining steps of the process.

The draft report retains the original ARM Objective Statement, as recently updated to more explicitly reflect the red knot: *Manage harvest of horseshoe crabs in the Delaware Bay to maximize harvest but also to maintain ecosystem integrity, provide adequate stopover habitat for migrating shorebirds, and ensure that the abundance of horseshoe crabs is not limiting the red knot stopover population or slowing recovery*. However, the draft report proposes to replace the red knot utility function, which is the mechanism by which this Objective Statement is translated into harvest policy. It is the replacement of the utility function that is my key concern.

In short, my procedural concern is that the new utility function proposed in the draft report does not reflect the values and risk attitudes that were clearly expressed by the original group of stakeholders during initial setup of the existing ARM framework. The proposed new utility function substitutes very different values and risk attitudes under the umbrella of technical updates, outside of a forum for meaningful stakeholder input and absent any process to solicit updated stakeholder viewpoints. We, the ARM Subcommittee, have returned to the set-up phase (top box in Figure 1), but have failed to consult a broad array of stakeholders in the reinterpretation of previously agreed-upon objectives.

The existing utility function has recommended zero female crab harvest since 2013, and would likely continue doing so for at least the next few years.² In contrast, even using Virginia Tech

² Looking only at Virginia Tech data, crab abundance has ranged from 5.3 to 10.9 million females from 2016-2020 (Hallerman and Jiao, Table 6), and has never exceeded the current “female harvest threshold” of 11.2 million since surveys began in 2002. Thus, I surmise that the existing utility function would likely continue to recommend 0 female harvest for at least the next few years.

data rather than the higher CMSA abundance estimates, the proposed new utility function would have recommended harvest in the range of 125,000 to 172,000 females per year had it been in place between 2017 and 2021 (B. Nuse, *personal communication*, 2021). Adoption of the proposed new utility function would immediately allow for female harvest, possibly as soon as 2023, with a likely harvest recommendation in the range of 175,000 to 190,000 females³ per year (B. Nuse, *personal communication*, 2021). A precautionary, risk-averse approach to female crab harvest is a central tenet of the existing framework as expressed by the stakeholders during the initial development and adoption of the ARM (see Box 1). Such a major reinterpretation of this tenet as is represented by the proposed new utility function should not be pursued under the mantle of technical updates, but should instead involve the reconvening of a broad stakeholder group and a robust elicitation to update their views on risk tolerance with respect to female crab harvest.

The existing ARM framework does not value female crab harvest until either red knots or horseshoe crabs reach agreed-upon threshold population levels. These population thresholds act as a constraint on female harvest. Under the current framework there is no female crab harvest until female abundance reaches 11.2 million crabs OR until the Delaware Bay total red knot stopover population reaches 81,900 birds. These threshold values act as a constraint on female harvest, which was the express intent of the stakeholders. The draft report (p. 76) states: *...in contrast to the original ARM model, where red knot abundance acted as a constraint in the reward, here red knots are assigned a separate utility and their abundance contributes directly to the reward. The ARM workgroup felt that this way of accommodating red knot abundance – via direct contribution to the reward, rather than as constraint – better reflected the values reflected in the ARM project’s objective statement.* I strongly disagree with this conclusion on two bases. First, the formulation of these values as a constraint was an explicit and clear choice in the development of the existing framework. Second, the high risk-aversion to female crab harvest by the stakeholders is clear, and thus it can be presumed that the new utility function, which would immediately recommend female harvest—potentially at levels nearing the ultimate cap of 210,000 females per year—would be of considerable concern to those same stakeholders. Support for my conclusions comes from numerous statements in the original ARM document (ASMFC 2009a) and Addendum VII (ASMFC 2012), excerpted in Box 1.

It is useful to consider this 2009 statement as shown in Box 1: *The utility functions reflect the stakeholders risk tolerance to the possibility of red knot extinction and can be revised and updated to reflect shifting society values or new data in future iterations of the adaptive management paradigm.* If anything, society has subsequently declared even greater desire to avoid red knot extinction, and even lower risk tolerance, by listing this bird as threatened under the Endangered Species Act. The red knot and horseshoe crab thresholds for resuming female

³ This range of likely female harvest levels under the proposed new framework assumes that 2022 crab and knot abundance estimates will be similar to 2017-2021 levels and is based on the proposed (equally weighted) CMSA estimates of crab abundance. In addition to this expected range of female harvest, the new ARM framework would also continue to recommend male harvest at the maximum level of 500,000 per year (B. Nuse, *personal communication*, 2021), which has been the male harvest quota since 2013.

harvest were value judgements made by stakeholders through a formal SDM process. They should not be discarded under the umbrella of a package of technical updates. If the ARM Subcommittee wishes to discard them, we should reconvene an equivalent stakeholder group and revisit those value judgements. This conclusion is consistent with the process for the “Longer Term Cycle” (*i.e.*, the “outer loop” of the double-loop paradigm, in which we return to the top box in Figure 1). According to Addendum VII, these are the first two steps of the longer-term cycle (ASMFC 2012, p. 4):

- *Solicit formal stakeholder input on ARM Framework to be provided to the relevant technical committees.*
- *Technical committees review stakeholder input and technical components of ARM models and provide recommendations to the Board.*

In my view and interpretation, we, the ARM Subcommittee, are attempting to proceed with the second step but have failed to carry out the first step. I recommend that we return to the first step and fully vet the proposed new utility function, and its implications for female harvest, with a broad group of stakeholders before advancing the draft report to peer review.

11.3.3.2 Substantive Concerns

In my view, risk and uncertainty are both too high for the resumption of female crab harvest at this point in time. As discussed at length above, it was the considered and collective opinion of the stakeholders during ARM development that both red knot and horseshoe crab population levels and growth were too tenuous to risk female crab harvest. There may be some indicators of more recent increases in crab abundance; however, any such trends are associated with high uncertainty and any growth to date remains modest. Furthermore, best available information indicates that red knot populations remain unchanged since the time of ARM development. In 2020 and 2021, dramatic aberrations in the temporal and spatial patterns of red knot presence in Delaware Bay have raised new alarms about the long-term viability of this critical staging area. I offer the following points in support of a continued precautionary and risk-averse approach to female crab harvest.

1. The Southern wintering red knot population has remained between roughly 9,800 and 14,000 birds since 2011. This is about 75 percent lower than during the 1980s or early 2000s (USFWS 2020, p. 22; Matus 2021, entire). The Southern wintering population is a bellwether for the subspecies as a whole because these longest-distance migrants are the most vulnerable to threats throughout their annual cycle—threats that also affect the other three populations but to a lesser degree and/or later in time. The higher intrinsic vulnerability of the Southern wintering population stems from the greater energy demands and greater timing constraints associated with this longest-distance of the four migration strategies. Relative to the other three populations, the Southern wintering population is disproportionately reliant on the Delaware Bay staging area (USFWS 2021, pp. 13, 23).

2. A CMSA model prepared for the 2019 stock assessment found that adult crab abundance was stable from 2003 to 2012 and then rose considerably by 2017 (ASMFC 2019, p. 78). The draft report likewise presents CMSA outputs showing a recent increase in the estimates of adult crab numbers (p. 49). The most recent Virginia Tech trawl survey found that mature crabs in the coastal Delaware Bay area show increasing trends since 2002, but uncertainty is high (Hallerman and Jiao, 2021, pp. 6, 8); these authors make no claims of significance, they only note a general trend relative to the low point in the data series. Considering all data sets and methods, the stock assessment concluded that the Delaware Bay horseshoe crab population is in a neutral condition (ASMFC 2019, p. 83).
3. The 2020 stopover season was noteworthy because red knot numbers peaked during the earliest (rather than the latest) part of the stopover season (Lyons 2020, pp. 3, 7), a phenomenon that had not previously been documented since arrival/departure phenologies began being tracked in 2011. Aerial surveys conducted in May 2021 found only 6,880 red knots at the peak of the spring stopover season (Lyons 2021, p. 7), the lowest count since surveys began in 1981. For context, the 3-year average count from 2018 to 2020 was 27,736 birds, and the previous 1-year record low count was 12,375 birds in 2007 (Lyons 2021, p. 7; Service 2019, p. 31). Red knots in 2021 were also extremely concentrated in just a few of the Delaware Bay beaches, with birds essentially absent from many of the beaches where they would normally occur in a typical year (A.Dey, *personal communication*, 2021; H. Bellman, *personal communication*, 2021). Although the total red knot stopover population estimate for Delaware Bay held relatively steady over this period (Lyons 2021, p. 7), these two unprecedented years in a row do raise serious concerns about if/how/why this single most important staging area may be changing, and with what implications for the recovery of this subspecies.
4. A recent Species Status Assessment for the red knot summarized current information regarding the impacts of accelerating climate change on the red knots and the virtually certain continuation of these trends into the future. Key climate-related threats include sea level rise; ocean warming and acidification; numerous and rapid changes in the Arctic; and timing asynchronies in the knot's annual cycle (USFWS 2020, pp. 18, 32-40). The most recent international benchmark report continues to underscore the climate trajectories that are driving these threats to the red knot (IPCC 2021, entire).
5. Under all scenarios, significant climate-driven threats will continue to influence knot populations well into the future, and it is unknown if the rufa red knot's limited inherent adaptive capacity is sufficient for the subspecies to persist over the long term (Service 2020, entire). Therefore, the essential rufa red knot recovery strategy is to prevent erosion of its adaptive capacity by maintaining representation and improving resiliency and redundancy to support the rufa subspecies as it copes with inexorably changing conditions across its range and across its annual cycle. One key element of this strategy to maintain adaptive capacity is to protect, restore, maintain, and manage important

nonbreeding habitats. This includes monitoring and safeguarding ample food supplies (USFWS 2021, pp. 12-13).

6. I appreciate that a maximum harvest of 210,000 female crabs per year is considered a low level of removal from a population with recent estimates between 6.6 and 11.5 million female crabs (based on the equally weighted CMSA model; draft report Table 32). The draft report states that maximum harvest levels are expected to have little effect on long-run equilibrium abundances of horseshoe crabs, and that the horseshoe crab projection model is not especially sensitive to changes in harvest. For example, increasing harvest in the model from 0 to the maximum (210,000 females, 500,000 males) decreased the projected equilibrium crab abundance by only 5 to 6 percent (draft report pp. 78-79). However, if the bait harvest—through effects of slowing the rate of increase in crab abundance and/or lowering its eventual equilibrium point—has even a small effect of slowing red knot population growth, then it is contrary to the recently updated ARM Objective Statement and it runs counter to the strategy outlined in the recent draft Recovery Plan (USFWS 2021, pp. 12-13). Given uncertainty associated with some of the inputs, and the fact that the proposed modeling framework is new and untested, I question if model outputs will be sufficiently precise—and if the models will “learn” fast enough— to reliably predict and entirely avoid any risk of slowing knot population growth.
7. The new red knot projection model (IPM) found only a small effect of horseshoe crab abundance on red knot abundance (draft report p. 69). However, the IPM is brand new and untested. And the previous Multistate model that IPM is replacing, and upon which harvest recommendations were based since 2013, essentially malfunctioned during the recently attempted update and had to be abandoned. Given the high uncertainty and high stakes, reliance on the new IPM should be tentative and cautious, increasing gradually over time as the model demonstrates its stability, accuracy, and adaptability.
8. Based on the linked system of models in the proposed new ARM framework, equilibrium abundances for male and female horseshoe crabs and red knots are predicted to be high. However, red knot abundances in particular are very uncertain throughout the simulation time period (draft report p. 78). Revised Figures 54-59 reflect this high uncertainty in projected red knot population levels, and show considerable potential for the knot population to remain at or below its current level for at least the next 30 years, a scenario that is incompatible with recovery.
9. The CMSA-based horseshoe crab projection model is quite sensitive to changes in recruitment estimates (*i.e.*, annual expected numbers of new breeding adults). Expected recruitment is based on a relatively short time period, and it is possible that the current estimate is not very close to the true value (draft report p. 80). The draft report (p. 55) states that recruitment estimates are likely to become more robust over time. However, in the meantime, a risk-averse approach seems prudent given both high uncertainty and high sensitivity around this parameter in the new modeling framework.

10. Concerns have been raised about a potential spike in horseshoe crab harvest due to the COVID-19 pandemic (Wittenberg 2021). We do not yet know if the biomedical harvest recently increased in order to test COVID-19 vaccines, but at least some increase does seem likely. The revised ARM framework continues to apply a 15 percent mortality rate to bled crabs despite an acknowledged range of 4 to 30 percent (draft report p. 30) and sublethal effects that could potentially impact spawning behaviors or tendencies (Anderson et al. 2013, entire; Owings et al. 2019, entire). Biomedical harvesters preferentially target female crabs. Given high uncertainty around bleeding effects, and at least until the magnitude and duration of any COVID-related increase in biomedical harvest are known, a cautious approach to female bait harvest is sensible.

11.3.4 Conclusions and Recommendation

Procedurally, adoption of the proposed new utility function, and thus the immediate resumption of female crab harvest, runs counter to the basic SDM principals of stakeholder engagement and transparency, given the original stakeholders' clearly articulated views and values around female harvest. Substantively, many factors argue for a continued risk-averse approach to female crab harvest. Individually, and especially collectively, the 10 factors listed above lay out a situation of high uncertainty and high risk that make a strong case for continued caution.

Every year since 2013, the existing red knot utility function has concluded, based on expert and stakeholder input, that crab and knot populations were too low to safely resume female harvest. There has been no change in the knot population, modest and uncertain growth in the crab population, and two highly aberrant stopover seasons in a row. Yet the ARM Subcommittee is now proposing, without the benefit of updated stakeholder input, to discard the previous utility function and to replace it with one that concludes female harvest can be safely resumed. At the time of listing, the USFWS concluded that, as long as the ARM is in place and functioning as intended, ongoing horseshoe crab bait harvests should not be a threat to, or result in take of, the red knot (USFWS 2014, p. 247). Immediate resumption of female harvest by the means described in the draft report may prompt the USFWS to reconsider if the ARM is functioning as intended.

I recommend that the ARM Subcommittee consider one or both of these alternative paths forward.

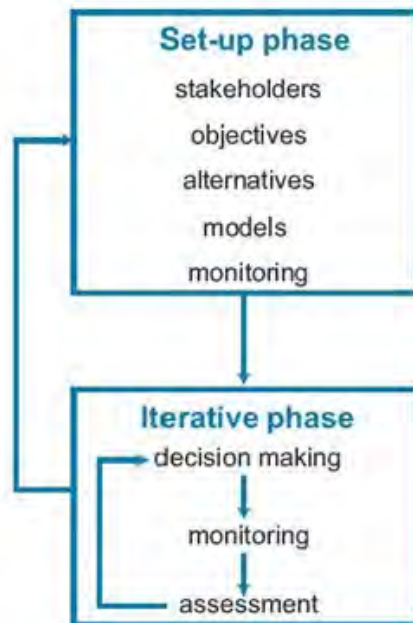
- Reconvene a broad and knowledgeable group of stakeholders to review, discuss, and weigh in on the proposed new utility function and corresponding resumption of female crab harvest.
AND/OR
- Evaluate technically sound mechanisms by which the previously agreed-upon crab and knot population thresholds can continue to act as a constraint on female harvest under the revised framework, in a manner that hews more closely to the original intent and

stated risk tolerances of the stakeholders as expressed during the initial development and adoption of the ARM.

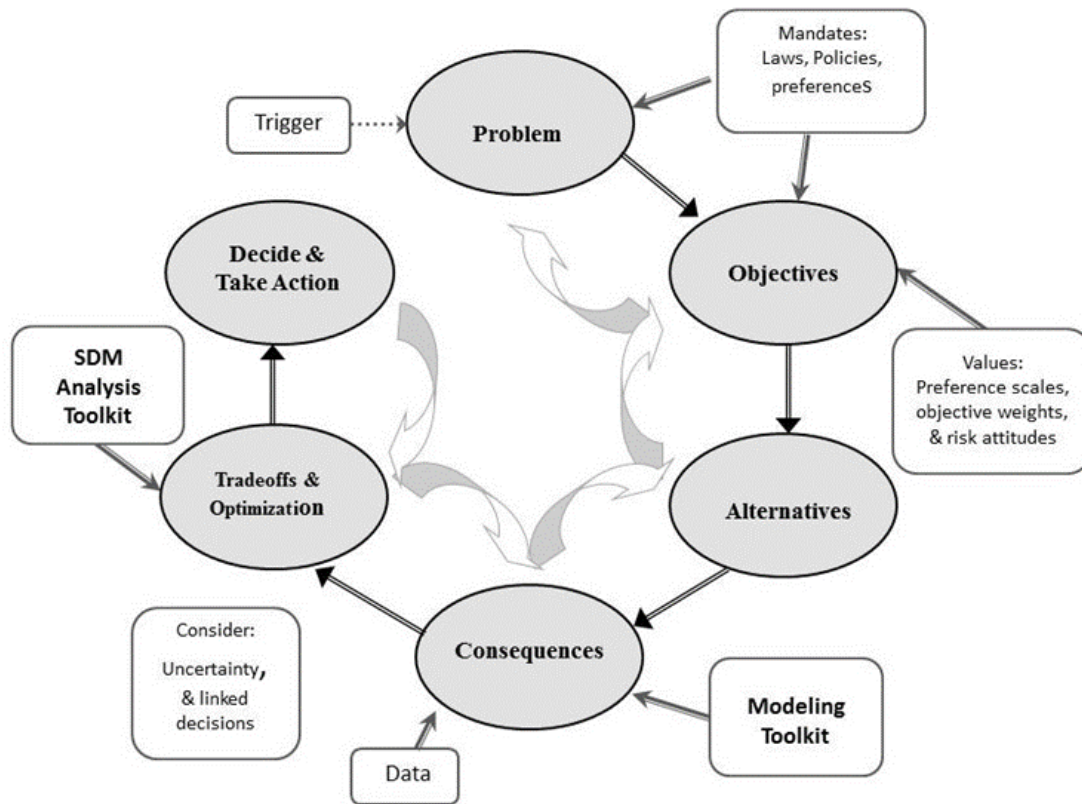
I also recommend that the ARM Subcommittee weight the three data inputs to CMSA as per the 2019 stock assessment (0.59 Virginia Tech trawl, 0.16 Delaware adult trawl, 0.25 New Jersey ocean trawl), rather than the equal weights assigned in the draft report. Such weighting is appropriate based on the intentional and robust design of the Virginia Tech survey, as well as the views of the stakeholders. This recommended weighting also supports a continued risk-averse approach to female harvest that remains a central imperative of prudent horseshoe crab management for the reasons given above.

My sincere thanks to the members of the Modeling Working Group and other expert advisors for the considerable work that has gone into the draft report. I generally concur with the draft report and appreciate its many technical innovations, updates, and upgrades, but with the important exceptions of weighting the CMSA data inputs, replacing the utility function, and resuming female harvest. With regard to these exceptions, I appreciate the time of the ARM Subcommittee in considering my concerns, objections, and recommendations as detailed above. I look forward to working cooperatively with the rest of the Subcommittee to seek consensus on a path forward that addresses my concerns while still advancing the draft report for consideration by the Delaware Bay Ecosystem Technical Committee.

11.3.5 Tables and Figures



Walsh Figure 1. Double-loop learning diagram of adaptive management (ASMFC 2009a, p. 41)



Walsh Figure 2. SDM conceptual diagram
<https://www.usgs.gov/centers/pwrc/science/structured-decision-making>

The objective statement and utility functions, which were developed through lengthy discussion with the Technical Committees, are the first step to identifying optimal horseshoe crab harvest policy. The utility functions specify the value placed on harvest as a function of the population sizes of both species. To achieve multi-species objectives, harvest of female horseshoe crabs is devalued when red knot and female horseshoe crab abundance are low ... The utility functions reflect the stakeholders risk tolerance to the possibility of red knot extinction and can be revised and updated to reflect shifting society values or new data in future iterations of the adaptive management paradigm (ASMFC 2009, p. iii).

Translating the qualitative [objective] statement into a quantitative objective statement framed in terms of the measurable state variables of interest is a fundamental challenge ... We developed a set of utility functions that define under what conditions horseshoe crab harvest is valued. The utility functions...reflect the stakeholders' risk tolerance/aversion to the possibility of red knot extinction due to horseshoe crab harvest regulations. The Technical Committees often preferred to invoke caution when determining management objective and set management thresholds with the intent of being conservative to account for our scientific uncertainty. The utility functions...can be adapted, as the adaptive management effort moves forward, to reflect changes in societal values or new data and information about the system (ASMFC 2009, p. 2).

The current objective statement is: Maximize harvest of horseshoe crabs in the Delaware Bay with constraints that 1) harvest of female crabs is valued only when red knots exceed an abundance threshold or female horseshoe crabs exceed an abundance threshold ... (ASMFC 2009, p. 3).

The harvest objective and utility functions are quantitative translations of the objective statement... The utility functions assign no value to female horseshoe crab harvest when red knot abundance is below [81,900] individuals, unless horseshoe crab numbers are sufficiently high that they are not likely to be limiting red knot numbers. ... Secondly, the utility function will assign value to female horseshoe crab harvest if abundance of female horseshoe crabs reaches 11.2 million individuals, regardless of red knot status. ... The specific values of these thresholds are the result of the collective judgment and extensive discussion of the Joint Technical Committees, the professional opinions of shorebird and horseshoe crab biologists, and the modeling expertise of the members of the ARM working group (ASMFC 2009, pp. 3-4).

While horseshoe crab abundance in the Delaware Bay Region continues rebuilding, the red knot (rufa subspecies), one of many shorebird species that feed on horseshoe crab eggs, is at low population levels. Red knots have shown no sign of recovery ... despite a nearly four-fold reduction in horseshoe crab landings since 1998 ... Technical advisors recommend continued precautionary management (ASFMC 2012, p.1)

Box 1. Excerpts from the foundational ARM documents related to the red knot utility function and to stakeholder input and risk tolerance around female harvest (emphasis added)

11.4 Majority Response to Walsh and Justification for Why Opinion Not Adopted

The minority opinion provided by Walsh was not adopted in this revision to the ARM Framework because the proposed changes are not consistent with updating the Framework using existing data or with the technical advice given to the workgroup regarding adaptive management or the CMSA by collaborators and previous peer reviewers. The task given to the workgroup was to revise the adaptive resource management framework, and the proposed use of the population thresholds by Walsh is more consistent with a simple harvest control rule. A static harvest control rule approach could be explored if the committees are interested, but it would not be adaptive management and would not require the Framework developed in this assessment. The minority opinion focuses on a proposed change to the survey weights in the CMSA, the red knot utility function, and the perceived lack of stakeholder input to the ARM Revision process. A response to each of those is provided below, along with responses to the enumerated list of substantive concerns.

11.4.1 CMSA Survey Weights

There is concurrence by Walsh with the use of the CMSA as the estimation method for horseshoe crab population size, and there is also concurrence on the move from the former stage-based projection model to a projection model following the dynamics of the CMSA. Where Walsh differs from the majority is with the weighting scheme for the surveys in the CMSA. Walsh bases her survey weight recommendation on the fact that the VA Tech Trawl Survey was designed specifically for monitoring the abundance of horseshoe crabs in the Delaware Bay region. She expressed concerns that the VA Tech estimates of abundance were lower than those from the CMSA estimates from 2016 through 2019 and quoted the 2019 assessment report where it stated that equal weighting of the surveys resulted in higher abundance estimates by allowing the model to more closely align with the increasing trends seen in the DE Adult Trawl and NJ Ocean Trawl surveys. However, the report also stated on page 79, “In reality, the VT swept area estimates are likely minimum estimates of abundance given: 1) the VA Tech Trawl gear efficiency is less than 100%; and 2) the VA Tech Survey spatial area may be a low estimate of Delaware Bay unit stock spatial area (excludes inside waters of Delaware Bay)” (ASMFC 2019). Differences in survey sampling and data inputs, both temporally (spring for DE and NJ surveys, fall for VA Tech) and spatially (DE survey through Delaware Bay; NJ survey beyond VA Tech survey bounds of 12 nm offshore and northern limit Atlantic City; VA Tech survey extending to MD and VA), may also argue for equal weighting of the surveys as they each contribute sampling inputs not shared by the others. As both DE and NJ trawl surveys have begun staging female horseshoe crabs for maturity, the utility of these surveys for future assessments will rise and more fully complement the VA Tech Survey.

During the 2019 benchmark assessment, survey weights (or lambda values) were based on results of a hierarchical analysis of adult female indices from the VA Tech Trawl, DE Adult Trawl, and NJ Ocean Trawl Surveys (Conn 2009). The Conn (2009) hierarchical analysis produced a composite index from multiple indices, whereby process error variances (σ^2) generated for each index could be used as an inverse measure of how well the index contributes to the composite

(Conn 2009). The inverse Conn variances (σ^p)⁻¹ for VT, DE, and NJ survey indices (4.3, 1.12, and 1.8, respectively) were scaled to sum to 1 (0.59, 0.16, 0.25) and used as survey weights in the base model of the CMSA. During the peer review workshop, the panel stated that it was “not clear whether uncertainties were double counted or that the product of the two types of inverse variance weights (one standardized the other not) is appropriate” (ASMFC 2019). However, it was noted in the 2019 assessment that equally weighting the surveys resulted in higher population estimates and that characterization by Walsh is accurate.

During the development of the ARM Revision, the ARM Subcommittee discussed survey weights at its data workshop and supported not using any weights so as to eliminate the possibility of double-weighting the survey inputs and to acknowledge the differences in the surveys discussed above. Only one member objected to this decision, but it was to the inclusion of the NJ Ocean Trawl Survey in its entirety and not the survey weights specifically, and a sensitivity run was done in this Revision to address that concern (Section 6.1.5). In that spirit, the workgroup did a sensitivity run with the 2019 benchmark survey weights but with the understanding that the previously used survey weights were based on the CVs of the surveys at that time and were only calculated for female horseshoe crabs (Walsh Response Table 1 and Table 2). If calculated in the same way as the 2019 benchmark, the weights would not be the same values as in the assessment or between sexes given additional years of survey data. Therefore, the use of the 2019 lambdas should be understood in the context of a sensitivity run and qualitatively represent the appropriate weightings of each survey based on committee consensus. If the committees support the use of survey weights, the weights should be determined in a different manner from the previous benchmark. The decision to not weight the surveys was based on previous ARM subcommittee discussions, but could be revisited if that would improve consensus on the proposed methods for peer review. Also, if the surveys were to be weighted in the CMSA, a new formulation of the horseshoe crab projection model would need to be developed because estimates of median primiparous crabs would change resulting in a different recruitment function for horseshoe crabs. Likewise, the IPM model results for red knots and subsequent projection model would change because input values of horseshoe crab abundance changed.

11.4.2 Red Knot Utility Function

It is true that if the previous ARM Framework remained in place in its entirety that it would likely continue to recommend zero female crab harvest. However, knowledge of both species has increased, the amount of data has increased, and the ARM Subcommittee’s expertise on adaptive management and optimization techniques has increased. To continue the use of the previous ARM Framework would be to ignore these technical advancements.

Projection of the CMSA shows an equilibrium population size (i.e., carrying capacity) in the absence of any anthropogenic mortality of 13.24 million females. Following the approach to set a utility threshold for the harvest of females horseshoe crabs in the previous ARM Framework (80% of carrying capacity), the updated utility threshold would now become 10.59 million females. Female harvest would have 0 utility below this knife-edge utility threshold and utility

would reach 1.0 above this threshold. Table 16 shows CMSA population estimates would have exceeded the new 10.59 million threshold in 2013, 2016, and 2017. Under the previous ARM Framework and its utility functions, this would have triggered the recommendation of harvest package 5 in these years (210,000 females and 420,000 males). Thus, the system is hovering near the threshold which would allow female harvest even under the tenets of the previous ARM Framework.

A major problem with the knife-edge utility functions in the previous ARM Framework was that they essentially operated as harvest control rules and resulted in “all or nothing” harvest management. Simulations of the previous version (McGowan et al. 2015) showed harvest packages 2 (250,000 male only) and 4 (140,000 females and 280,000 males) were very rarely selected. This is because the limits of harvest within all packages were sufficiently small to not cause a substantial decline in the abundance of horseshoe crabs. Thus, once an abundance threshold in the former utility functions was crossed, female harvest had value, and the optimal harvest strategy would be to immediately move to the maximum allowable harvest. Package 3 (500,000 male only) was selected when female abundance was <11.2 million crabs, and package 5 (210,000 females and 420,000 males) was selected when female abundance was >11.2 million crabs. Reinstating these knife-edge utility functions in this ARM Revision would have similar effects – harvest of males near the maximum allowable, and an immediate increase of female harvest from 0 to near maximum once the female utility threshold is crossed.

The previous reward function, with its knife-edge horseshoe crab utility functions and manipulation of horseshoe crab utility via constraints informed by red knot abundance, was deemed inappropriate by an adaptive decision modeling expert and ARM collaborator, Paul Fackler (NC State University, Center for Environmental and Resource Economic Policy), and the previous peer review panel. Fackler had several reasons for his objection to the previous reward function structure. It may have had unpredictable side effects on the overall optimization, preventing the dynamic programming algorithm from reaching an optimal solution to the problem as the ARM understood it. It also did not quite work as understood by stakeholders as a harvest control rule based on abundance of each species. Having decided that the old reward function was inappropriate on these technical grounds, the ARM model workgroup did its best to frame the reward function to reflect the ARM objectives and previously established stakeholder attitudes, in a manner that would allow the optimization to work as intended.

The ARM subcommittee admits that Walsh’s minority opinion highlights inadequate communication and detail on why the previous utility functions were abandoned in this ARM Revision. The majority hopes that this response clarifies why this was done from a technical and practical standpoint.

11.4.3 Procedural Concerns

Although it is true that the ARM subcommittee did not explicitly invite the public to participate in meetings, ASMFC meetings (even virtual ones) are open to the public and time is allotted for public comment. The ARM Subcommittee has diverse membership representing expertise and conservation concerns from both the fisheries and shorebird communities. Likewise, the formation of the DBETC was established to provide oversight to the ARM Subcommittee and represent the various stakeholder groups. Also, within the ASMFC management structure, stakeholders' voices are heard through the Advisory Panel and public comment periods should an addendum to the FMP be considered. Stakeholders in this process do not represent only those in red knot conservation, but also biomedical representatives, the fishing industry, members of the public, academics and researchers, and various interest and environmental groups that do not have uniform interests.

During the ARM Revision, a broader stakeholder group was not engaged the way it was for the original ARM (ASMFC 2009a) because many of the earlier decisions made by stakeholders were maintained. For example, the maximum harvest levels of male and female horseshoe crabs remains the same, 500,000 and 210,000, respectively. Additionally, male harvest is avoided if the spawning beach sex ratio limits population growth, horseshoe crab harvest is avoided at lower red knot and horseshoe crab population numbers, and the model links horseshoe crab and red knot abundances to recommend harvest. As for the utility functions, the original ARM (ASMFC 2009a: iii) says, "The utility functions reflect the stakeholders risk tolerance to the possibility of red knot extinction and can be revised and update(d) to reflect shifting society values or new data in future iterations of the adaptive management paradigm." The model workgroup found the changes to the utility function to be consistent with this statement since more data is now available and the understanding of how the threshold constraints were functioning in the original ARM Framework evolved to be inconsistent with adaptive management. This seemed in line with the intent of the process, similar to how the committees revised the objective statement during the Revision but did not solicit outside comment on it.

A feature of the revised ARM Framework is the ability of the Approximate Dynamic Programming routine to accommodate complex functions for assigning value to harvest. The workgroup adopted a simple function that returned a proportionally scaled utility value (0 – 1) for predicted red knot abundance between the limits of 0 birds (0 utility) and the threshold value of 81,900 birds (full utility). However, more complex functions that relate to red knot persistence or a quasi-extinction threshold could be envisioned. These may correspond to objectives contained in recovery plans or species status assessments. Because the optimization structure is directly linked to the predictive models, output quantities from long-term population viability projections such as red knot abundance, trend, or persistence probability could be translated into utilities for harvest.

However, in response to concerns on procedural grounds, the red knot utility function could revert back to the form that was proposed during the ARM Subcommittee review of the Revision in October, 2021. During the review, it was changed to be linear, but the originally proposed function replicates the original red knot utility function:

$$u_t^k = \begin{cases} 1, & \text{if } s_t^k \geq N_k^*, \\ \frac{s_t^k}{(1-p)N_k^*} - \frac{p}{1-p}, & \text{if } 0.9 \cdot N_k^* \geq s_t^k < N_k^*, \\ 0, & \text{if } s_t^k < 0.9 \cdot N_k^* \end{cases}$$

where utility is zero when red knot abundance s_t^k is below $p = 90\%$ of the threshold $N_k^* = 81,900$; as s_t^k moves from 90% to 100% of N_k^* , utility rises linearly from zero to one; at and above the threshold, utility is one. This utility function is consistent with the stakeholder preferences incorporated in the original ARM Framework because it maintains reference to the historical abundance of red knots. The same knife-edge utility function as the original ARM Framework was not used because this utility function was criticized in the peer-review of the original Framework. This suggested approach attempts to address the comments of the original peer review and maintain consistency with the stakeholder values incorporated in the original Framework. Because the utility function above is consistent with stakeholder preferences, there are no procedural grounds on which to object to the Revision.

[Following the DBETC Review of the ARM Revision, the committees agreed to revert back to the utility function above and that change is reflected in the body of the report.]

Finally, the majority is not opposed to greater stakeholder involvement, but argues that the modeling work done here should go to peer review. If the model passes peer review or improvements are made during that process, then the proposed new Framework would be taken out to stakeholder groups through a new management document. However, if Walsh is proposing that retaining the old form of the reward be an option during those deliberations, the majority strongly opposes that idea on technical grounds. Reverting to the former reward and utility functions does not take advantage of the increase in data collection and empirically derived models since the ARM Framework was originally developed and results in simple harvest control rules, which cannot be considered true adaptive management.

11.4.4 Responses to Numbered Items

The Walsh minority opinion listed 10 substantive concerns. The following are point-by-point responses to each of those:

1. As noted in the minority report, the Southern wintering red knot population has remained between roughly 9,800 and 14,000 birds since 2011. Thus, there is no clear trend in these population estimates over this time period. This period of relative stability in the Southern wintering population is consistent with the mark-resight superpopulation estimates, which also indicate a relatively stable stopover population at Delaware Bay since 2011.

Additionally, the decline is not necessarily related to horseshoe crab harvest, which is the current management tool. By asserting that the Southern population serves as a bellwether for the subspecies as a whole, Walsh points to the decline as justification for a precautionary approach to horseshoe crab harvest. Factors responsible for that

decline may or may not be operative in the other populations, and whether horseshoe crab harvest exacerbates those factors is unknown. However, as the report describes, the revised ARM Framework, compared to its predecessor, is far more amenable to the acquisition of new data that may ultimately enhance understanding of the relationship between harvest and bird abundance.

2. Multiple lines of evidence show that the Delaware Bay horseshoe crab population has increased (ASMFC 2019). Additionally, a simple linear Poisson regression fit to the VA Tech population estimates reveals a significant increase in mature females ($P < 0.01$). AICc model selection shows that the temporal trend model, with an increasing slope, is more supported than a null (i.e., intercept only) model with no temporal trend.

The 2019 benchmark stock assessment declared the Delaware Bay population to be in a “neutral” stock status based upon ARIMA modeling of fishery-independent surveys and the probability that the terminal year of each survey was less than a 1998 reference point when management for horseshoe crabs began. Stock status was based on the percentage of surveys within a region (or coastwide) having a >50% probability of their terminal year fitted value being less than the 1998 index-based reference point. “Poor” status was >66% of surveys meeting this criterion, “Good” status was <33% of surveys, and “Neutral” status was 34 – 65% of surveys. In Delaware Bay, 2 out of 5 surveys showed a terminal year having a >50% chance of being below the 1998 reference point, and thus a neutral stock status was assigned. However, four out of the five surveys considered had increasing trends over the last five years, and three out of the five had increasing trends over the last ten years. No survey showed a declining trend in recent times.

3. The annual stopover population estimates generated by Lyons 2021 represent the committee’s best estimates of red knots visiting the Delaware Bay each year and are used as input to the ARM Framework. Aerial counts have fluctuated greatly compared to stopover population estimates that have remained very stable through time. Aerial counts have a number of sources responsible for observation error including timing of flights with respect to true peak stopover, changing observers through time, and observer detection bias. The caveats of aerial counts as a population estimator are well documented in the literature (Conroy et al. 2008; Fleming and Tracey 2008; Laursen et al. 2008; Smith and Francis 2010). Additionally, the argument made does not indicate that horseshoe crabs were the limiting factor in the red knot estimates (see response to #1).
4. Arctic snow cover was included as a covariate in the IPM and remains within the ARM Revision if and when it is shown to affect red knot population dynamics and can be modeled into the future. The argument made by Walsh indicates that there are numerous other causes of red knot decline independent of horseshoe crabs and the proposed harvest levels.
5. Walsh cites uncertainty about the bird’s inherent adaptive capacity for response in the face of climate change as justification for a precautionary approach to harvest.

However, as new data are gathered and incorporated into the ARM Framework over time, which is facilitated by the ARM Revision, any signal that connects harvest to population persistence should emerge (see response to #1).

6. Walsh's reservations about whether the proposed model can adapt quickly enough to new data is more of a concern for the original than the revised ARM Framework. The attractive feature of the revised ARM Framework is that routine monitoring data can be used to quickly adjust model parameters and modify optimal horseshoe crab harvest recommendations. It is possible that these updates could take place on an annual basis. If it is found that additional horseshoe crab harvest were affecting red knots, this would be apparent in declining horseshoe crab population estimates and declining red knot survival estimates as a function of horseshoe crab abundance. Also, the ARM Revision better represents the uncertainty in the population dynamics of both species compared to the original ARM Framework. Importantly, the uncertainty is carried forward through the optimization.
7. An appropriate "test" of the new IPM will be provided by annual updating and adjustment. There is also no evidence that the multistate model provided better information than the IPM. In fact, the IPM may be better than the multistate approach since the IPM takes advantage of more data, not just more years of data. The IPM integrates count and mark recapture data to estimates parameters whereas the multistate model was only mark recapture.
8. Horseshoe crabs and red knot population projections are uncertain. This was the case under the original ARM Framework and will continue to be the case. Managers need to make decisions in the face of uncertainty. The role of science is to appropriately account for the uncertainty in the comparison of management options. In the ARM Revision, uncertainty in horseshoe crab and red knot dynamics is considered and accounted for in the ADP optimization. Adaptive management is well suited to exactly this kind of uncertainty. Portraying the uncertainty as somehow undermining the validity of the IPM and the ARM is inaccurate.
9. Horseshoe crab recruitment is a large source of uncertainty in the modeling and optimization. If the expected recruitment is an underestimate, horseshoe crab populations would be more robust than is currently thought and can withstand greater harvest without decline. If the expected recruitment is an overestimate, crab populations would decline even in the absence of any harvest. The effects of uncertainty on median horseshoe crab recruitment was examined by allowing it to vary by $\pm 5\%$ and $\pm 10\%$ (see Section 8.8.2). These sensitivity analyses generally showed more conservative optimal harvest for a given abundance of female horseshoe crabs as uncertainty increased. The ability of the ARM Revision model set to be updated with ongoing monitoring is key to decreasing this uncertainty and making adjustments in the models and management recommendations.

10. The CMSA accounts for biomedical mortality, unlike the original ARM, in order to address the Revision's TORs. Any potential increase in biomedical mortality will be incorporated into population estimates and harvest recommendations. The 15% bleeding mortality rate was reviewed and approved during the 2019 benchmark stock assessment. One of the TORs for the benchmark was to evaluate the sub-lethal effects of biomedical bleeding on horseshoe crabs. The assessment team considered Anderson et al. (2013) and Owings (2017), both of which were hard to assess against the actual biomedical industry since neither study adhered to the Best Practices established for the industry and had very small sample sizes. The assessment concluded that more work is needed to evaluate sub-lethal effects of the biomedical industry on the population, particularly studies using the methods of the industry.

11.4.5 Conclusions and Recommendations

Regarding the first alternative path forward, there is representation from a diversity of stakeholders on the ARM Subcommittee, DBETC, Advisory Panel, and public participating in this process from initiation to the completion of any follow-up management documents. The majority argues that the modeling work done here addresses the TORs and represents the available data, current knowledge of the species, and intentions of the original Framework. Therefore, it should go to peer review. If the Framework passes peer review, a new management document would be initiated that engages all stakeholders.

Regarding the second alternative, if the population thresholds were reinstated, it is very likely female horseshoe crab harvest would still occur because the population is near the 80% carrying capacity threshold now. Once this threshold is crossed, the management effects would be the same as under the previous ARM Framework in that harvest would increase from 0 to a very high number within a year. The advantage of the revised ARM Framework and new harvest policy functions is that lower female harvest is possible on a continuous scale. But, as stated in the response to Walsh's procedural concerns, the majority strongly opposes retaining the old form of the reward on technical grounds. If a static harvest control rule is what is desired and the amount of female harvest should be prescribed rather than determined through empirical modeling, a harvest control rule should be developed and an adaptive management framework is no longer needed.

11.4.6 Tables for Walsh Response

Walsh Response Table 1. Sensitivity runs for the catch multiple survey analysis model for female horseshoe crabs. All runs that included CONFIDENTIAL biomedical data have been removed.

Name	M	λ			Biomed	Discard Mortality			Starting Values				Terminal Output Values			
		VT	DE	NJ		Dredge	Trawl	Gill Nets	R	N	q_de	q_nj	NegLL	R	N	F
Modeling Base Run	0.3	1	1	1	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	87.9	2,247,290	7,533,500	0.006
M	0.274	1	1	1	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	86.5	2,204,475	7,834,127	0.006
Discard	0.3	1	1	1	Coastwide 15%	5%	5%	5%	14.1	15.5	-15.3	-14.3	87.9	2,247,210	7,533,130	0.006
Discard	0.3	1	1	1	Coastwide 15%	12%	12%	12%	14.1	15.5	-15.3	-14.3	88.1	2,251,259	7,511,908	0.007
Discard	0.3	1	1	1	Coastwide 15%	50%	50%	50%	14.1	15.5	-15.3	-14.3	89.3	2,278,436	7,385,285	0.015
No NJ OT	0.3	1	1	0	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	66.8	2,039,061	7,572,244	0.006
2019 Survey Weights	0.3	0.59	0.16	0.25	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	22.2	1,934,390	6,734,470	0.007
Biomed	0.3	1	1	1	0% mortality	5%	5%	12%	14.1	15.5	-15.3	-14.3	87.6	2,242,272	7,564,675	0.002
Real (DB) Base Run	0.3	1	1	1	Delaware Bay 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	Confidential			

Walsh Response Table 2. Sensitivity runs for the catch multiple survey analysis model for male horseshoe crabs. All runs that included CONFIDENTIAL biomedical data have been removed.

Name	M	λ			Biomed	Discard Mortality			Starting Values				Terminal Output Values			
		VT	DE	NJ		Dredge	Trawl	Gill Nets	R	N	q_de	q_nj	NegLL	R	N	F
Modeling Base Run	0.3	1	1	1	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	131.3	3,901,880	20,031,800	0.010
M	0.274	1	1	1	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	127.8	3,863,175	20,707,365	0.010
Discard	0.3	1	1	1	Coastwide 15%	5%	5%	5%	14.2	16.4	-15.8	-15.2	131.3	3,902,001	20,035,174	0.010
Discard	0.3	1	1	1	Coastwide 15%	12%	12%	12%	14.2	16.4	-15.8	-15.2	131.6	3,902,001	20,015,149	0.011
Discard	0.3	1	1	1	Coastwide 15%	50%	50%	50%	14.2	16.4	-15.8	-15.2	132.9	3,913,724	19,955,194	0.015
No NJ OT	0.3	1	1	0	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	105.7	3,741,511	20,957,350	0.009
2019 Survey Weights	0.3	0.59	0.16	0.25	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	35.0	3,532,410	17,504,300	0.011
Biomed	0.3	1	1	1	0% mortality	5%	5%	12%	14.2	16.4	-15.8	-15.2	130.8	3,898,101	20,055,219	0.008
Real (DB) Base Run	0.3	1	1	1	Delaware Bay 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	Confidential			

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13 TABLES

Table 1. Horseshoe crab commercial bait harvest in numbers for the Delaware Bay states, 1998-2019, validated by ACCSP.

Year	DE	MD	NJ	VA	Total
1998	479,634	114,458	241,456	252,845	1,088,393
1999	446,874	134,068	297,680	651,992	1,530,614
2000	39,524	152,275	398,629	128,377	718,805
2001	6,384	170,653	261,239	59,686	497,962
2002	298,318	278,211	281,134	42,578	900,241
2003	356,380	168,865	113,940	102,184	741,369
2004	99,135	161,928	46,569	95,064	402,696
2005	131,453	169,821	87,250	87,599	476,123
2006	116,845	136,733	3,444	180,468	437,490
2007	81,612	172,117	0	89,903	343,632
2008	102,113	163,495	0	68,338	333,946
2009	118,535	165,434	0	187,546	471,515
2010	62,519	161,545	0	146,857	370,921
2011	107,583	167,053	0	121,650	396,286
2012	102,322	169,087	0	151,887	423,296
2013	163,582	240,688	0	156,761	561,031
2014	168,044	148,269	0	145,266	461,579
2015	151,262	27,494	0	102,235	280,991
2016	109,836	157,013	0	128,848	395,697
2017	201,132	237,146	0	160,643	598,921
2018	126,065	66,647	0	145,355	338,067
2019	164,225	145,907	0	151,727	461,859

Table 2. Delaware Bay origin horseshoe crab commercial bait harvest in numbers for use in the CMSA. Horseshoe crab landings from New Jersey and Delaware are considered to be 100% Delaware Bay origin (i.e., has spawned at least once in Delaware Bay) whereas 45% of Maryland’s harvest and 20% of Virginia’s are believed to be Delaware Bay origin.

Year	Female	Male
2003	202,614	364,132
2004	92,855	144,729
2005	103,972	208,670
2006	83,295	134,617
2007	54,773	122,272
2008	35,838	153,516
2009	35,793	194,426
2010	30,362	134,223
2011	24,906	182,131
2012	40,745	168,034
2013	16,635	286,609
2014	7,663	256,155
2015	6,680	177,402
2016	8,527	197,734
2017	10,136	329,840
2018	10,096	175,031
2019	10,224	250,005

Table 3. Total number of horseshoe crabs that are estimated to die due to biomedical bleeding for 2003-2019 along the US Atlantic Coast. A sex ratio was used to split the total amount of crabs into male and female for use in the CMSA.

Year	Total	% Female	Males	Females
2003	43,484	0.47	23,028	20,456
2004	66,452	0.49	34,115	32,337
2005	54,774	0.42	31,889	22,885
2006	56,190	0.46	30,536	25,654
2007	74,937	0.39	45,468	29,469
2008	66,148	0.44	37,007	29,141
2009	64,235	0.46	34,948	29,287
2010	68,746	0.48	35,581	33,165
2011	97,166	0.43	55,412	41,754
2012	82,064	0.45	45,389	36,675
2013	71,507	0.45	39,285	32,222
2014	71,577	0.43	40,712	30,865
2015	77,607	0.44	43,710	33,897
2016	48,783	0.54	22,579	26,204
2017	72,674	0.41	43,039	29,635
2018	77,825	0.42	45,420	32,405
2019	118,413	0.60	47,169	71,244

Table 4. Gear categories in NEFOP and ACCSP used in the commercial discard analysis.
***** NOT CODED** represents trips in ACCSP that do not have a gear code. These data were further examined for the discard analysis to exclude trips that captured species unlikely to encounter horseshoe crabs or that operated outside the statistical areas used. The trips without coded gear were then split among the gears of interest (trawls, gill nets, dredges) in proportion to how they appear in the dataset.

Gear Category	NEFOP Gear	ACCSP Gear
Trawls	TRAWL,OTTER,BOTTOM,FISH TRAWL,OTTER,BOTTOM,SCALLOP TRAWL,OTTER,BOTTOM,TWIN	OTTER TRAWL BOTTOM, CRAB OTTER TRAWL BOTTOM, FISH OTTER TRAWL BOTTOM, OTHER OTTER TRAWL BOTTOM, PAIRED OTTER TRAWL BOTTOM, SCALLOP OTTER TRAWLS
Gill Nets	GILL NET, FIXED OR ANCHORED,SINK, OTHER/NK SPECIES GILL NET,DRIFT-SINK, FISH	GILL NETS GILL NETS, SINK ANCHOR GILL NETS, SINK DRIFT
Dredges	DREDGE, SCALLOP,SEA DREDGE, CLAM, HYDRAULIC DREDGE, OTHER/NK SPECIES DREDGE, CRAB	DREDGE DREDGE, CLAM DREDGE, HYDRAULIC, CLAM DREDGE, NEW BEDFORD DREDGE, OYSTER DREDGE, SCALLOP
Not Coded		NOT CODED ***

Table 5. Species targeted in NEFOP that represented all trips with captured and discarded horseshoe crabs. Species are listed in the order of the amount of horseshoe crabs discarded in pounds by most to least. The first ten bolded species represent trips with approximately 99% of all trips that discarded horseshoe crabs in NEFOP.

Trip Target
FLOUNDER, SUMMER (FLUKE)
CRAB, HORSESHOE
SCALLOP, SEA
MONKFISH (GOOSEFISH)
SQUID, ATL LONG-FIN
CLAM, SURF
CROAKER, ATLANTIC
FLOUNDER, WINTER (BLACKBACK)
SKATE, LITTLE
SKATE, NK
BASS, STRIPED
DOGFISH, SPINY
BUTTERFISH
SKATE, WINTER (BIG)
SEA BASS, BLACK
HAKE, SILVER (WHITING)
DOGFISH, SMOOTH
BLUEFISH
SCUP
CRAB, BLUE
TAUTOG (BLACKFISH)
QUAHOG, OCEAN (BLACK CLAM)
SPOT
FISH, NK
HAKE, RED (LING)
MENHADEN, ATLANTIC
FLOUNDER, NK
KINGFISH, SOUTHERN
WEAKFISH (SQUETEAGUE SEA TROUT)
GROUND FISH, NK
CLAM, NK
SQUID, SHORT-FIN
DRUM, BLACK

Table 6. The annual proportion of discarded horseshoe crabs estimated to be mature versus immature based on the biological sampling in the NEFOP database for 2012-2019. An average of those years was used for 2003-2011.

Year	Proportion Mature
2003	43%
2004	43%
2005	43%
2006	43%
2007	43%
2008	43%
2009	43%
2010	43%
2011	43%
2012	60%
2013	42%
2014	51%
2015	34%
2016	33%
2017	33%
2018	35%
2019	59%

Table 7. Estimated horseshoe crab dredge discards in weight (lbs) and numbers. To convert pounds (lbs) to numbers, a conversion of 1.5 pounds/crab was used.

Year	Ratio	Ratio CV	Discards (lbs)	Discards LCI	Discards UCI	n Fish Counted	Total Subsample Weight (lbs)	n Subsamples	Mean Weight (lbs)	Discards (numbers)
2004	0.00080	0.21	250,591	146,164	355,019	NA	NA	NA	NA	166,950
2005	0.00069	0.21	189,532	111,162	267,901	NA	NA	NA	NA	126,270
2006	0.00333	0.46	1,000,945	81,829	1,920,060	NA	NA	NA	NA	666,852
2007	0.00060	0.26	212,580	100,398	324,761	NA	NA	NA	NA	141,625
2008	0.00093	0.25	294,799	149,602	439,995	NA	NA	NA	NA	196,401
2009	0.00199	0.25	558,520	280,203	836,837	NA	NA	NA	NA	372,099
2010	0.00232	0.34	590,768	192,298	989,238	21	75	1	3.57	393,583
2011	0.00128	0.28	317,715	141,521	493,908	NA	NA	NA	NA	211,669
2012	0.00067	0.51	126,260	0	255,406	NA	NA	NA	NA	84,117
2013	0.00016	0.34	24,403	7,651	41,155	NA	NA	NA	NA	16,258
2014	0.00635	0.83	1,141,141	0	3,029,165	NA	NA	NA	NA	760,254
2015	0.00831	0.23	1,383,891	738,829	2,028,953	NA	NA	NA	NA	921,980
2016	0.04201	0.28	8,049,390	3,536,075	12,562,704	NA	NA	NA	NA	5,362,685
2017	0.02231	0.47	4,394,923	241,382	8,548,463	NA	NA	NA	NA	2,927,996
2018	0.00751	0.46	1,283,404	98,807	2,468,002	NA	NA	NA	NA	855,033
2019	0.01745	0.30	3,194,428	1,271,760	5,117,095	NA	NA	NA	NA	2,128,200

Table 8. Estimated horseshoe crab gill net discards in weight (lbs) and numbers. To convert pounds (lbs) to numbers, a conversion of 1.5 pounds/crab was used.

Year	Ratio	Ratio CV	Discards (lbs)	Discards LCI	Discards UCI	n Fish Counted	Total Subsample Weight (lbs)	n Subsamples	Mean Weight (lbs)	Discards (numbers)
2004	0.04378	0.39	379,360	80,657	678,062	NA	NA	NA	NA	252,738
2005	0.00383	0.30	39,484	16,005	62,963	1	4	1	4	26,305
2006	0.00250	0.39	21,070	4,786	37,355	NA	NA	NA	NA	14,038
2007	0.01485	0.38	210,517	48,972	372,061	NA	NA	NA	NA	140,251
2008	0.01161	0.39	123,136	28,070	218,202	NA	NA	NA	NA	82,036
2009	0.01534	0.49	186,607	2,777	370,437	NA	NA	NA	NA	124,322
2010	0.03400	0.21	330,667	189,883	471,452	NA	NA	NA	NA	220,298
2011	0.05530	0.29	596,092	248,696	943,487	NA	NA	NA	NA	397,130
2012	0.01197	0.30	112,009	44,224	179,794	NA	NA	NA	NA	74,623
2013	0.05793	0.39	548,466	121,718	975,214	NA	NA	NA	NA	365,400
2014	0.01253	0.46	197,240	17,325	377,155	NA	NA	NA	NA	131,406
2015	0.01072	0.25	119,830	59,646	180,015	NA	NA	NA	NA	79,834
2016	0.00372	0.17	25,441	16,998	33,884	NA	NA	NA	NA	16,949
2017	0.00427	0.24	28,880	15,079	42,681	NA	NA	NA	NA	19,241
2018	0.00459	0.28	30,391	13,546	47,236	NA	NA	NA	NA	20,247
2019	0.00274	0.25	17,682	8,792	26,572	NA	NA	NA	NA	11,780

Table 9. Estimated horseshoe crab trawl discards in weight (lbs) and numbers. Year-specific data were used to convert weight to numbers for 2012-2016. For the remaining years, data was pooled among all years of available data for the conversions.

Year	Ratio	Ratio CV	Discards (lbs)	Discards LCI	Discards UCI	n Fish Counted	Total Subsample Weight (lbs)	n Subsamples	Mean Weight (lbs)	Discards (numbers)
2004	0.00746	0.36	103	30	176	NA	NA	NA	NA	132
2005	0.01386	0.66	84,096	0	194,502	NA	NA	NA	NA	107,988
2006	0.00651	0.52	1,383	0	2,822	NA	NA	NA	NA	1,776
2007	0.06592	0.36	72,093	19,780	124,406	NA	NA	NA	NA	92,575
2008	0.04477	0.34	27,537	8,909	46,166	NA	NA	NA	NA	35,361
2009	0.03535	0.43	23,658	3,487	43,830	735	249	4	0.34	30,380
2010	0.02289	0.55	16,546	0	34,623	NA	NA	NA	NA	21,247
2011	0.06382	0.31	43,332	16,742	69,922	NA	NA	NA	NA	55,643
2012	0.02619	0.47	18,700	1,274	36,126	1,751	1,935	14	1.11	24,013
2013	0.04015	0.39	40,351	8,796	71,907	2,791	1,710	13	0.61	51,815
2014	0.01777	0.37	4,312	1,129	7,495	488	360	6	0.74	5,537
2015	0.07430	0.46	141,012	12,577	269,447	3,641	2,638	33	0.72	181,075
2016	0.06954	0.32	87,367	31,694	143,040	1,739	1,864	27	1.07	112,189
2017	0.05051	0.23	429,568	232,314	626,821	1,711	1,027	22	0.60	551,611
2018	0.01217	0.37	18,219	4,813	31,626	305	288	3	0.94	23,395
2019	0.02408	0.28	478	214	741	926	810	12	0.87	613

Table 10. Number of dead discards by sex for use in the CMSA model. A sex ratio, mortality rate by gear, and proportion mature was applied to total discards to determine total dead horseshoe crabs.

Year	Male	Female
2003	9,117	6,567
2004	13,265	9,554
2005	4,209	3,031
2006	12,028	8,664
2007	9,024	6,500
2008	7,059	5,084
2009	11,767	8,475
2010	16,004	11,527
2011	20,468	14,742
2012	6,488	4,673
2013	15,179	10,933
2014	21,919	15,787
2015	16,096	11,593
2016	70,904	51,069
2017	43,451	31,295
2018	12,752	9,184
2019	50,177	36,140

Table 11. Sex ratios of male to female horseshoe crabs 1999-2019 (source: The 2019 Delaware Bay Horseshoe Crab Spawning Survey).

Year	Sex Ratio (M:F)
1999	3.72
2000	3.67
2001	3.38
2002	3.48
2003	3.61
2004	3.85
2005	3.89
2006	4.53
2007	4.90
2008	4.90
2009	5.04
2010	4.25
2011	5.36
2012	4.41
2013	3.74
2014	4.38
2015	4.47
2016	4.54
2017	5.15
2018	5.54
2019	5.38

Table 12. Stopover (passage) population estimate using mark-resight methods compared to peak-count index using aerial- or ground-survey methods. The mark-resight estimate of stopover (passage) population accounts for population turnover during migration; peak-count index, a single count on a single day, does not account for turnover.

Year	Stopover population ^a (mark-resight N^*)	95% CI Stopover population N^*	Peak-count index [aerial (A) or ground (G)]
2011	43,570	(40,880 – 46,570)	12,804 (A) ^b
2012	44,100	(41,860 – 46,790)	25,458 (G) ^c
2013	48,955	(39,119 – 63,130)	25,596 (A) ^d
2014	44,010	(41,900 – 46,310)	24,980 (A) ^c
2015	60,727	(55,568 – 68,732)	24,890 (A) ^c
2016	47,254	(44,873 – 50,574)	21,128 (A) ^b
2017	49,405 ^e	(46,368 – 53,109)	17,969 (A) ^f
2018	45,221	(42,568 – 49,508)	32,930 (A) ^b
2019	45,133	(42,269 – 48,393)	30,880 (A) ^g
2020	40,444	(33,627 – 49,966)	19,397 (G) ^c

^a passage population estimate for entire season, including population turnover

^b 23 May

^c 24 May

^d 28 May

^e Data management procedures to reduce bias from recording errors in the field; data from observers with greater than average misread rate were not included in the analysis

^f 26 May

^g 22 May

Table 13. Catch multiple survey analysis base model inputs for female horseshoe crabs. Biomedical numbers represent coastwide mortality, not Delaware Bay-specific. Values shown for the Virginia Tech (VT) survey's swept area estimations for primiparous (*R*) and multiparous (*N*) are in millions of horseshoe crabs.

Year	Removals				Indices				CVs			
	Bait	Discard	Biomedical	Total	VT, <i>R</i>	VT, <i>N</i>	DE Adult	NJ OT	VT, <i>R</i>	VT, <i>N</i>	DE	NJ
2003	202,614	6,567	20,456	229,637	1.537	4.959	1.605	2.246	0.26	0.30	0.49	0.19
2004	92,855	9,554	32,337	134,747	0.794	3.379	0.028	2.502	0.49	0.25	1.00	0.23
2005	103,972	3,031	22,885	129,888	0.358	2.735	0.028	2.770	0.29	0.23	1.00	0.24
2006	83,295	8,664	25,654	117,613	0.479	3.138	1.526	1.856	0.27	0.27	0.36	0.26
2007	54,773	6,500	29,469	90,742	2.051	6.611	1.612	1.474	0.31	0.42	0.31	0.25
2008	35,838	5,084	29,141	70,063	2.373	7.746	0.221	2.370	0.40	0.31	0.40	0.32
2009	35,793	8,475	29,287	73,555	2.571	6.311	0.377	1.368	0.43	0.29	0.34	0.29
2010	30,362	11,527	33,165	75,055	0.885	2.975	0.223	0.579	0.26	0.32	0.55	0.30
2011	24,906	14,742	41,754	81,403	1.338	5.178	0.318	2.215	0.59	0.23	0.41	0.26
2012	40,745	4,673	36,675	82,093	0.845	5.290	0.304	1.804	0.30	0.18	0.31	0.25
2013	16,635	10,933	32,222	59,790			0.028	7.996			1.00	0.35
2014	7,663	15,787	30,865	54,315			1.518	3.358			0.27	0.24
2015	6,680	11,593	33,897	52,169			0.772	3.145			0.29	0.25
2016	8,527	51,069	26,204	85,800			1.442	3.989			0.21	0.24
2017	10,136	31,295	29,635	71,066	1.608	6.024	2.363	5.613	0.23	0.21	0.22	0.25
2018	10,096	9,184	32,405	51,686	1.480	7.185	3.868	3.118	0.26	0.23	0.25	0.23
2019					1.773	7.326	3.247	6.966	0.31	0.21	0.35	0.40

<i>M</i>	Starting Values				
	<i>R</i>	<i>N</i>	<i>q</i> _{DE}	<i>q</i> _{NJ}	<i>s</i>
0.3	1.4E+06	5.3E+06	2.2E-07	5.9E-07	1

Table 14. Catch multiple survey analysis base model inputs for male horseshoe crabs. Biomedical numbers represent coastwide mortality, not Delaware Bay-specific. Values shown for the Virginia Tech (VT) survey's swept area estimations for primiparous (*R*) and multiparous (*N*) are in millions of horseshoe crabs.

Year	Removals				Indices				CVs			
	Bait	Discard	Biomedical	Total	VT, <i>R</i>	VT, <i>N</i>	DE Adult	NJ OT	VT, <i>R</i>	VT, <i>N</i>	DE	NJ
2003	364,132	9,117	23,028	396,277	0.548	11.584	1.186	2.647	0.28	0.24	0.58	0.22
2004	144,729	13,265	34,115	192,109	0.078	8.069	0.000	2.077	0.84	0.29	1.00	0.25
2005	208,670	4,209	31,889	244,768	0.789	5.150	0.000	3.260	0.21	0.25	1.00	0.28
2006	134,617	12,028	30,536	177,181	0.597	5.844	0.758	1.783	0.33	0.22	0.43	0.27
2007	122,272	9,024	45,468	176,764	3.113	15.825	2.430	1.016	0.31	0.27	0.43	0.26
2008	153,516	7,059	37,007	197,581	3.129	15.795	0.247	2.319	0.28	0.28	0.42	0.34
2009	194,426	11,767	34,948	241,141	0.757	14.647	0.387	1.421	0.31	0.33	0.25	0.30
2010	134,223	16,004	35,581	185,809	0.725	6.240	0.595	0.684	0.34	0.30	0.32	0.31
2011	182,131	20,468	55,412	258,011	1.422	13.963	0.703	1.726	0.55	0.28	0.29	0.25
2012	168,034	6,488	45,389	219,911	0.749	15.060	0.304	2.069	0.36	0.40	0.28	0.30
2013	286,609	15,179	39,285	341,073			0.138	8.248			0.50	0.39
2014	256,155	21,919	40,712	318,786			2.644	3.610			0.33	0.27
2015	177,402	16,096	43,710	237,207			1.289	3.205			0.32	0.29
2016	197,734	70,904	22,579	291,218			1.614	5.041			0.28	0.31
2017	329,840	43,451	43,039	416,330	2.608	21.941	3.873	7.183	0.42	0.29	0.28	0.29
2018	175,031	12,752	45,420	233,203	1.523	20.664	7.961	4.564	0.28	0.25	0.30	0.28
2019					3.341	15.749	5.370	7.683	0.29	0.18	0.36	0.48

<i>M</i>	Starting Values				
	<i>R</i>	<i>N</i>	<i>q</i> _{DE}	<i>q</i> _{NJ}	<i>s</i>
0.3	1.5E+06	1.3E+07	1.3E-07	2.6E-07	1

Table 15. The number of parameters estimated in the catch multiple survey analysis: median primiparous abundance (1); primiparous abundance for each year (16); catchability coefficients (2) for the Delaware and New Jersey surveys; and multiparous abundance for the start of the time series (1).

Parameter	No. Estimates	Description
R_{median}	1	Median primiparous abundance (log-scale)
Φ	17	Deviations from median primiparous abundance (log-scale)
N_0	1	Initial multiparous abundance (log-scale)
q_{de}	1	Catchability coefficient for the Delaware trawl survey (log-scale)
q_{nj}	1	Catchability coefficient for the New Jersey survey (log-scale)

Table 16. Catch multiple survey analysis female horseshoe crab model outputs: q =catchability coefficients; R =primiparous abundance; N =multiparous abundance; μ =exploitation rate; Z = instantaneous total mortality rate; A =annual mortality rate; and F =instantaneous fishing mortality rate.

Year	R	N	$R+N$	μ	Z	A	F
2003	1,544,840	5,070,510	6,615,350	0.035	0.341	0.289	0.041
2004	1,177,750	4,703,120	5,880,870	0.023	0.327	0.279	0.027
2005	413,385	4,240,680	4,654,065	0.028	0.333	0.283	0.033
2006	579,474	3,336,020	3,915,494	0.030	0.336	0.285	0.035
2007	2,334,590	2,799,440	5,134,030	0.018	0.321	0.274	0.021
2008	1,430,330	3,725,280	5,155,610	0.014	0.316	0.271	0.016
2009	1,249,240	3,759,070	5,008,310	0.015	0.317	0.272	0.017
2010	832,049	3,646,940	4,478,989	0.017	0.320	0.274	0.020
2011	1,834,400	3,253,520	5,087,920	0.016	0.319	0.273	0.019
2012	761,074	3,699,160	4,460,234	0.018	0.322	0.275	0.022
2013	9,366,720	3,233,560	12,600,280	0.005	0.306	0.263	0.006
2014	162,355	9,283,060	9,445,415	0.006	0.307	0.264	0.007
2015	3	6,950,580	6,950,583	0.008	0.309	0.266	0.009
2016	7,837,230	5,104,220	12,941,450	0.007	0.308	0.265	0.008
2017	2,004,180	9,513,410	11,517,590	0.006	0.307	0.265	0.007
2018	1,757,930	8,471,280	10,229,210	0.005	0.306	0.264	0.006
2019	2,247,290	7,533,500	9,780,790				
Average	2,090,167	5,195,491	7,285,658	0.016	0.318	0.273	0.018

q_{DE}	1.44E-07
q_{NJ}	3.81E-07

Table 17. Catch multiple survey analysis male horseshoe crab model outputs:
 q =catchability coefficients; **R** =primiparous abundance; **N** =multiparous abundance;
 μ =exploitation rate; **Z** = instantaneous total mortality rate; **A** =annual mortality rate; and
 F =instantaneous fishing mortality rate.

Year	R	N	$R+N$	μ	Z	A	F
2003	554,656	14,640,000	15,194,656	0.026	0.331	0.282	0.031
2004	81,794	10,915,400	10,997,194	0.017	0.320	0.274	0.020
2005	879,707	7,981,570	8,861,277	0.028	0.333	0.283	0.032
2006	841,100	6,353,920	7,195,020	0.025	0.329	0.280	0.029
2007	4,949,330	5,177,700	10,127,030	0.017	0.320	0.274	0.020
2008	3,433,970	7,350,140	10,784,110	0.018	0.322	0.275	0.021
2009	778,775	7,819,010	8,597,785	0.028	0.333	0.283	0.033
2010	870,926	6,161,840	7,032,766	0.026	0.331	0.282	0.031
2011	3,644,500	5,050,080	8,694,580	0.030	0.335	0.285	0.035
2012	739,524	6,219,030	6,958,554	0.032	0.337	0.286	0.037
2013	8,581,000	4,965,740	13,546,740	0.025	0.330	0.281	0.030
2014	14,922,600	9,742,110	24,664,710	0.013	0.315	0.270	0.015
2015	29	17,997,700	17,997,729	0.013	0.315	0.271	0.015
2016	29,623,200	13,128,900	42,752,100	0.007	0.308	0.265	0.008
2017	3,707,470	31,420,800	35,128,270	0.012	0.314	0.269	0.014
2018	1,645,680	25,665,300	27,310,980	0.009	0.310	0.267	0.010
2019	3,901,880	20,031,800	23,933,680				
Average	4,656,244	11,801,238	16,457,481	0.020	0.324	0.277	0.024

q_{DE}	6.97E-08
q_{NJ}	1.89E-07

Table 18. Sensitivity runs for the catch multiple survey analysis model for female horseshoe crabs. All runs that included CONFIDENTIAL biomedical data have been removed.

Name	M	λ			Biomed	Discard Mortality			Starting Values				Terminal Output Values			
		VT	DE	NJ		Dredge	Trawl	Gill Nets	R	N	q_de	q_nj	NegLL	R	N	F
Modeling Base Run	0.3	1	1	1	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	87.9	2,247,290	7,533,500	0.006
M	0.274	1	1	1	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	86.5	2,204,475	7,834,127	0.006
Discard	0.3	1	1	1	Coastwide 15%	5%	5%	5%	14.1	15.5	-15.3	-14.3	87.9	2,247,210	7,533,130	0.006
Discard	0.3	1	1	1	Coastwide 15%	12%	12%	12%	14.1	15.5	-15.3	-14.3	88.1	2,251,259	7,511,908	0.007
Discard	0.3	1	1	1	Coastwide 15%	50%	50%	50%	14.1	15.5	-15.3	-14.3	89.3	2,278,436	7,385,285	0.015
No NJ OT	0.3	1	1	0	Coastwide 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	66.8	2,039,061	7,572,244	0.006
Biomed	0.3	1	1	1	0% mortality	5%	5%	12%	14.1	15.5	-15.3	-14.3	87.6	2,242,272	7,564,675	0.002
Real (DB) Base Run	0.3	1	1	1	Delaware Bay 15%	5%	5%	12%	14.1	15.5	-15.3	-14.3	Confidential			

Table 19. Sensitivity runs for the catch multiple survey analysis model for male horseshoe crabs. All runs that included CONFIDENTIAL biomedical data have been removed.

Name	M	λ			Biomed	Discard Mortality			Starting Values				Terminal Output Values			
		VT	DE	NJ		Dredge	Trawl	Gill Nets	R	N	q_de	q_nj	NegLL	R	N	F
Modeling Base Run	0.3	1	1	1	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	131.3	3,901,880	20,031,800	0.010
M	0.274	1	1	1	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	127.8	3,863,175	20,707,365	0.010
Discard	0.3	1	1	1	Coastwide 15%	5%	5%	5%	14.2	16.4	-15.8	-15.2	131.3	3,902,001	20,035,174	0.010
Discard	0.3	1	1	1	Coastwide 15%	12%	12%	12%	14.2	16.4	-15.8	-15.2	131.6	3,902,001	20,015,149	0.011
Discard	0.3	1	1	1	Coastwide 15%	50%	50%	50%	14.2	16.4	-15.8	-15.2	132.9	3,913,724	19,955,194	0.015
No NJ OT	0.3	1	1	0	Coastwide 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	105.7	3,741,511	20,957,350	0.009
Biomed	0.3	1	1	1	0% mortality	5%	5%	12%	14.2	16.4	-15.8	-15.2	130.8	3,898,101	20,055,219	0.008
Real (DB) Base Run	0.3	1	1	1	Delaware Bay 15%	5%	5%	12%	14.2	16.4	-15.8	-15.2	Confidential			

Table 20. Parameter values used in the revised horseshoe crab population projection model. The 'Equation(s)' column gives the equation number(s) where the parameter appears, within the present report section (6.2). Table continues on next page.

Symbol	Description	Value	Equation(s)	Notes
z	Timing of harvest	0.7	1,2	The annual cycle in the HSC projection model begins in October; z indicates the midpoint of bait harvest, which occurs in June.
μ^M	Mean instantaneous natural mortality (M)	0.3	3	Same value for females and males.
σ^M	Standard deviation of instantaneous natural mortality (M)	0.0182799	3	Same value for females and males.
L_{bg}^f	Minimum background harvest of females	41,589	4	This value will change, when using biomedical mortality estimates specific to Delaware Bay.
U_{bg}^f	Maximum background harvest of females	77,273	4	This value will change, when using biomedical mortality estimates specific to Delaware Bay.
L_{bg}^m	Minimum background harvest of males	58,171	5	This value will change, when using biomedical mortality estimates specific to Delaware Bay.
U_{bg}^m	Maximum background harvest of males	93,483	5	This value will change, when using biomedical mortality estimates specific to Delaware Bay.
μ^f	Female component of the mean vector used in the bivariate normal that annually generates the logarithm of primiparous HSCs	14.9493	6	
μ^m	Male component of the mean vector used in the bivariate normal distribution that annually generates the logarithm of primiparous HSCs	15.7447	6	

Table	Continued			
Symbol	Description	Value	Equation(s)	Notes
σ^f	Female standard deviation used in the bivariate normal distribution that annually generates the logarithm of primiparous HSCs	0.4909	6,7	
σ^m	Male standard deviation used in the bivariate normal distribution that annually generates the logarithm of primiparous HSCs	0.8837	6,7	
ρ	Correlation used in the bivariate normal distribution that annually generates the logarithm of primiparous HSCs	0.6871	6,7	
N^*	Threshold in the 'broken-stick' function that determines whether recruitment is depressed in year t	3.75×10^6	10	

Table 21. Model selection results from an analysis of multistate open robust design models of annual survival and body mass dynamics of red knots at Delaware Bay. Models 1–3 are the three most supported models from the candidate model set. Parameters of each model are annual survival of red knots and mass state transition probabilities: from light to heavy (ψ^{LH}) and from heavy to light (ψ^{HL}). Annual survival in these models was a function of mass state (“state”) and year (additive main effects). Transitions between mass states were a function of horseshoe crab abundance as estimated with a Catch Multiple Survey Model (“HSC”), the proportion of the population that spawned in May (“% May”) and the stopover period (“period”) in additive and interaction effects.

Mass state transition							
Model	Survival	ψ^{LH}	ψ^{HL}	K	$\log \mathcal{L}$	AIC	ΔAIC
1	state + year	HSC × % May × period	HSC × % May × period	201	-76927.3	154256.6	0.0
2	state + year	HSC + % May × period	HSC + % May × period	197	-76971.8	154337.5	80.9
3	state + year	HSC × % May × period	period	189	-77007.4	154392.8	136.2

Table 22. Parameter estimates from Model 1 (Table 21) to evaluate mass gain of red knots at Delaware Bay, i.e., transitions from the light to heavy mass state (ψ^{LH}) in a multistate open robust design model. The transition probability ψ^{LH} was modeled as a function of horseshoe crab abundance (“HSC”) and proportion spawning in May (“% May”) and their interaction. Transitions 1 and 2 occur between the stopover (secondary) periods of the robust design.

95% Confidence Limits					
Transition	Parameter	Estimate	SE	Lower	Upper
1	Intercept	-4.38	0.37	-5.10	-3.65
	% May	2.21	0.31	1.59	2.82
	HSC	1.46	0.23	1.01	1.91
	% May × HSC	-1.61	0.19	-1.99	-1.23
2	Intercept	-2.19	0.13	-2.45	-1.92
	% May	-0.35	0.07	-0.50	-0.21
	HSC	-0.81	0.14	-1.08	-0.54
	% May × HSC	-0.09	0.06	-0.21	0.03

Table 23. Model parameter notation and definitions. Years was denoted with j , which are the primary sampling occasions, and t was used to denote the secondary 3-day sampling periods within each year.

Notation	Definition
ϕ_y	Adult apparent annual survival probability – the probability that an adult bird that is alive in year y will survive until year $y+1$
ρ_y	Recruitment– the per capita number of new recruits entering the population in year $y+2$
τ_y	Transience probability—the probability that an individual will remain at the stopover site for more than one secondary sampling period in year y
γ_y^{II}	Temporary emigration probability—the probability that an individual that is alive and present in year $y-1$ will stop in Delaware Bay in year y given that it has survived
γ_y^{OI}	Temporary emigration probability—the probability that an individual that is alive in year y and not present in year $y-1$ will stop in Delaware Bay in year y given that it has survived
p_y^*	Primary period detection probability – the probability that an individual alive and present at the site in year y is detected at least once
$\psi_{y,t}$	Stopover persistence probability—the probability that an individual present in secondary sampling period t will remain in the study area until secondary period $t+1$
$\delta_{y,t}$	Entry probability—the probability that an individual that has not yet entered the stopover site will enter in time t
$p_{y,t}$	Secondary period detection probability—the probability that an individual present in period t of year y is detected
λ_y	Population growth rate – the proportional change in population size from year y to year $y+1$
$\pi_{y,t}$	Proportion of the flyway population present in the study area in period t of year y
$\omega_{y,t}$	Availability probability – the probability that a bird that is present in Delaware Bay during the aerial count in year y is available on a beach included in the survey to be counted
σ^{obs}	Count observation error – counts are assumed to be Normally distributed around the true number of birds present, which allows for both undercounting and overcounting

Table 24. Prior distributions for all IPM parameters.

Parameter	Model notation	Prior Distribution
Regression coefficients	$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$	$Normal(0, 0.37)$
Initial population size (log scale)	$\log(N_1)$	$Normal(10.5, 0.01)$
Recruitment rate intercept	μ^ρ	$Unif(0, 0.5)$
Recruitment rate random annual variance	σ^ρ	$Unif(0, 5)$
Observation error	σ^{obs}	$Unif(0, 1)$
Availability probability, 2005-2008	$\omega_{2005-2008}$	$Beta(4, 3)$
Availability probability, 2009-2016	$\omega_{2009-2016}$	$Beta(6, 2)$
Availability probability, 2017-2018	$\omega_{2017-2018}$	1
Survival probability intercept	μ^ϕ	$Beta(3, 3)$
Survival probability random annual variance	σ^ϕ	$Unif(0, 5)$
Temporary emigration 1	γ^{II}	$Beta(8, 2)$
Temporary emigration 2	γ^{OI}	$Beta(1, 9)$
Stopover residency	τ	$Beta(6.5, 3.5)$
Resighting probability intercept	μ^p	$Beta(3, 3)$
Resighting probability random variance	σ^p	$Unif(0, 10)$
Effect of dark green flag color on resighting probability	β_G	$Normal(0, 0.01)$
Arrival probabilities	$\delta_{j,1:t}$	$Dirichlet(1, 1, 2, 3, 3, 2, 1, 1, 1)$
Persistence probability	ψ_{jt}	$Beta(1, 1)$

Table 25. Estimates of average survival (ϕ), recruitment (ρ), and population growth rate (λ) for red knot from 2005-2018. Average survival probability and recruitment rate were calculated using the average horseshoe crab abundance. The average population growth rate was calculated using the geometric mean of year-specific estimates for each MCMC iteration. 95% CRI (credible intervals) are the upper and lower bounds that contain 95% of the posterior distribution.

Parameter	Mean	95% CRI
Annual apparent survival probability (ϕ)	0.93	0.90, 0.96
Recruitment rate (ρ)	0.075	0.011, 0.15
Population growth rate (λ)	1.04	1.00, 1.06

Table 26. Estimated effects of horseshoe crab abundance, timing of spawning, and Arctic snow cover on red knot survival probability and recruitment rate, presented as the mean and 95% credible interval of the posterior distribution.

Demographic rate	Covariate	Mean	95% CRI
Survival probability	HSC	0.38	0.13, 0.67
	MaySpawnPct	-0.05	-3.35, 3.33
	HSC x MaySpawnPct	0.01	-0.59, 0.59
	Arctic snow	-1.06	-3.76, 1.74
Recruitment rate	HSC	-0.08	-0.4, 0.41

Table 27. Model versions tested in sensitivity runs. Multiple models were run with varying prior distributions for availability ($\omega_{y,t}$), recruitment intercept (μ^p), and recruitment annual variance (σ^p) to test the sensitivity of model outputs to these priors.

Model	$\omega_{2005-2008}$	$\omega_{2009-2016}$	$\omega_{2017-2018}$	μ^p	σ^p
2	<i>Beta</i> (3,4)	<i>Beta</i> (4,3)	<i>Beta</i> (4,3)	<i>Unif</i> (0, 0.5)	<i>Unif</i> (0, 3)
3	<i>Beta</i> (4,3)	<i>Beta</i> (8,2)	$\omega_{2017} = 1, \omega_{2018} = 1$	<i>Unif</i> (0, 0.5)	<i>Unif</i> (0, 3)
4	<i>Beta</i> (4,3)	<i>Beta</i> (6,2)	$\omega_{2017} = 1, \omega_{2018} = 1$	<i>Unif</i> (0, 0.5)	<i>Unif</i> (0, 3)
5	<i>Beta</i> (4,3)	<i>Beta</i> (6,2)	$\omega_{2017} = 1, \omega_{2018} = 1$	<i>Unif</i> (0, 1)	<i>Unif</i> (0, 5)
6	<i>Beta</i> (4,3)	<i>Beta</i> (6,2)	<i>Beta</i> (25,1)	<i>Unif</i> (0, 0.5)	<i>Unif</i> (0, 5)
7	<i>Beta</i> (4,3)	<i>Beta</i> (6,2)	<i>Beta</i> (25,1)	<i>Unif</i> (0, 1)	<i>Unif</i> (0, 5)

Table 28. Harvest packages available to the original ARM framework. One of these packages was recommended for each possible state of the system.

Package number	Females harvested (thousands)	Males harvested (thousands)
1	0	0
2	0	250
3	0	500
4	140	280
5	210	420

Table 29. Summary of changes to components of the optimization algorithm from the original to the revised ARM model.

Aspect	Original ARM model	Revised ARM model
Optimization approach	Stochastic Dynamic Programming	Approximate Dynamic Programming
Number of state variables	6	6
State variable type	Discrete	Continuous
Number of decision variables	6	3
All decision variables observed?	No	Yes
Harvest function output (recommendations)	Discrete	Continuous
Optimization algorithm	Dynamic	Static

Table 30. Parameters relevant to optimization of the revised ARM model using the genetic algorithm.

Symbol / Name	Description	Value
T	Time horizon	100
K	Number of iterations (simulations) carried out for a given value of θ , to determine $g(\theta)$	10,000
$[\alpha_{\min}^f, \alpha_{\max}^f]$	Upper and lower bounds for α^f	$[0.001, 30] / (2 \times 10^7)$
$[\beta_{\min}^f, \beta_{\max}^f]$	Upper and lower bounds for β^f	$[1, 2 \times 10^7]$
$[\alpha_{\min}^m, \alpha_{\max}^m]$	Upper and lower bounds for α^m	$[0.001, 30] / (3 \times 10^7)$
$[\beta_{\min}^m, \beta_{\max}^m]$	Upper and lower bounds for β^m	$[1, 3 \times 10^7]$
$[\alpha_{\min}^k, \alpha_{\max}^k]$	Upper and lower bounds for α^k	$[0.001, 30] / (1.8 \times 10^5)$
$[\beta_{\min}^k, \beta_{\max}^k]$	Upper and lower bounds for β^k	$[1, 1.8 \times 10^5]$
popSize	Number of individuals in the ‘population’ (argument of the ga() function in package {GA})	200
run	Number of iterations without change in the solution, before stopping (argument of the ga() function in package {GA})	200
parallel	Number of cores to use, for parallel processing (argument of the ga() function in package {GA})	30

Table 31. Optimal values of θ , the parameters of the harvest function h , for the canonical version of the revised ARM model. Slope parameters are displayed to make them comparable; they are multiplied by the maximum abundance values for each of male HSC, female HSC and REKN (Table 30).

Symbol / Name	Description	Value
α^f	Slope of the female HSC harvest factor.	5.017 / (2×10^7)
β^f	Inflection point of the female HSC harvest factor.	7.219×10^6
α^m	Slope of the male HSC harvest factor.	16.908 / (3×10^7)
β^m	Inflection point of the male HSC harvest factor.	7.953×10^6
α^k	Slope of the red knot harvest factor.	15.783 / (1.8×10^5)
β^k	Inflection point of the red knot harvest factor.	9.929×10^4

Table 32. Comparison of harvest recommendations from the previous (top section) and revised (bottom section) ARM models when applied to recent abundance estimates of horseshoe crabs and red knots in the Delaware Bay. Coastwide biomedical mortality was used for model development, so actual Delaware-Bay specific values will result in slightly lower population estimates.

Year	VA Tech Swept Area Estimates		Red knots	Optimal HSC Harvest (previous ARM)	
	Female HSC	Male HSC		Female	Male
2017	6,654,877	21,405,997	49,405	0	500,000
2018	7,555,622	19,346,403	45,221	0	500,000
2019	7,934,057	16,645,912	45,133	0	500,000
Year	CMSA Estimates		Red knots	Optimal HSC Harvest (revised ARM)	
	Female HSC	Male HSC		Female	Male
2017	11,517,590	35,128,270	49,405	157,358	500,000
2018	10,229,210	27,310,980	45,221	143,441	499,991
2019	9,780,790	23,933,680	45,133	138,243	499,939

14 FIGURES

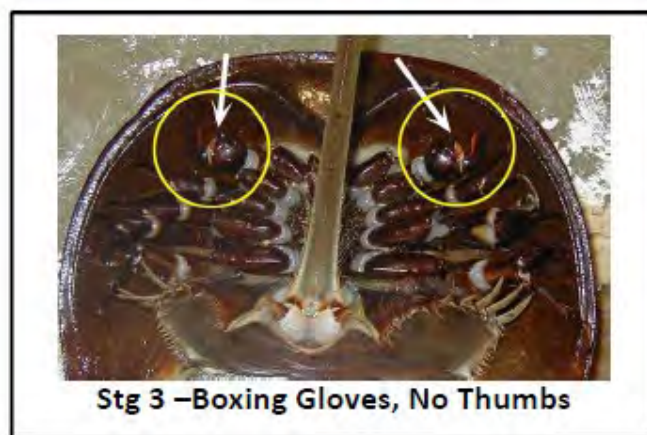


Figure 1. Male horseshoe crab maturity stages where stage 1 is immature, stage 2 is primiparous, and stage 3 is multiparous (Source: Northeast Area Monitoring and Assessment Program).

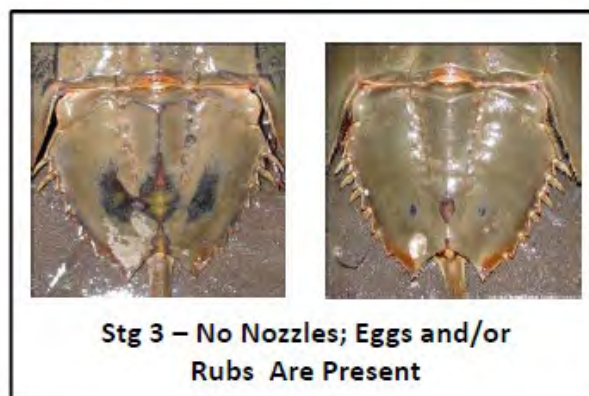
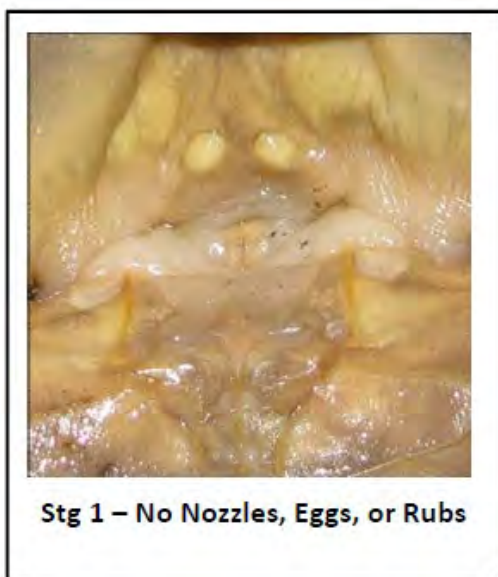


Figure 2. Female horseshoe crab maturity stages where stage 1 is immature, stage 2 is primiparous, and stage 3 is multiparous (Source: Northeast Area Monitoring and Assessment Program).

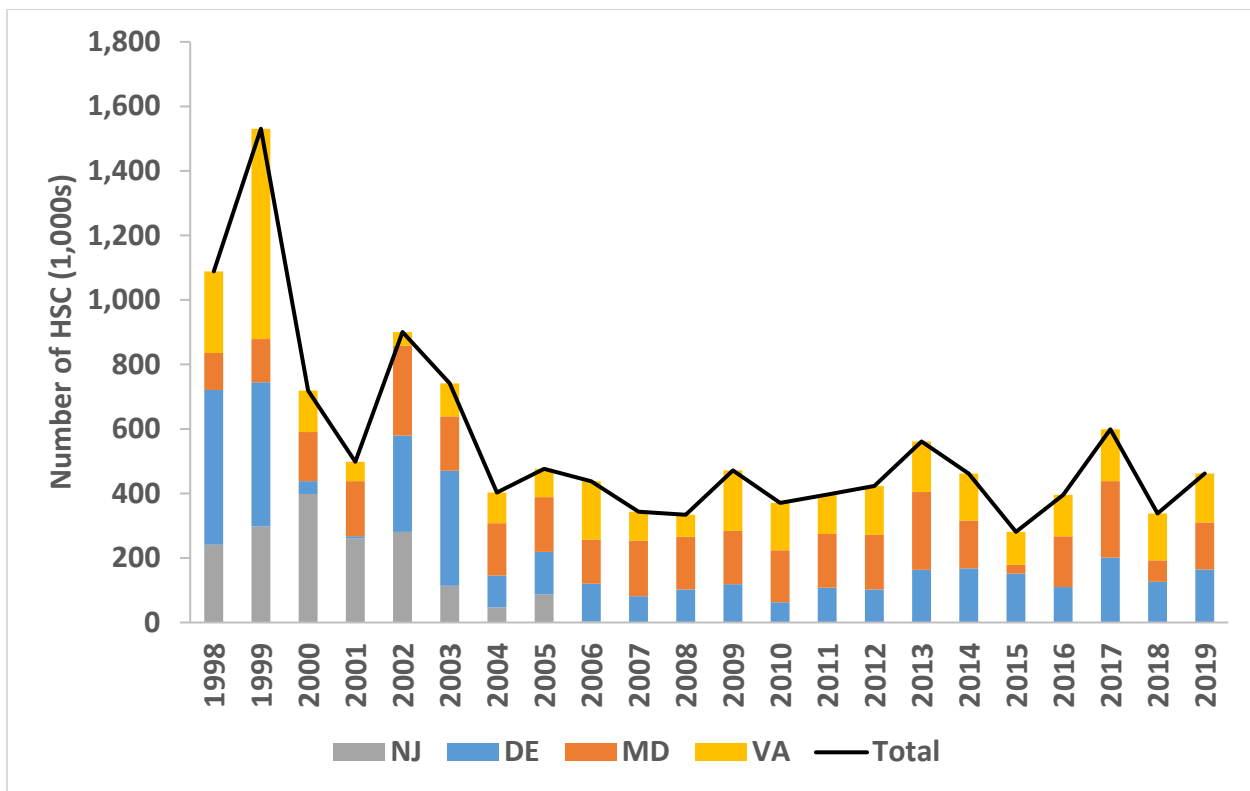


Figure 3. Commercial bait landings of horseshoe crabs in the Delaware Bay region by state, 1998-2019 (Source: ACCSP).

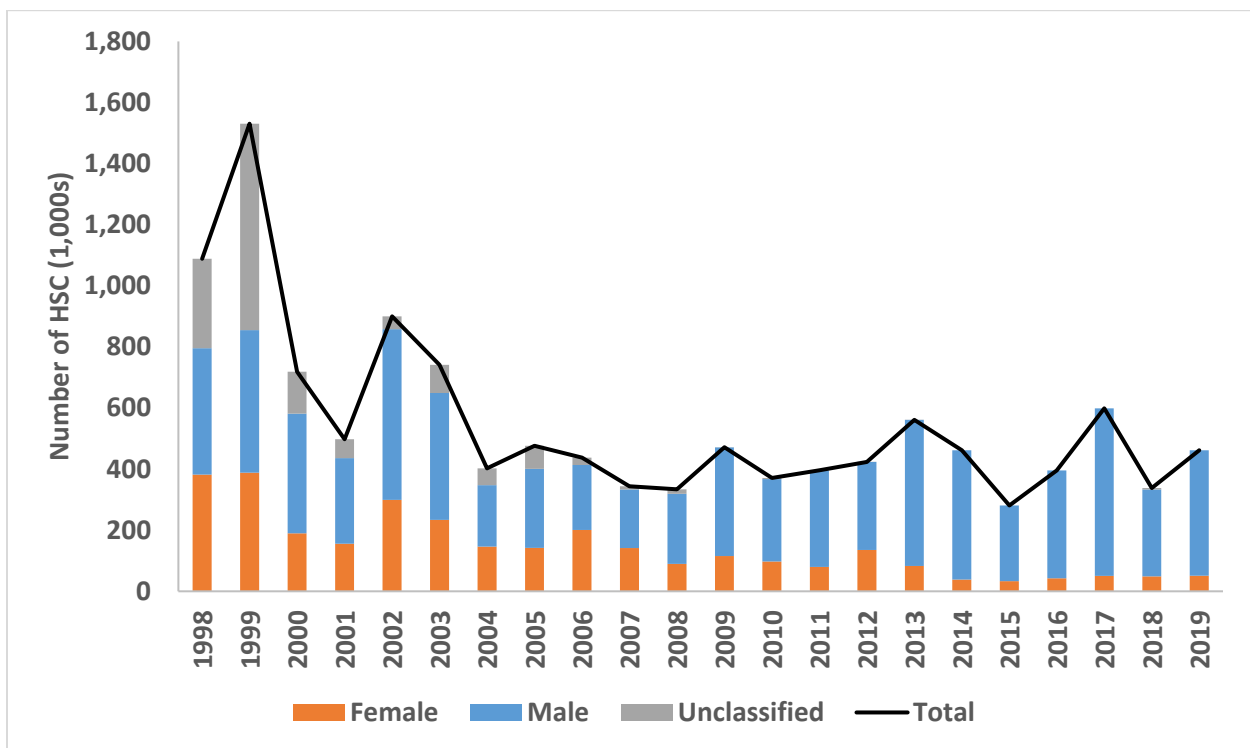


Figure 4. Commercial bait harvest of horseshoe crabs in the Delaware Bay region by sex (Source: ACCSP).

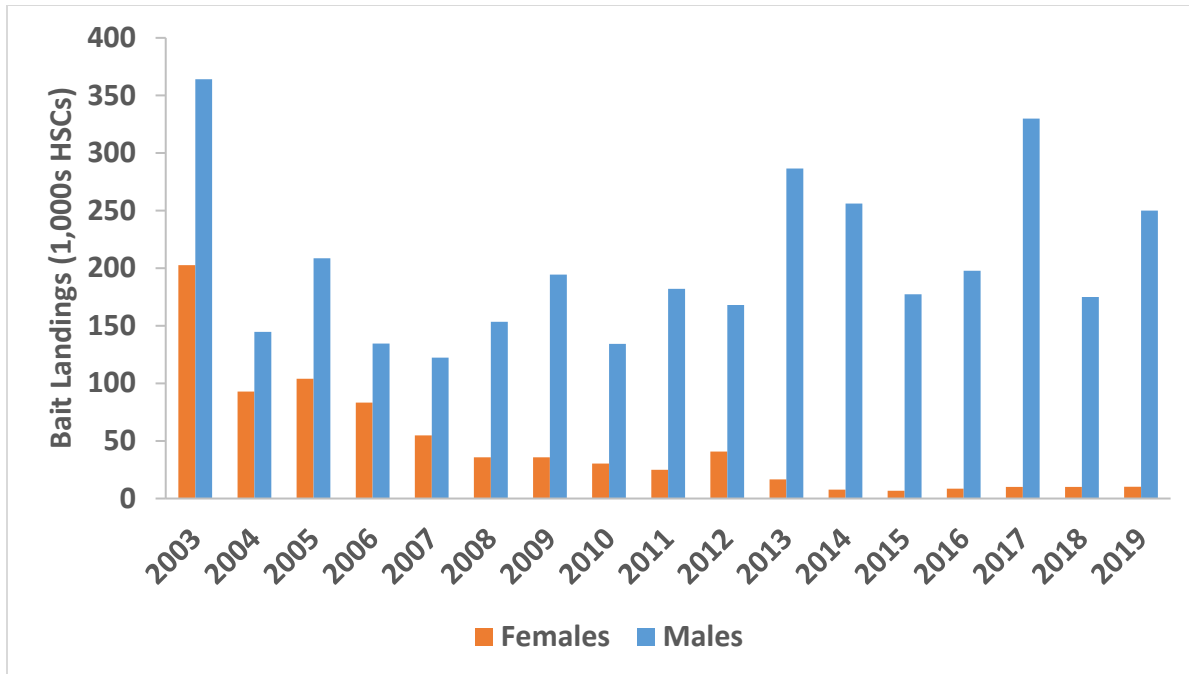


Figure 5. Delaware Bay origin horseshoe crab commercial bait harvest by sex in numbers for use in the CMSA. Horseshoe crab landings from New Jersey and Delaware are considered to be 100% Delaware Bay origin (i.e., has spawned at least once in Delaware Bay) whereas 45% of Maryland’s harvest and 20% of Virginia’s are believed to be Delaware Bay origin.



Figure 6. Estimated mortality due to biomedical bleeding for the coastwide population of horseshoe crabs, 2003-2019, by sex for use in the CMSA.

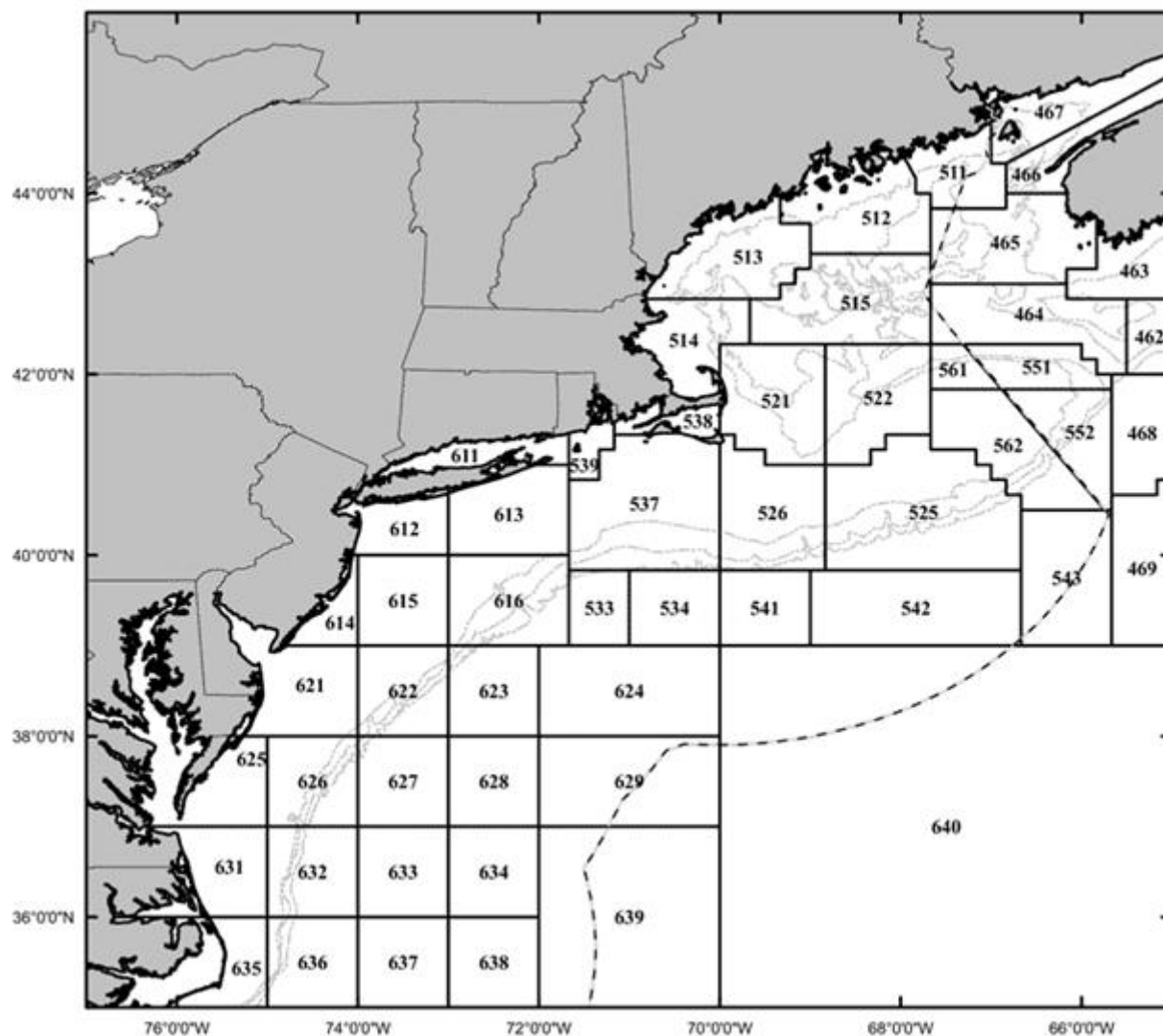


Figure 7. Statistical areas sampled in the Northeast Fisheries Observer Program (NEFOP). For estimating discards of horseshoe crabs from commercial fisheries, areas 612, 614, 615, 621, 625, and 626 were used.

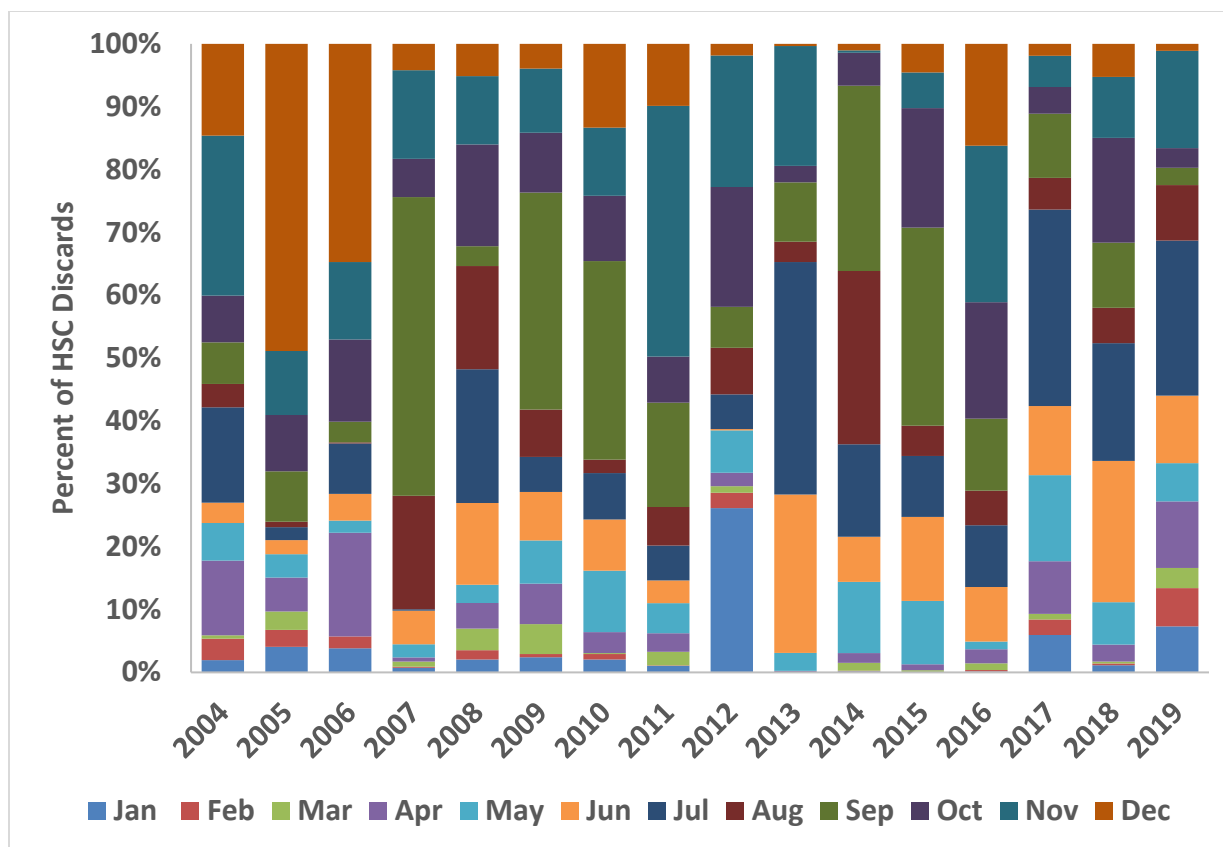


Figure 8. Percent of trips that caught and discarded horseshoe crabs in the NEFOP data by month for 2004-2019.

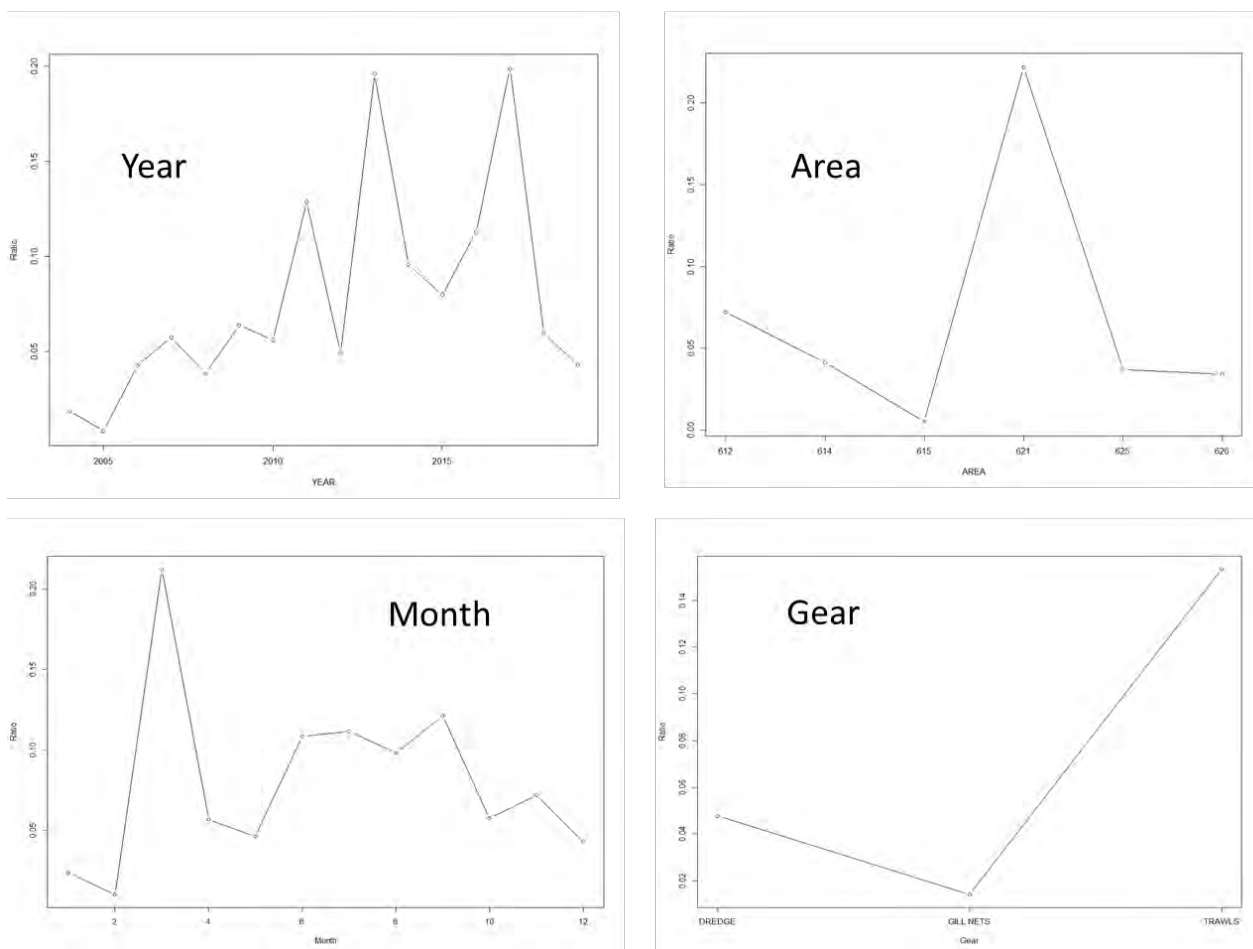


Figure 9. Ratios of discarded horseshoe crabs to all species landed in the NEFOP data by year, area, month, and gear.

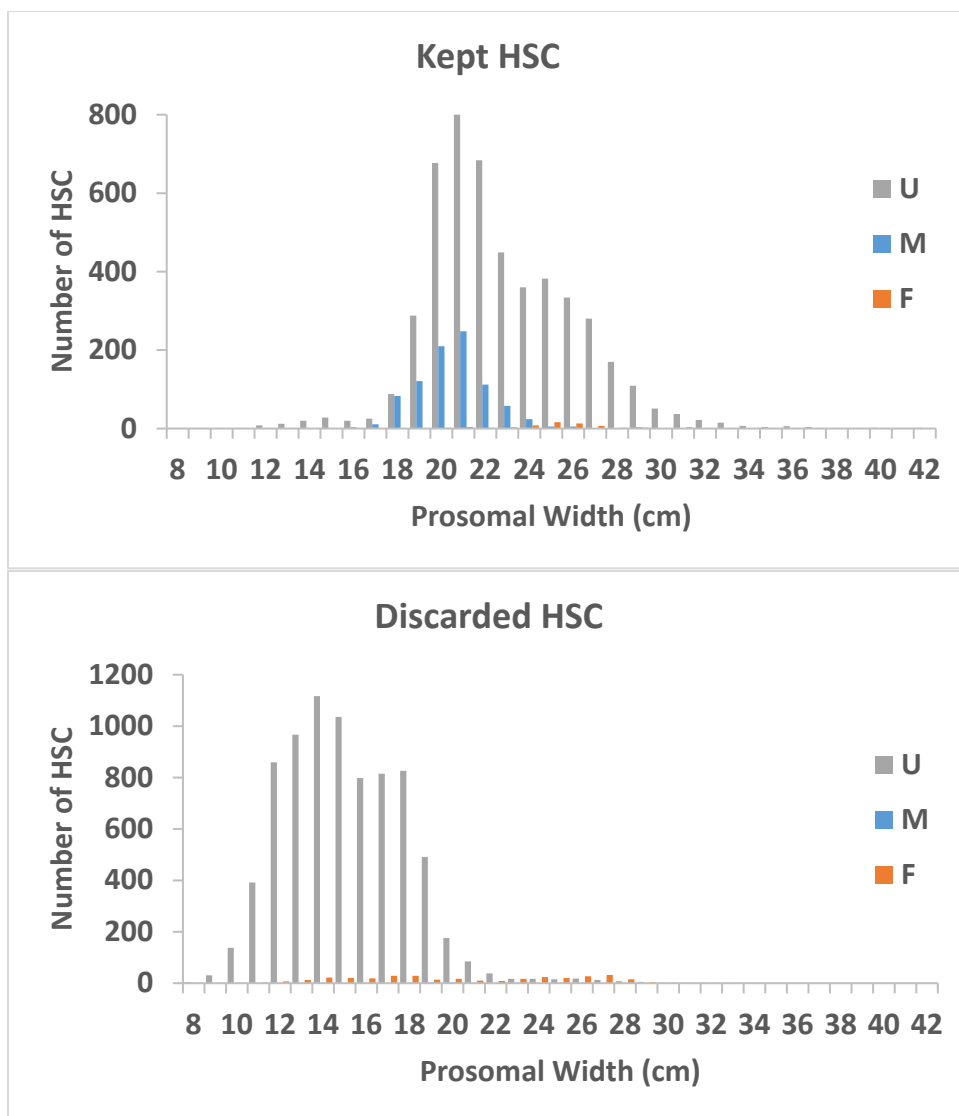


Figure 10. Prosomal width frequencies of horseshoe crabs kept (top) and discarded (bottom) on observed trips in the NEFOP database in the Delaware Bay region.

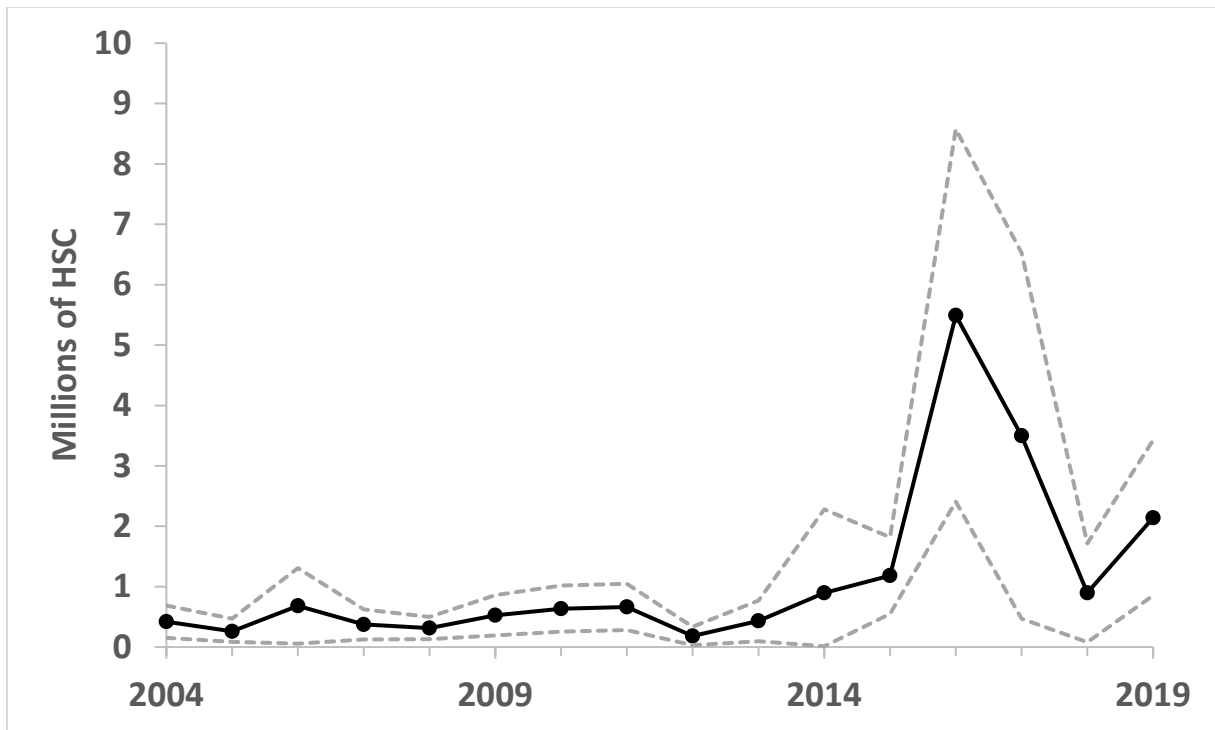


Figure 11. Estimated total number of horseshoe crabs discarded with 95% confidence intervals. Total discards represents all horseshoe crab sexes and maturities, alive and dead, in trawls, discards, and trawls.

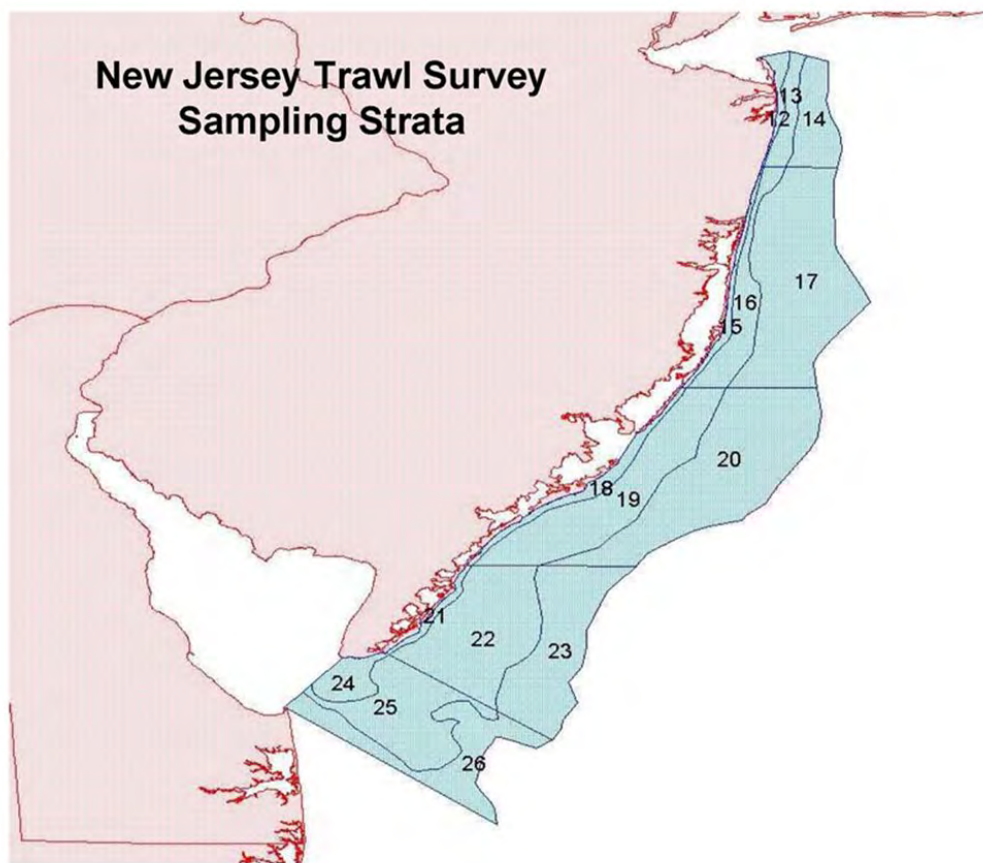


Figure 12. New Jersey Ocean Trawl Survey sampling area with survey strata defined.

NJ Ocean Trawl Female Horseshoe Crabs - April & August

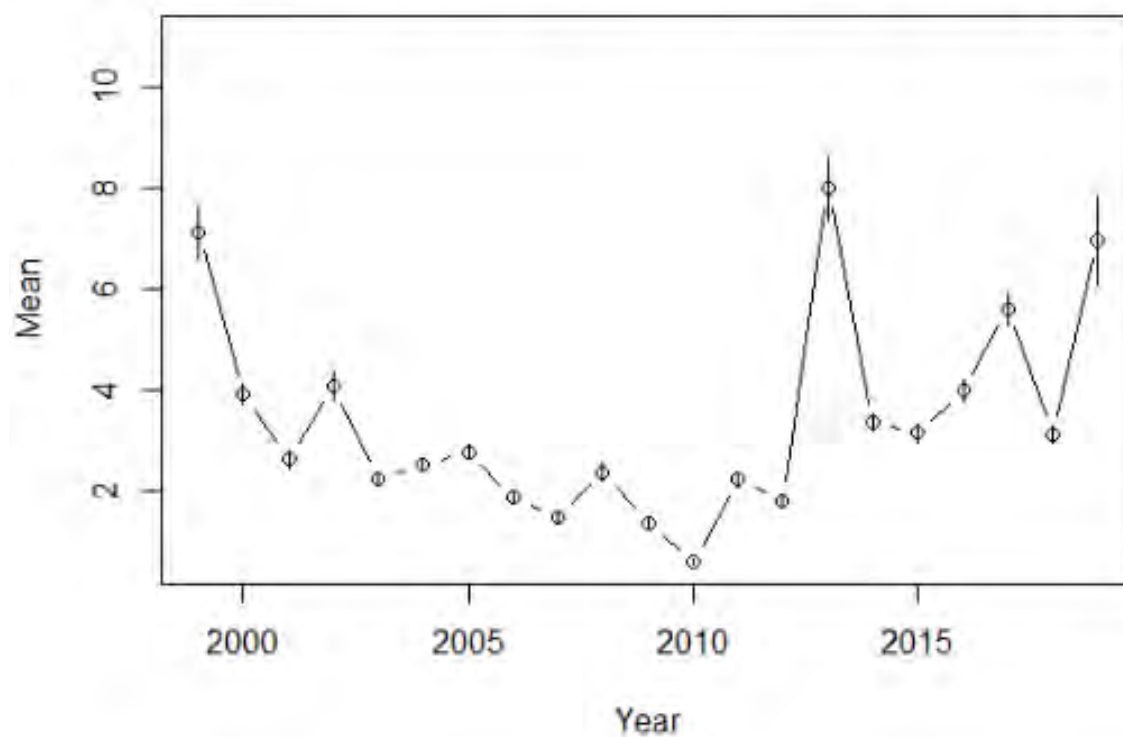


Figure 13. Abundance index for female horseshoe crabs in the New Jersey Ocean Trawl Survey for April and August tows.

NJ Ocean Trawl Male Horseshoe Crabs - April & August

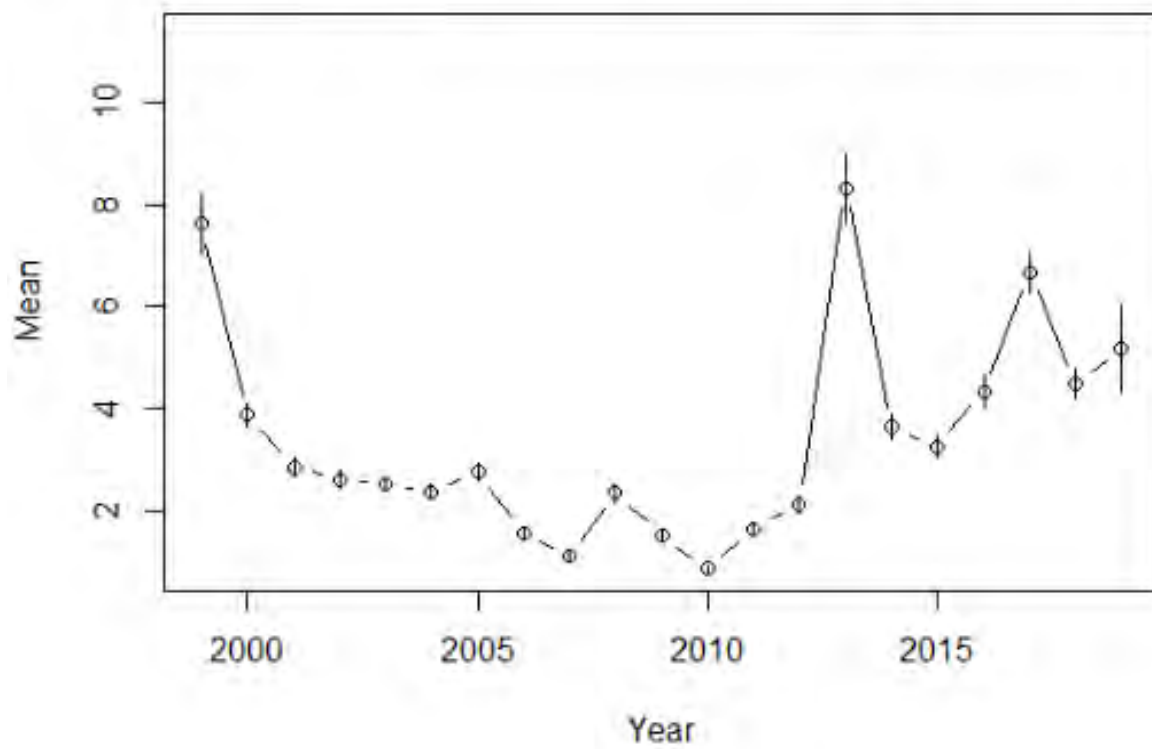


Figure 14. Abundance index for male horseshoe crabs in the New Jersey Ocean Trawl Survey for April and August tows.



Figure 15. Delaware Fish & Wildlife Adult Trawl Survey sampling area and stations.

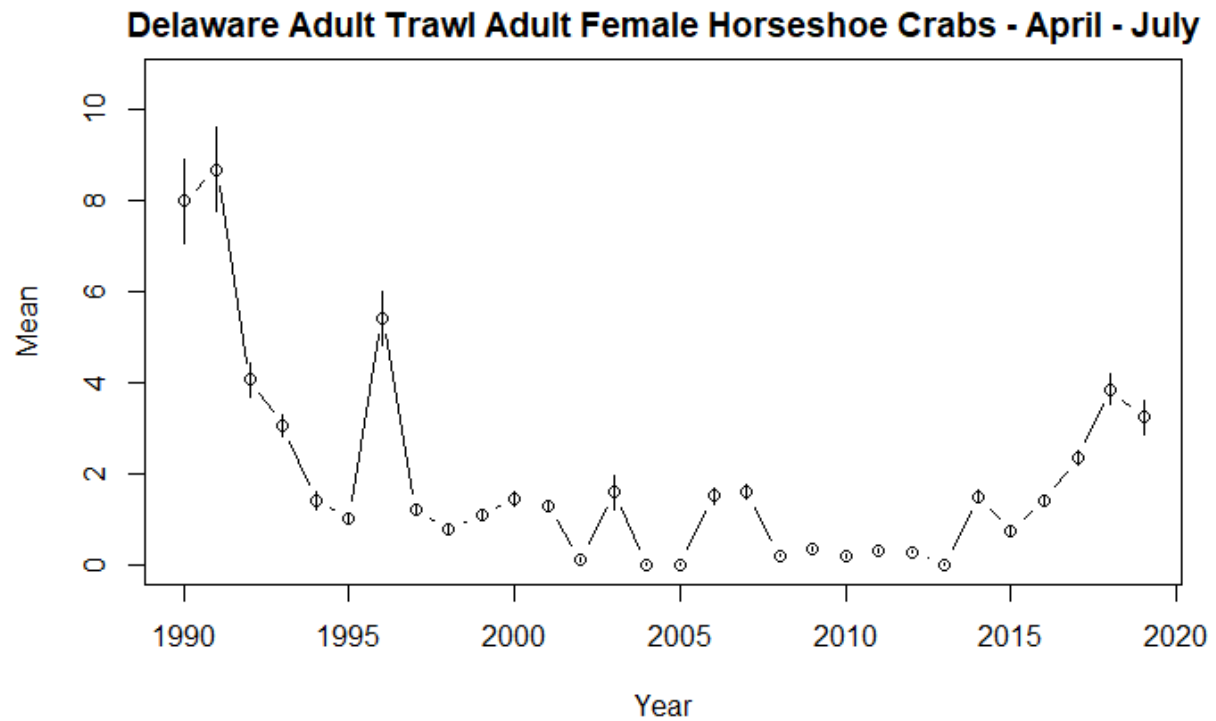


Figure 16. Delaware Fish and Wildlife Adult Trawl Survey abundance index for all adult female horseshoe crabs.

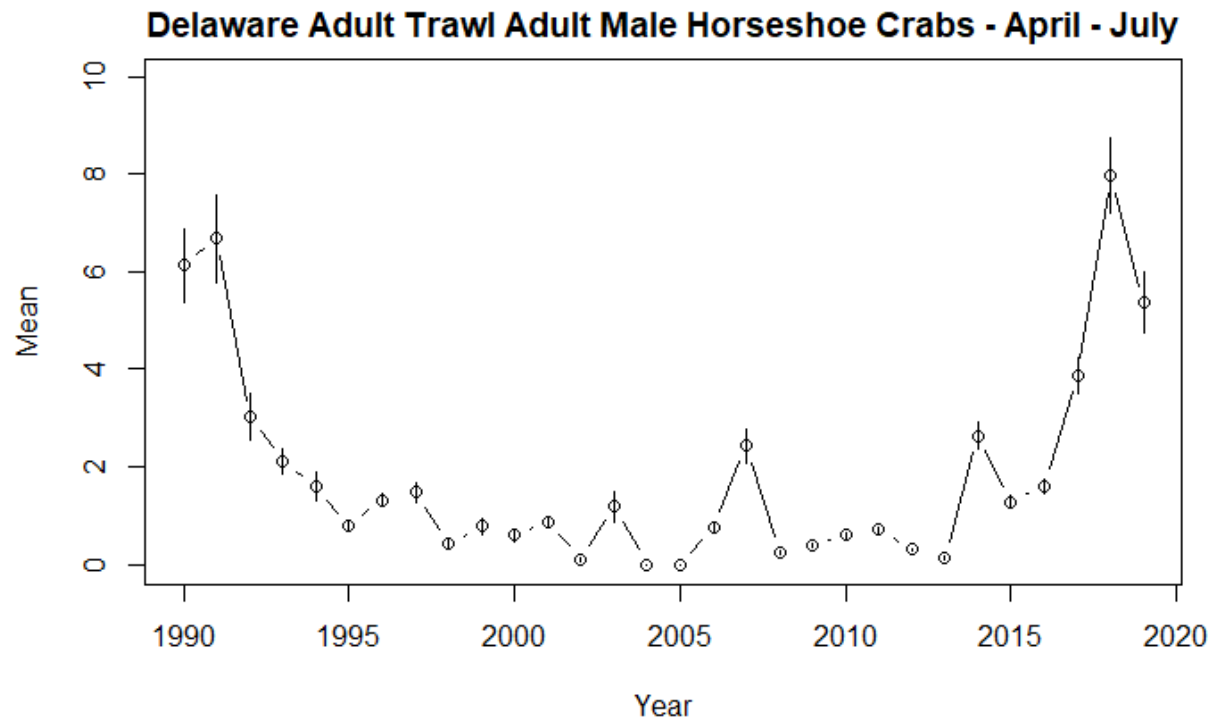


Figure 17. Delaware Fish and Wildlife Adult Trawl Survey abundance index for all adult male horseshoe crabs.

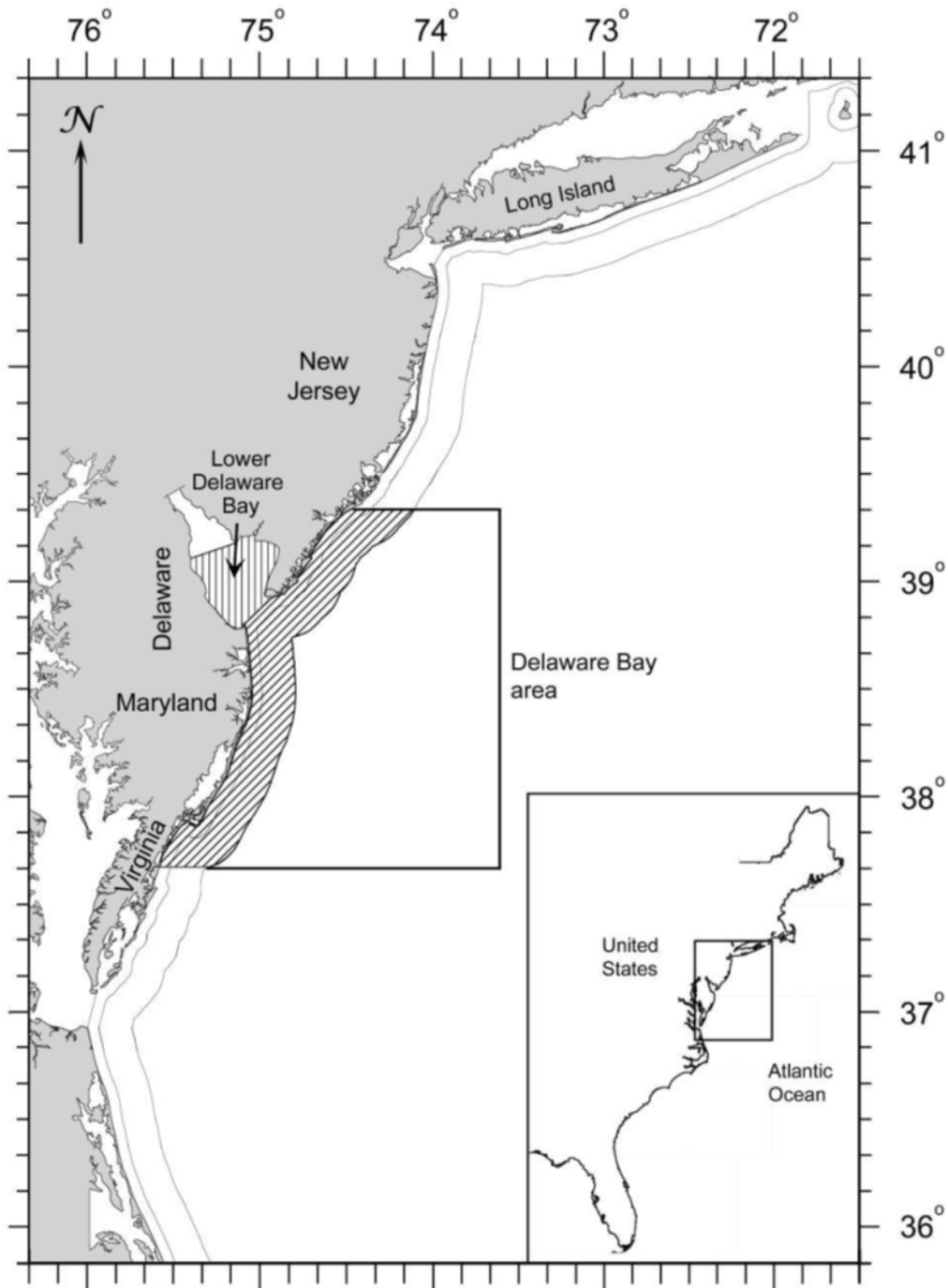


Figure 18. Virginia Tech trawl survey sampling area. The coastal Delaware Bay area (DBA) and Lower Delaware Bay (LDB) survey areas are indicated. Mean catches among years were compared using stations within the shaded portions of the survey area in the annual report (map provided by Virginia Tech).

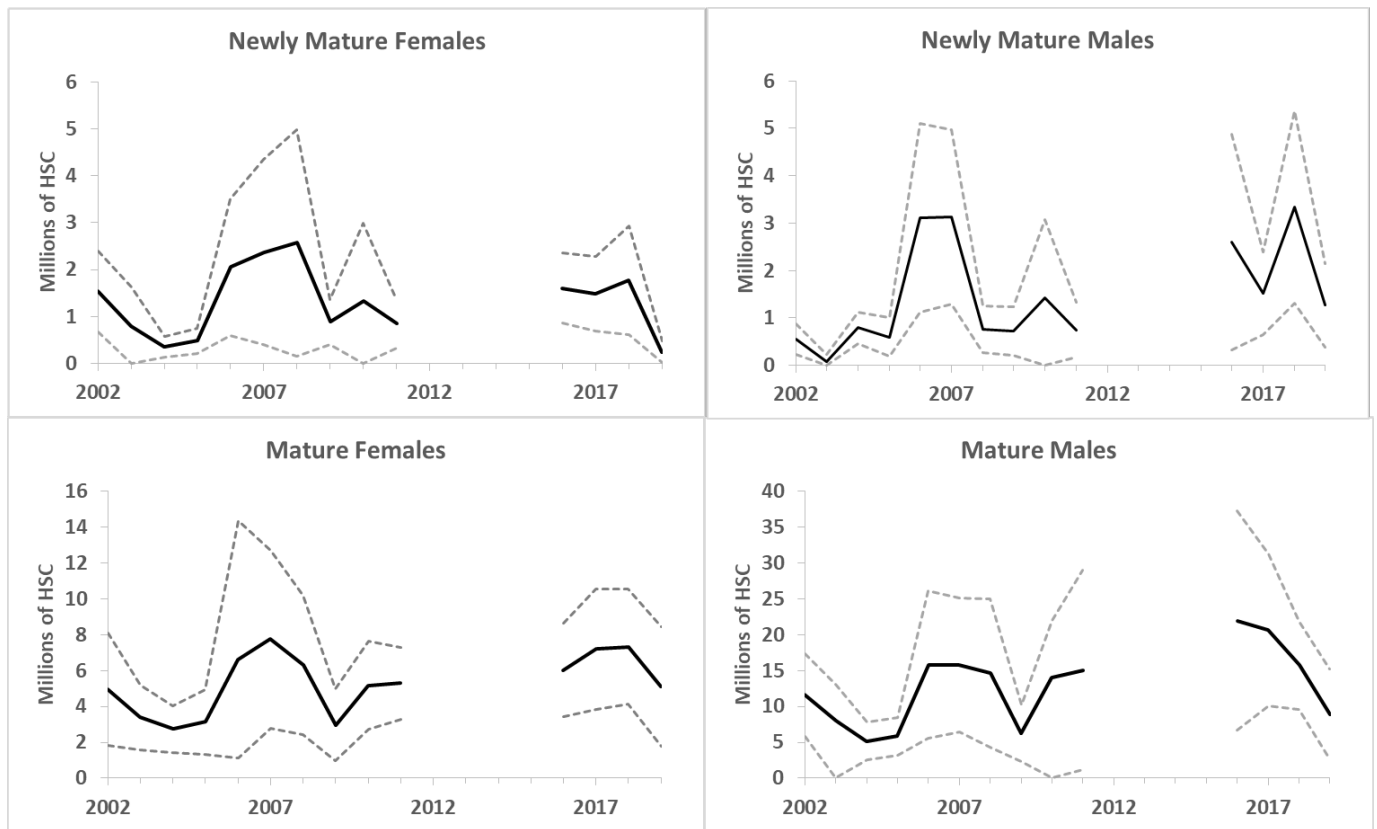
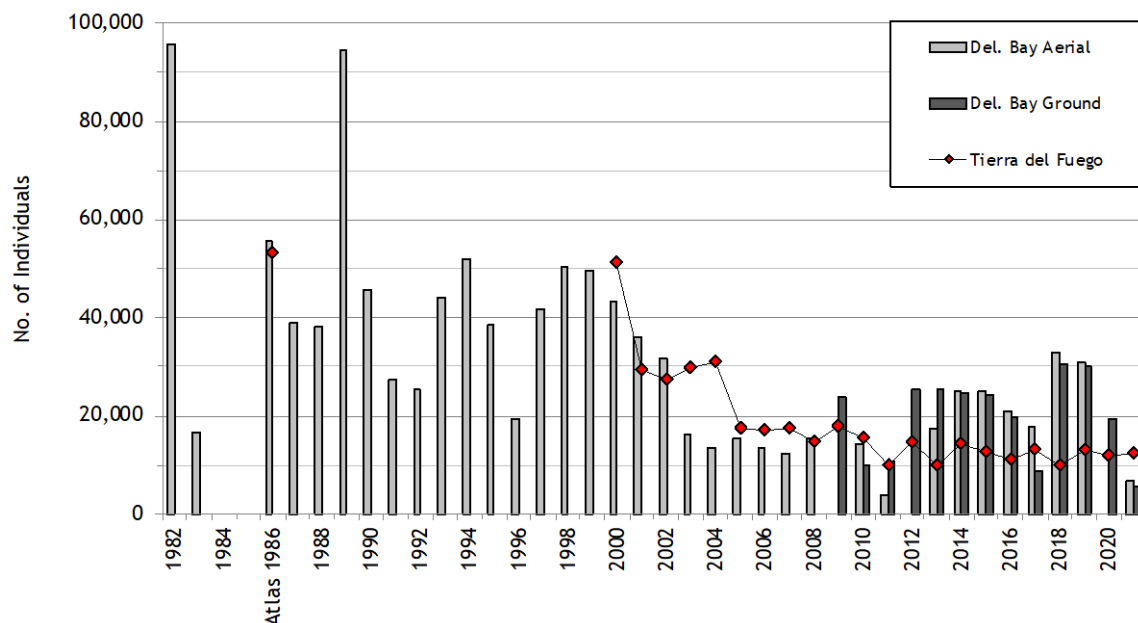


Figure 19. Swept area population estimates of horseshoe crabs in the coastal Delaware Bay by demographic group used in the CMSA with 95% confidence limits for 2002-2019. The survey did not run 2012-2015.



Aerial Counts: K Clark 1986-2008; W Pitts 2010; H Sitters 2011; L Niles 2013; M Peck 2014-2015, RIG Morrison 2016-2019. No aerial in 2020 (Covid), S. Feigin 2021. Peak aerial counts in 2009 and 2012 not conducted or not available, respectively. Tierra del Fuego RIG Morrison, K. Ross (1986-2020), R. Matus, H. Norambuena (2021).

Figure 20. Peak aerial count of Red Knots in Delaware Bay during spring stopover, 1982-2021; aerial count from Tierra del Fuego (major wintering area) are included for comparison, 1986-2021. Delaware Bay aerial counts in 1982-1983 were conducted by New Jersey Audubon; no aerial counts were conducted in 1984-1985. Aerial counts from 1986-present were conducted by New Jersey Division of Fish & Wildlife, Delaware Division of Fish & Wildlife and various individuals after 2008. Aerial counts in 2009 and 2012 were not conducted or not available, respectively; peak values for these years are from ground counts. Beginning in 2009 with a change of long-term observers, ground and boat counts were conducted simultaneously with aerial survey to help validate aerial abundances, particularly in Mispillion Harbor, DE, where birds can be missed by aerial observers, and Egg Island, NJ, where large numbers of birds stage and may be undercounted. Ground surveys are presented for years when comprehensive ground/boat surveys were conducted in NJ and DE. Source: Atlas 1986, Morrison, R. I. G. and R. K. Ross. 1989. Atlas of Nearctic shorebirds on the coast of South America. 2 vols. Special Publication, Canadian Wildlife Service, Ottawa, Ontario. 325 pp.

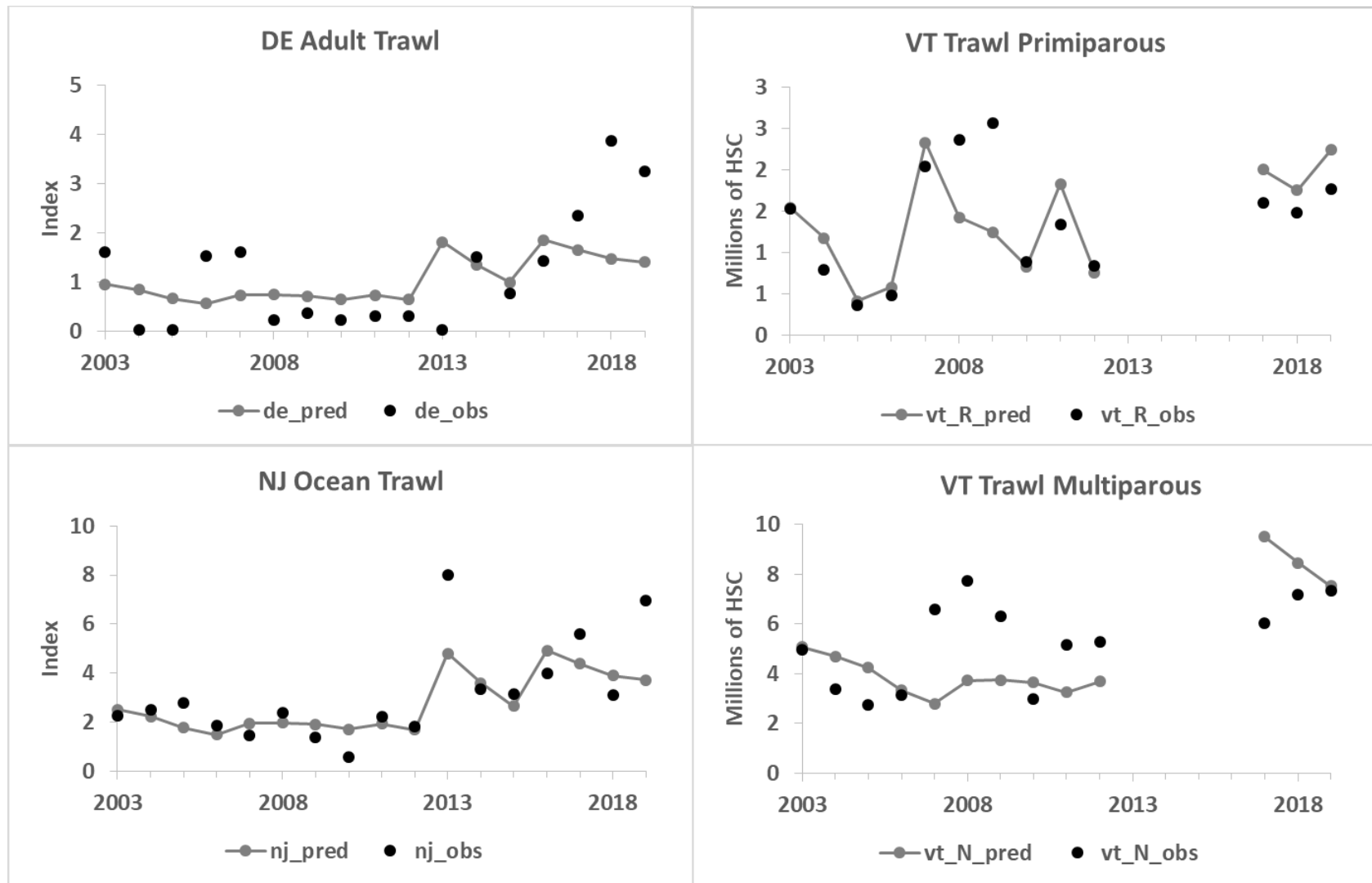


Figure 21. CMSA model fits to the indices for the Delaware (DE) Adult Trawl, New Jersey (NJ) Ocean Trawl, and Virginia Tech (VT) Trawl Surveys for primiparous and multiparous female horseshoe crabs.

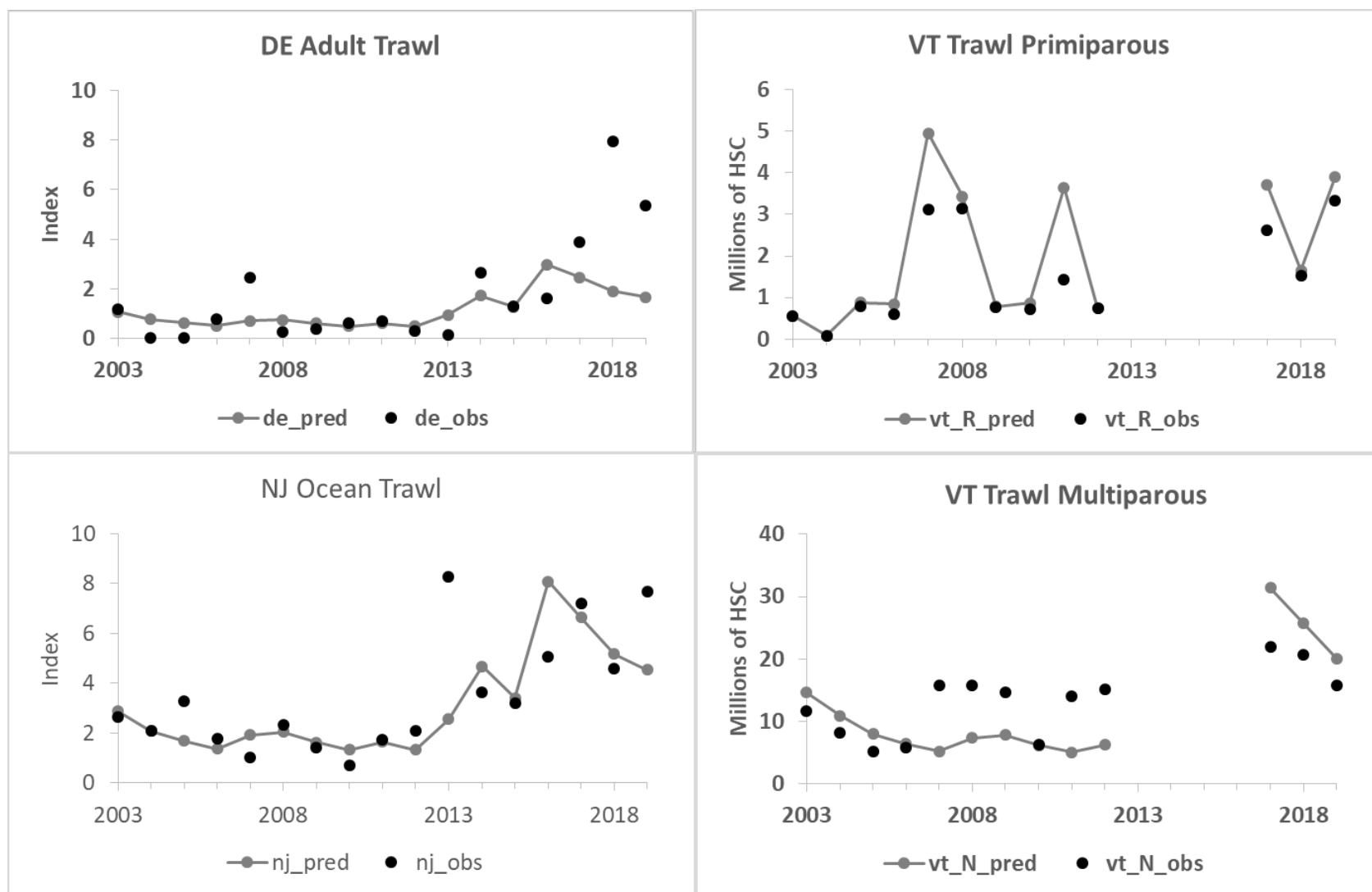


Figure 22. CMSA model fits to the indices for the Delaware (DE) Adult Trawl, New Jersey (NJ) Ocean Trawl, and Virginia Tech (VT) Trawl Surveys for primiparous and multiparous male horseshoe crabs.

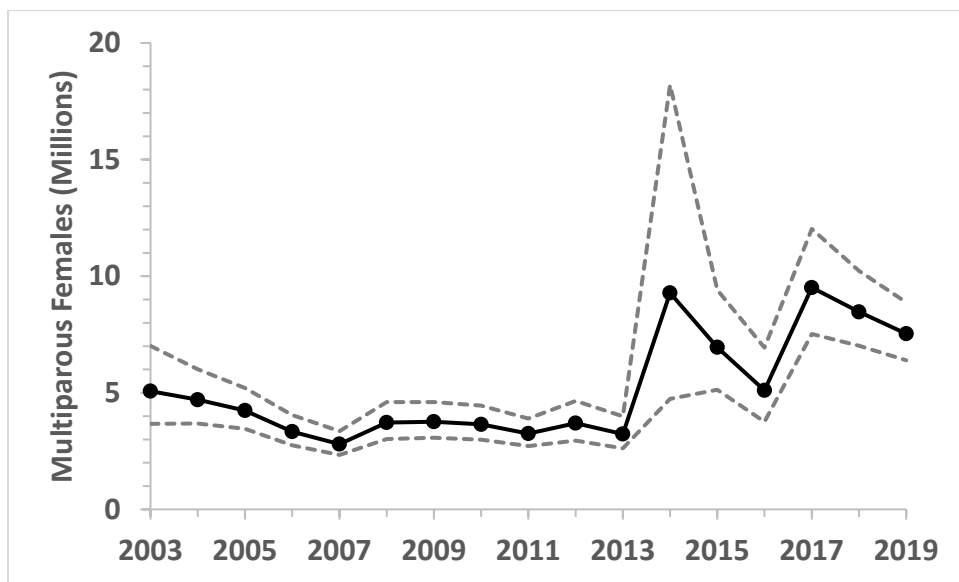
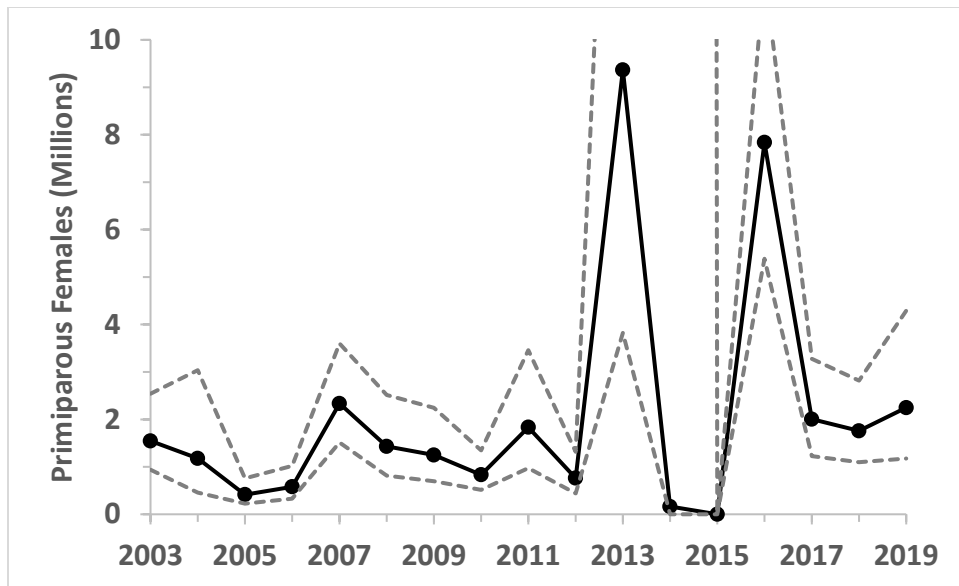


Figure 23. CMSA model estimated primiparous and multiparous female abundance with lower and upper 95% confidence limits. Upper confidence limits for 2013-2016 extend beyond y-axis for primiparous crabs due to missing years of data from the Virginia Tech Trawl Survey.

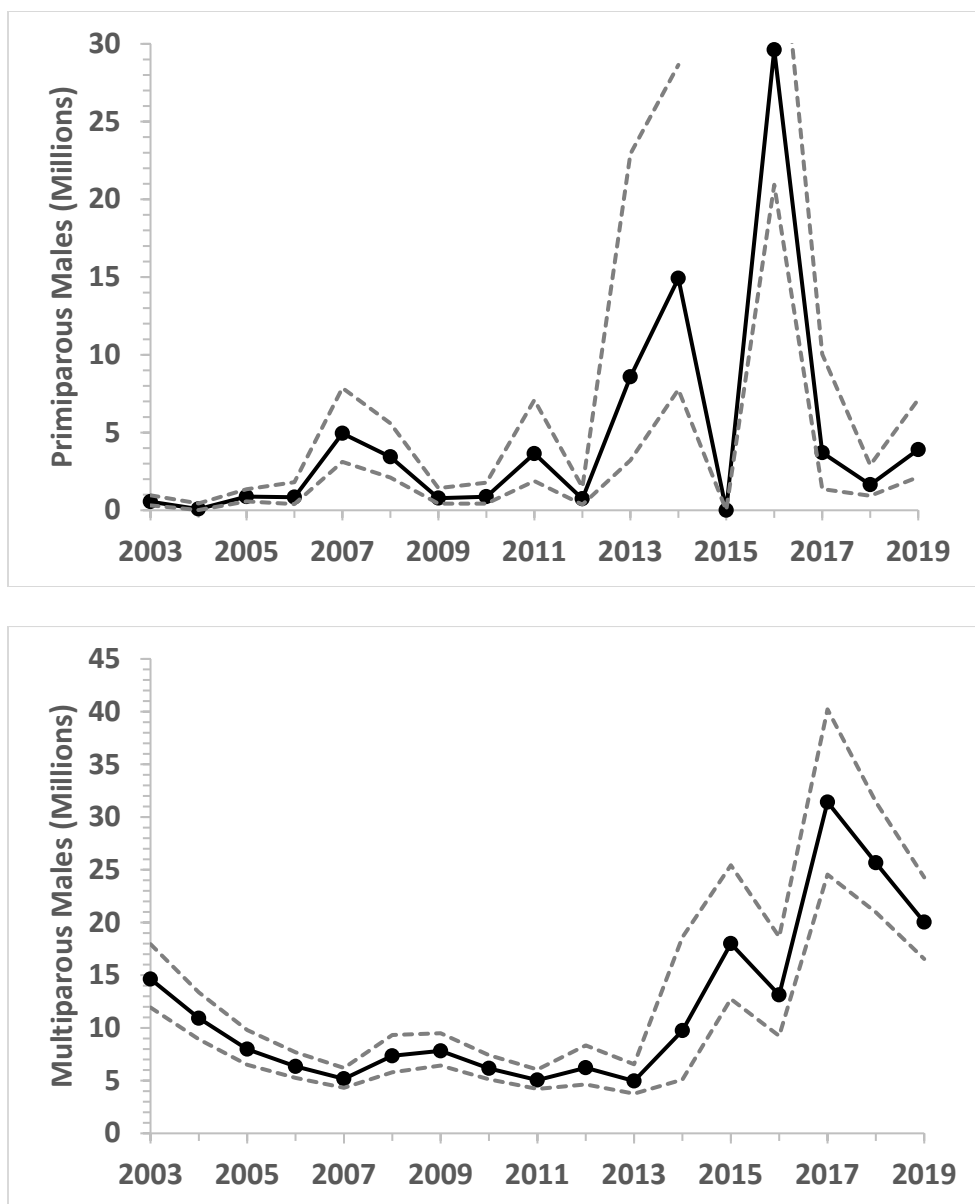


Figure 24. CMSA model estimated primiparous and multiparous male abundance with lower and upper 95% confidence limits. Upper confidence limits for 2013-2016 extend beyond y-axis for primiparous crabs due to missing years of data from the Virginia Tech Trawl Survey.

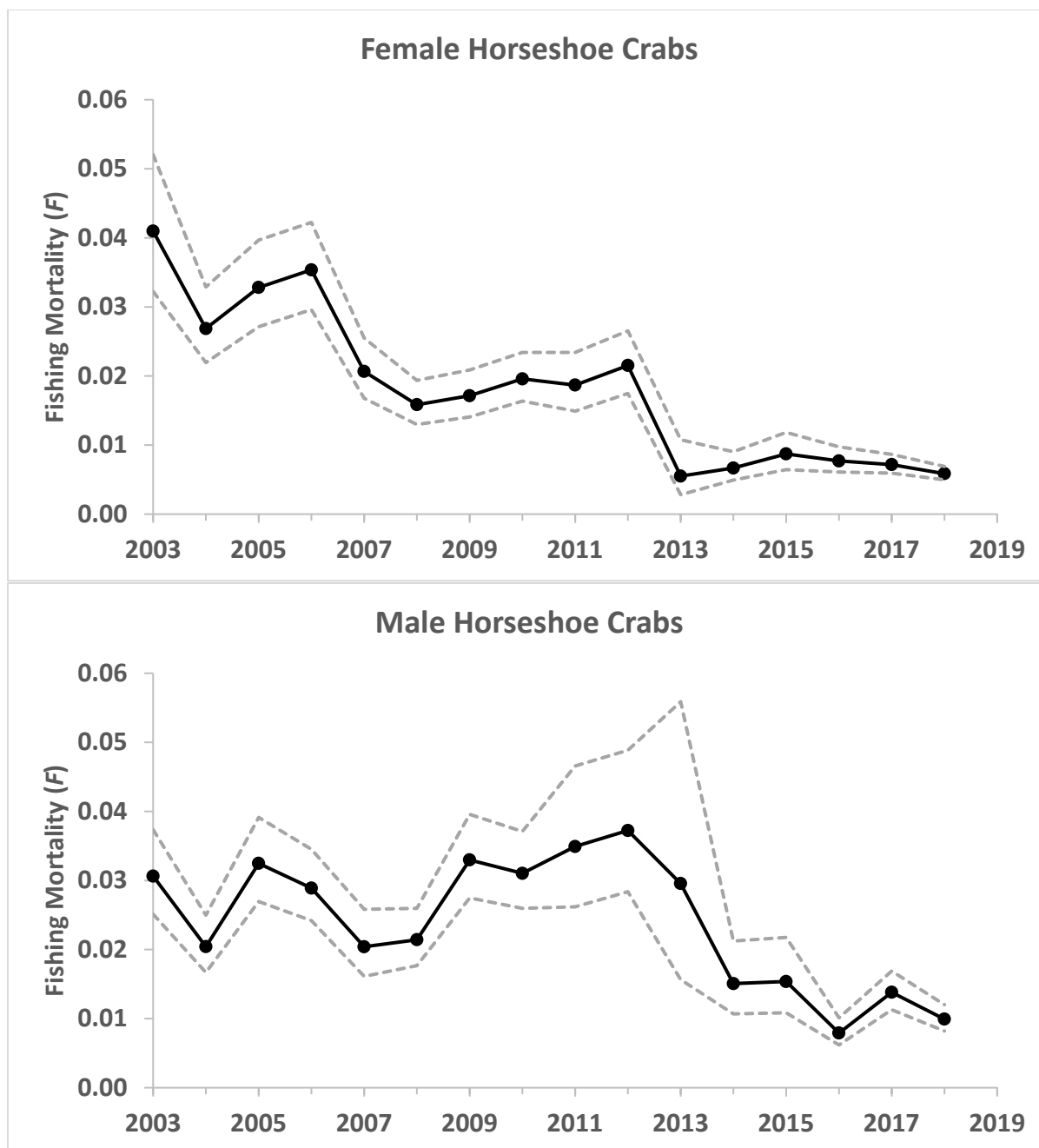


Figure 25. CMSA model estimates instantaneous fishing mortality rate (F) with lower and upper 95% confidence limits.

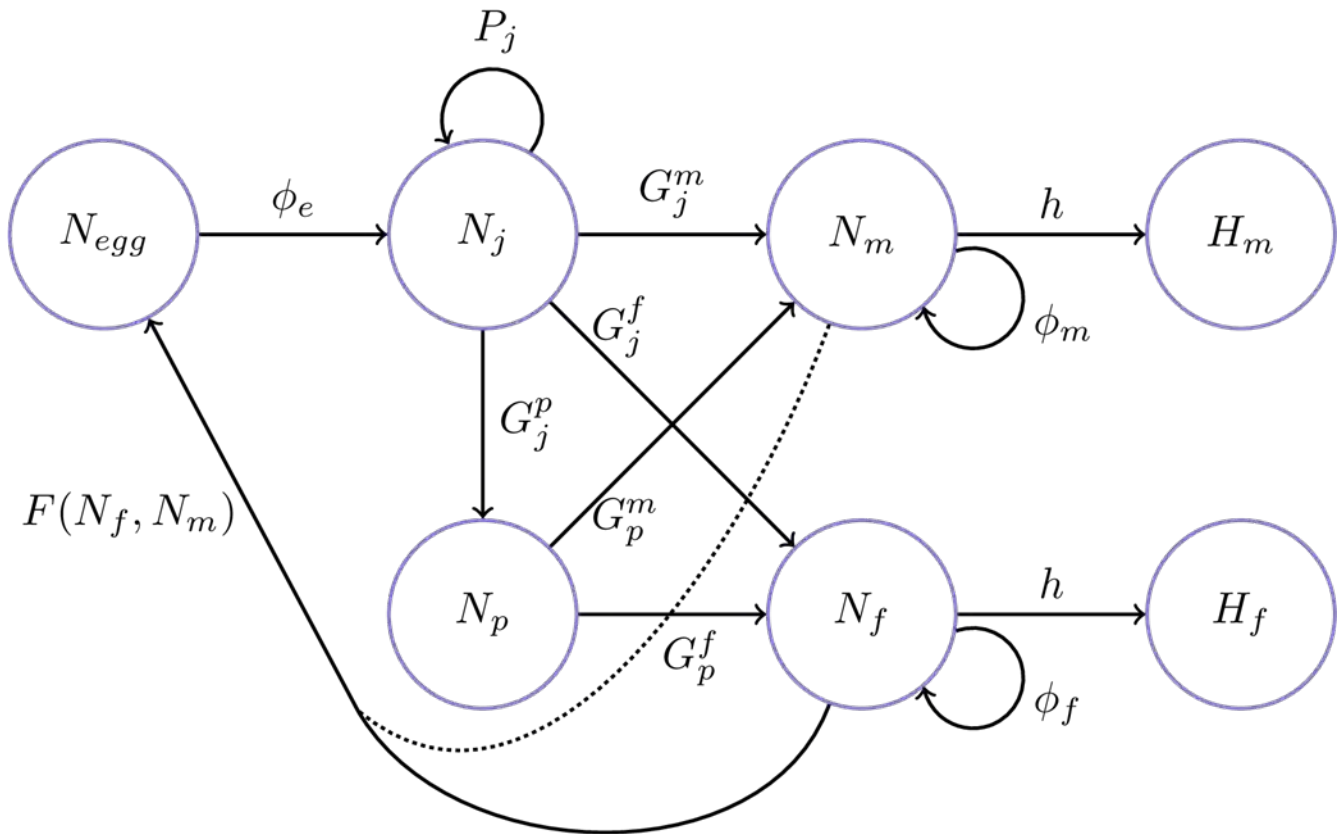


Figure 26. Life cycle diagram of the stage-based horseshoe crab population projection model used in the previous ARM version. Abundances (circle nodes): N , population segment; H , harvest. Rates (arrows): ϕ , survival; G , graduation from one stage to another; P , persistence in a stage; F , fecundity; h , harvest. Subscripts/superscripts: e , egg; j , juveniles; p , primiparous; f , multiparous females; m , multiparous males. For stage transition rates G , subscript indicates the previous stage, superscript the new. Fecundity is a function of both male and female abundance, via a fertility function that depends upon the sex ratio among multiparous adults.

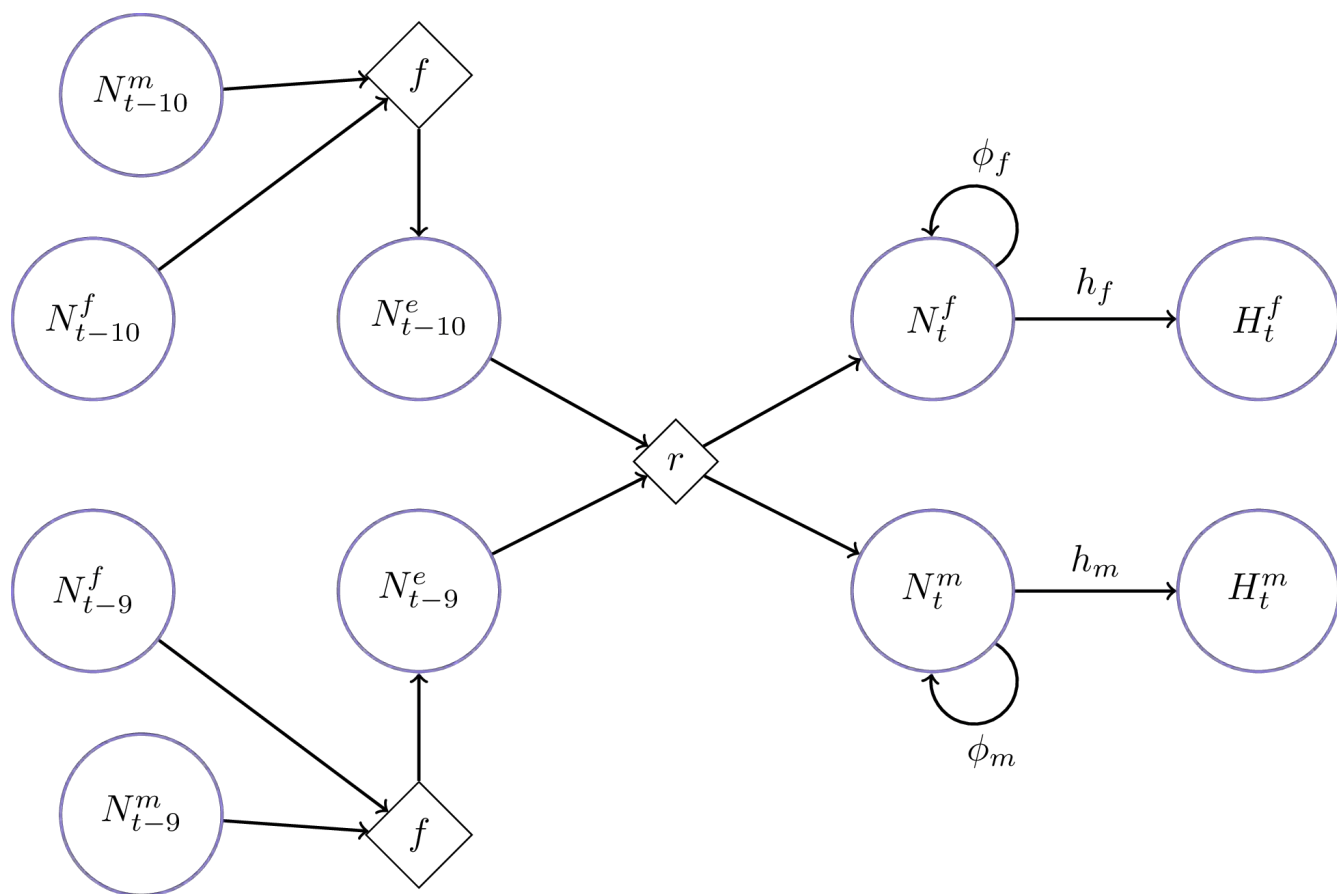


Figure 27. Annualized life cycle diagram of the CMSA-based horseshoe crab simulation model used in the revised ARM. Abundances (circle nodes): N , population segment; H , harvest. Rates (arrows): ϕ , survival; h , harvest. Superscripts: f , females; m , males; e , ‘effective’ spawning females, that is, those whose eggs are successfully fertilized. Processes (diamond nodes): f , fertility, which depends upon the sex ratio; r , recruitment, which generates primiparous crabs.

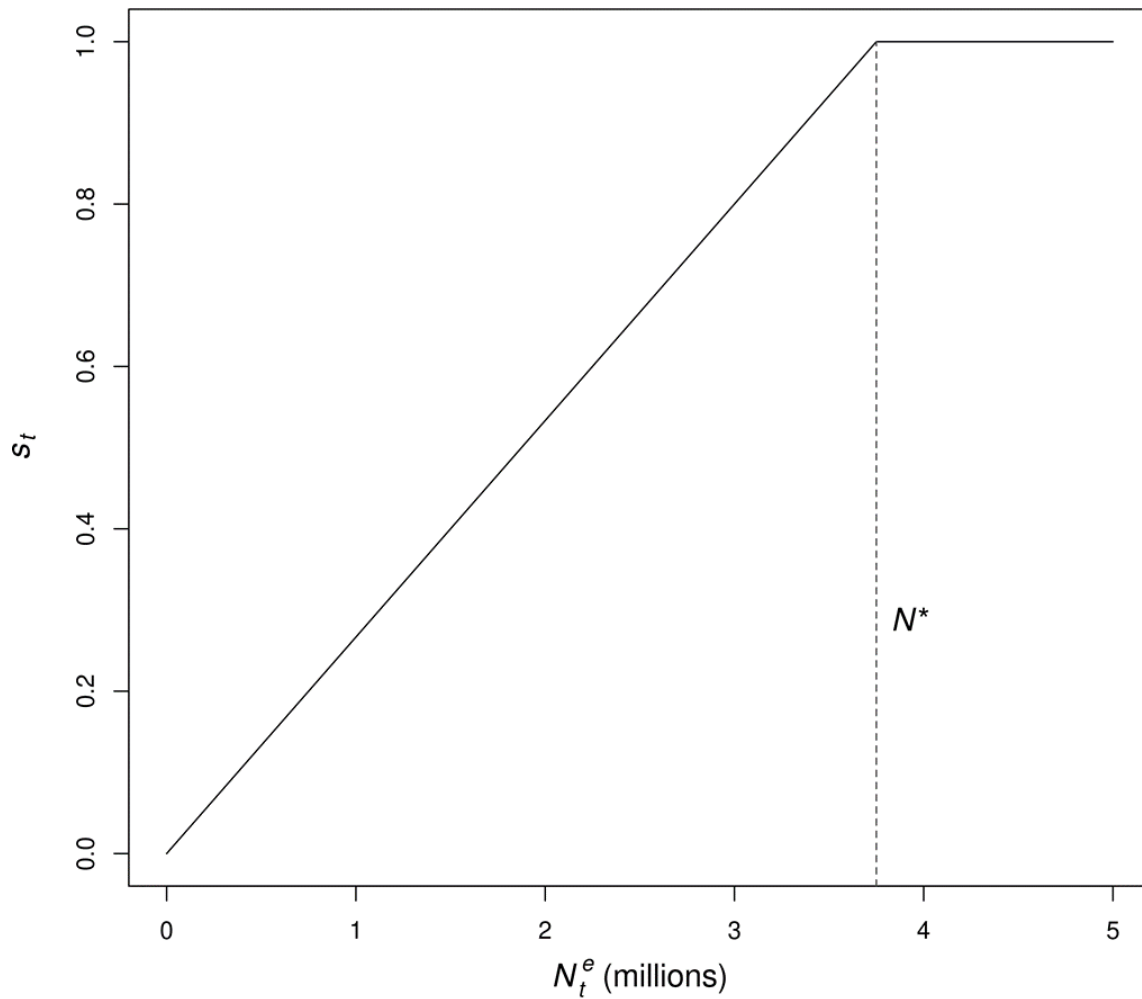


Figure 28. Broken-stick function to determine scalars s_t that are used to depress recruitment in year $t+9$ or $t+10$ (see Equations 10, 11) when the effective number of spawners N^e is below the threshold $N^* = 3,750,000$ in year t .

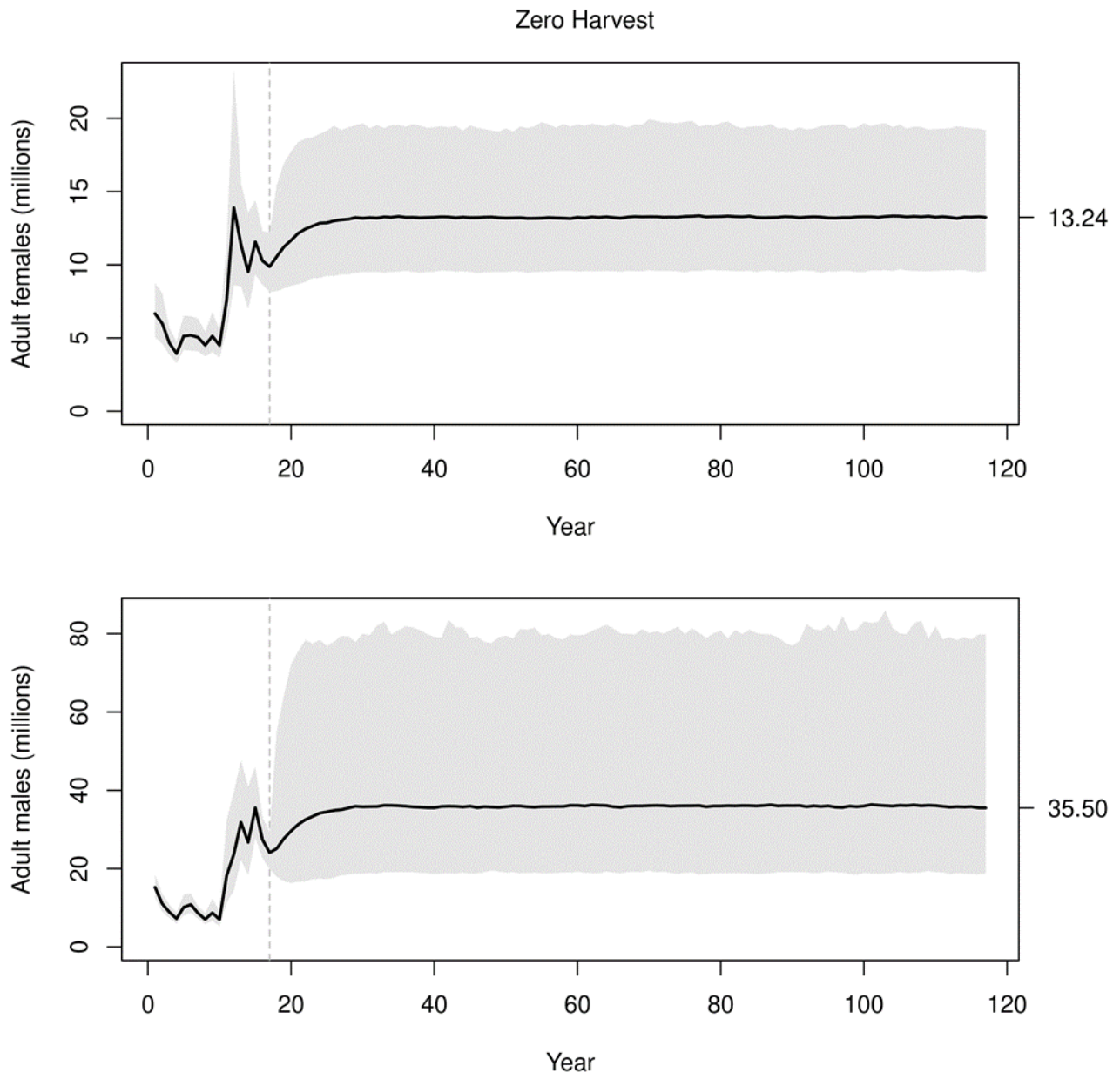


Figure 29. Summary of female (top panel) and male (bottom) horseshoe crab abundance from 5,000 simulations of the Delaware Bay population with no bait or background harvest. Black line indicates the median across simulations; the edges of the gray shaded region show the 2.5th and 97.5th quantiles. Dashed line indicates the final year for which abundance estimates from the Catch Multiple Survey Analysis are available (2019): curves to the left of this line represent CMSA estimates, those to the right are projections into the future. Value in the righthand margin gives the median abundance in year 100 of the simulations.

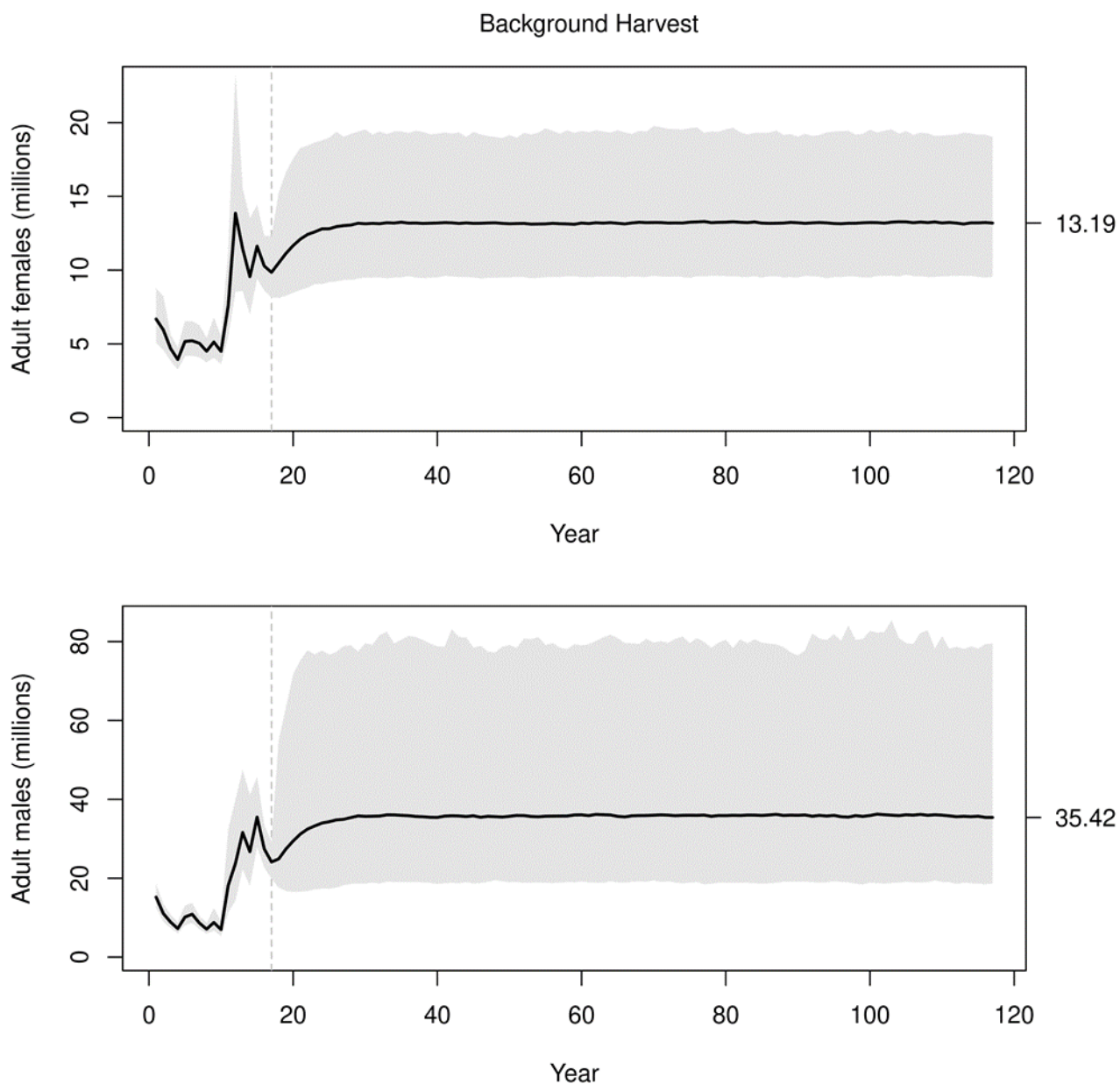


Figure 30. Summary of female (top panel) and male (bottom) horseshoe crab abundance from 5,000 simulations of the Delaware Bay population with background harvest only (no bait harvest). Black line indicates the median across simulations; the edges of the gray shaded region show the 2.5th and 97.5th quantiles. Dashed line indicates the final year for which abundance estimates from the Catch Multiple Survey Analysis are available (2019): curves to the left of this line represent CMSA estimates, those to the right are projections into the future. Value in the righthand margin gives the median abundance in year 100 of the simulations.

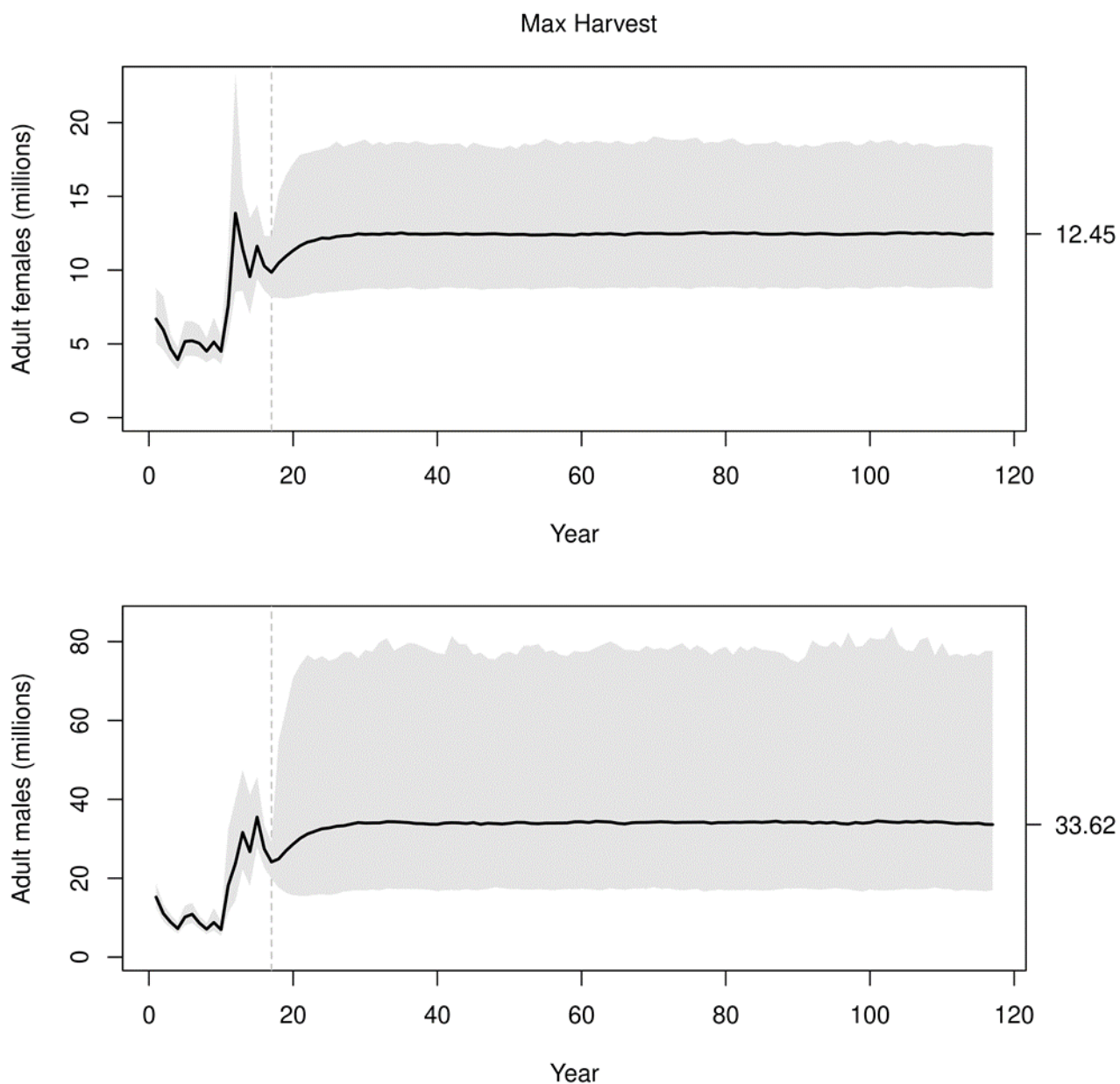


Figure 31. Summary of female (top panel) and male (bottom) horseshoe crab abundance from 5,000 simulations of the Delaware Bay population with maximum bait harvest allowed under the HSC-REKN ARM framework : 210,000 females annually, 500,000 males. Black line indicates the median across simulations; the edges of the gray shaded region show the 2.5th and 97.5th quantiles. Dashed line indicates the final year for which abundance estimates from the Catch Multiple Survey Analysis are available (2019): curves to the left of this line represent CMSA estimates, those to the right are projections into the future. Value in the righthand margin gives the median abundance in year 100 of the simulations.

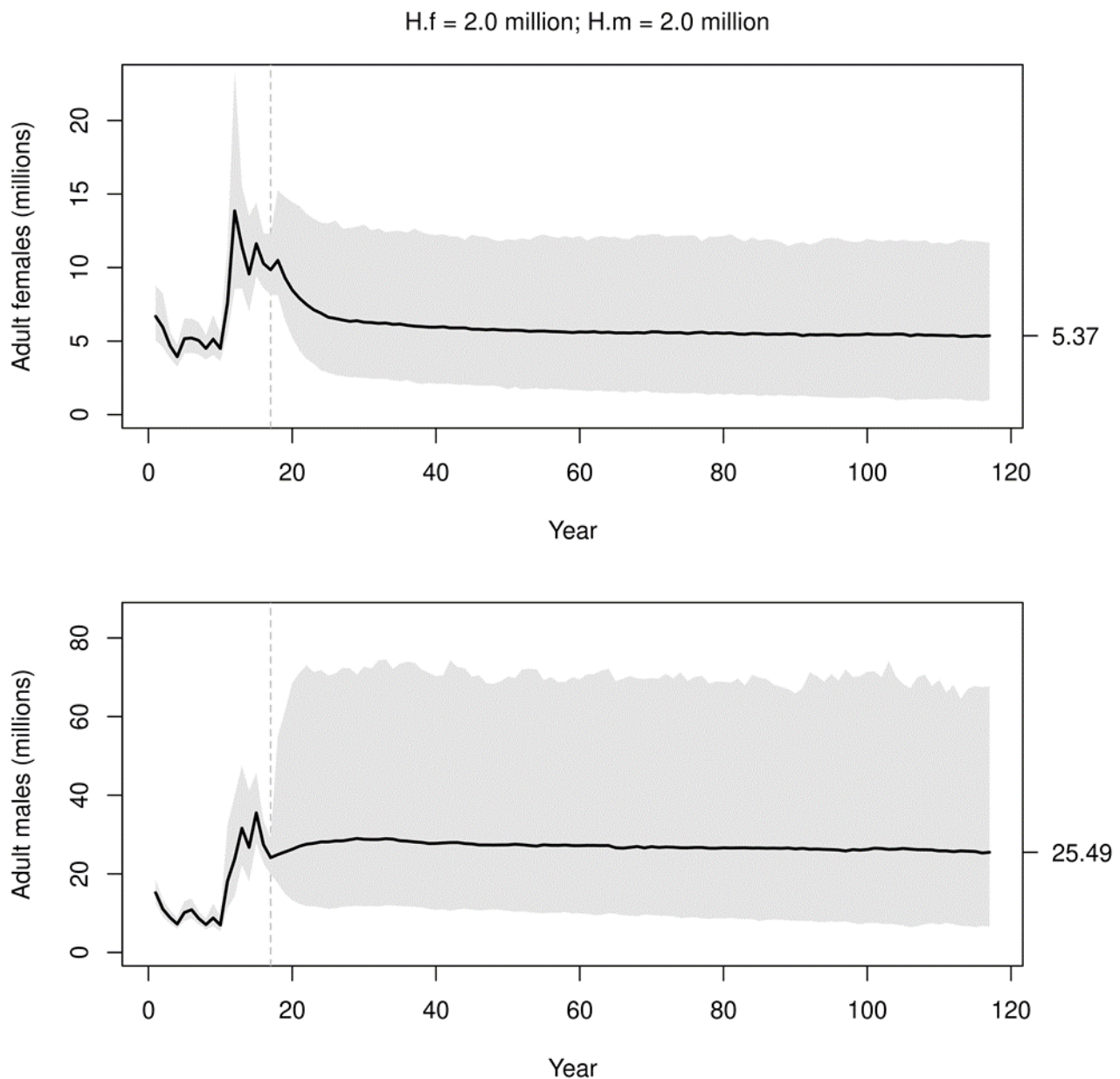


Figure 32. Summary of female (top panel) and male (bottom) horseshoe crab abundance from 5,000 simulations of the Delaware Bay population with very large harvest : 2 million females annually, and 2 million males. Black line indicates the median across simulations; the edges of the gray shaded region show the 2.5th and 97.5th quantiles. Dashed line indicates the final year for which abundance estimates from the Catch Multiple Survey Analysis are available (2019): curves to the left of this line represent CMSA estimates, those to the right are projections into the future. Value in the righthand margin gives the median abundance in year 100 of the simulations.

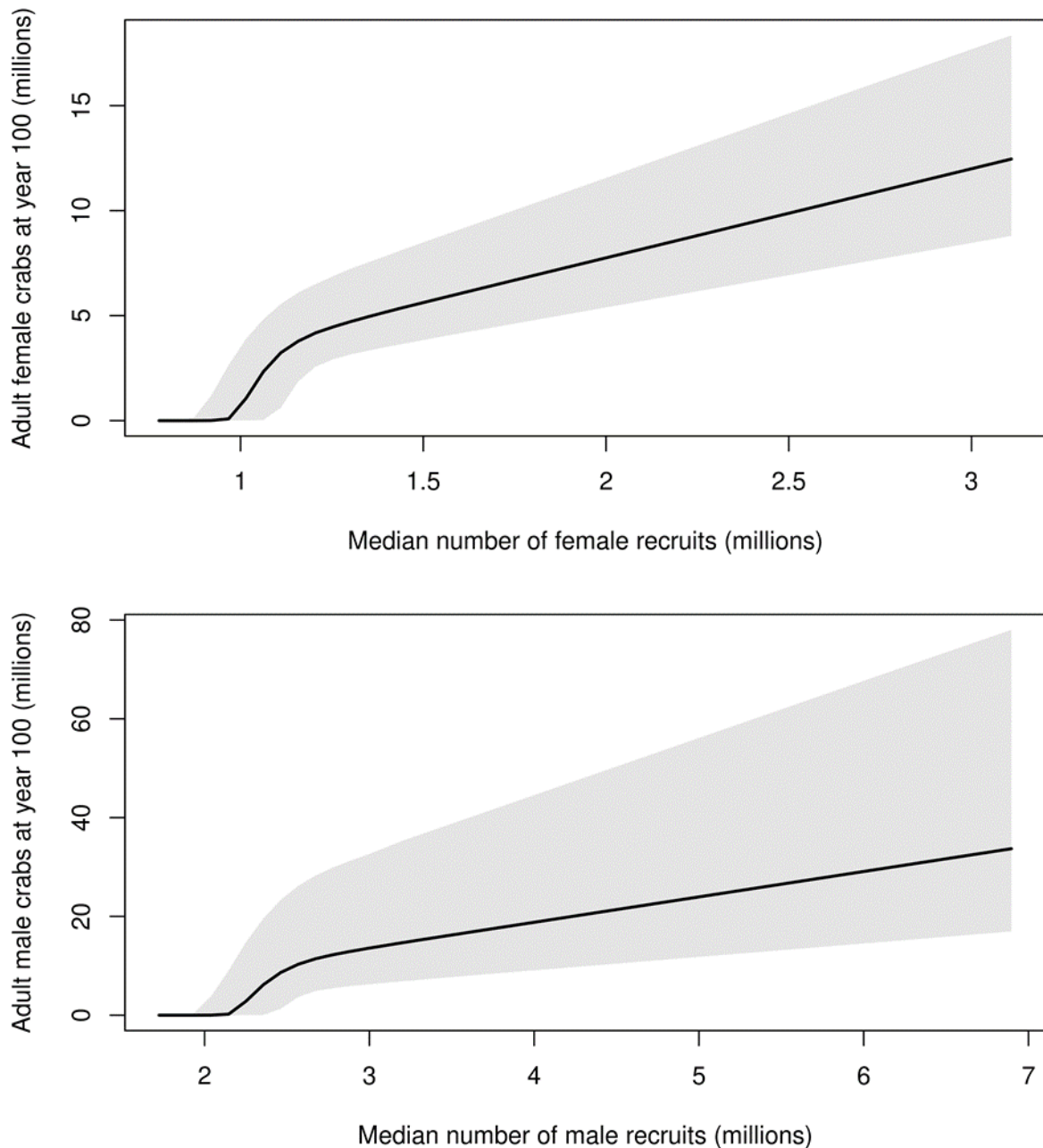


Figure 33. Sensitivity of female (top panel) and male (bottom) horseshoe crab abundance in projection year 100 to reductions in the value of $\exp(\mu)$, the median of the bivariate lognormal distribution that generates recruits in the projection model. The black line represents the median over 5,000 iterations, the gray region represents values between the 2.5th to 97.5th quantiles.

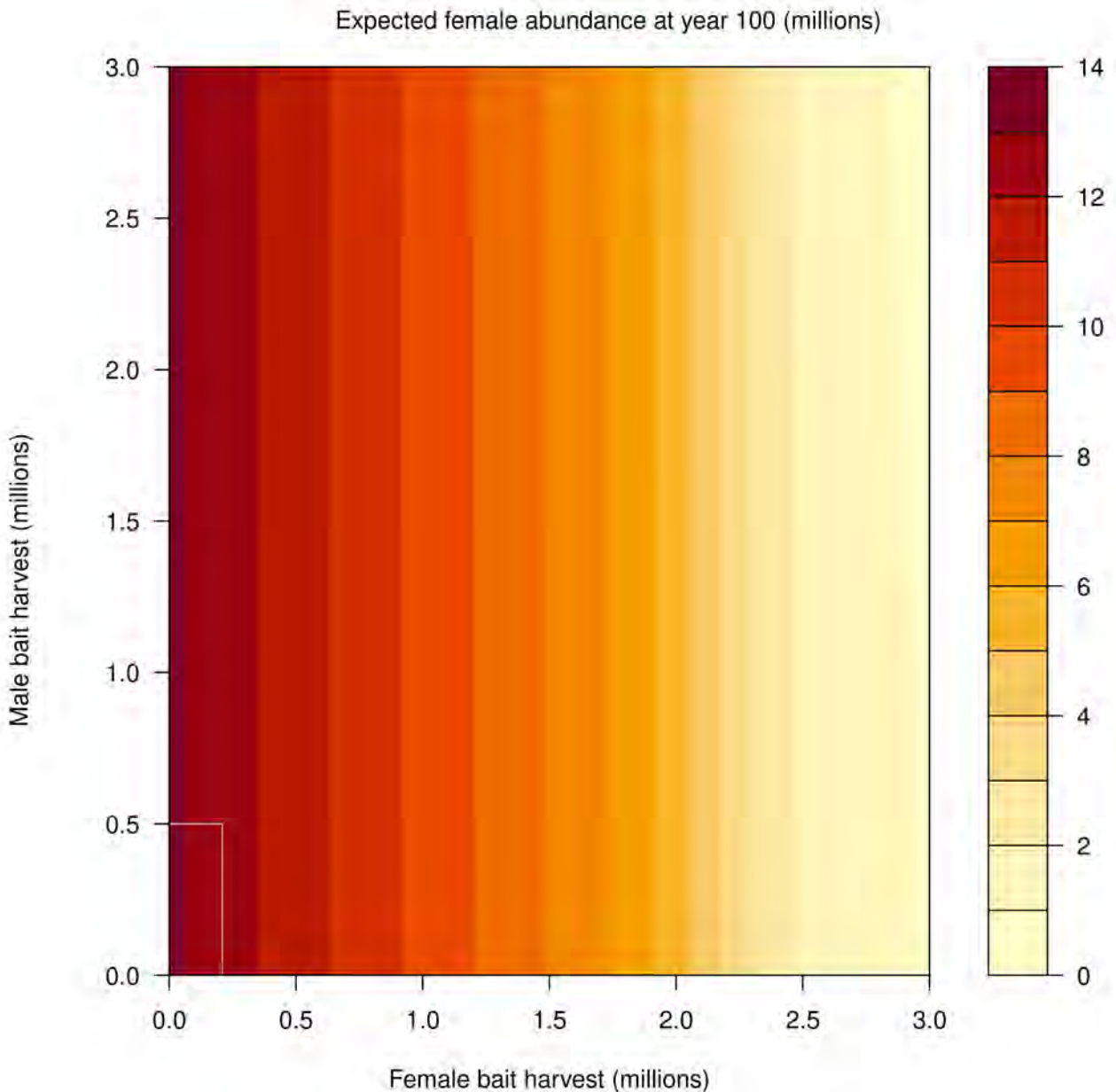


Figure 34. Expected female HSC abundance in projection year 100, over varying values of annual female and male harvest. Mean recruitment parameters μ were at their nominal values (Table 20). Each point in the graph represents the median abundance in year 100, over 5,000 simulations. Note that although harvest varied across scenario, it was constant through time. The gray lines represent the maximum harvest limits considered under the ARM framework.

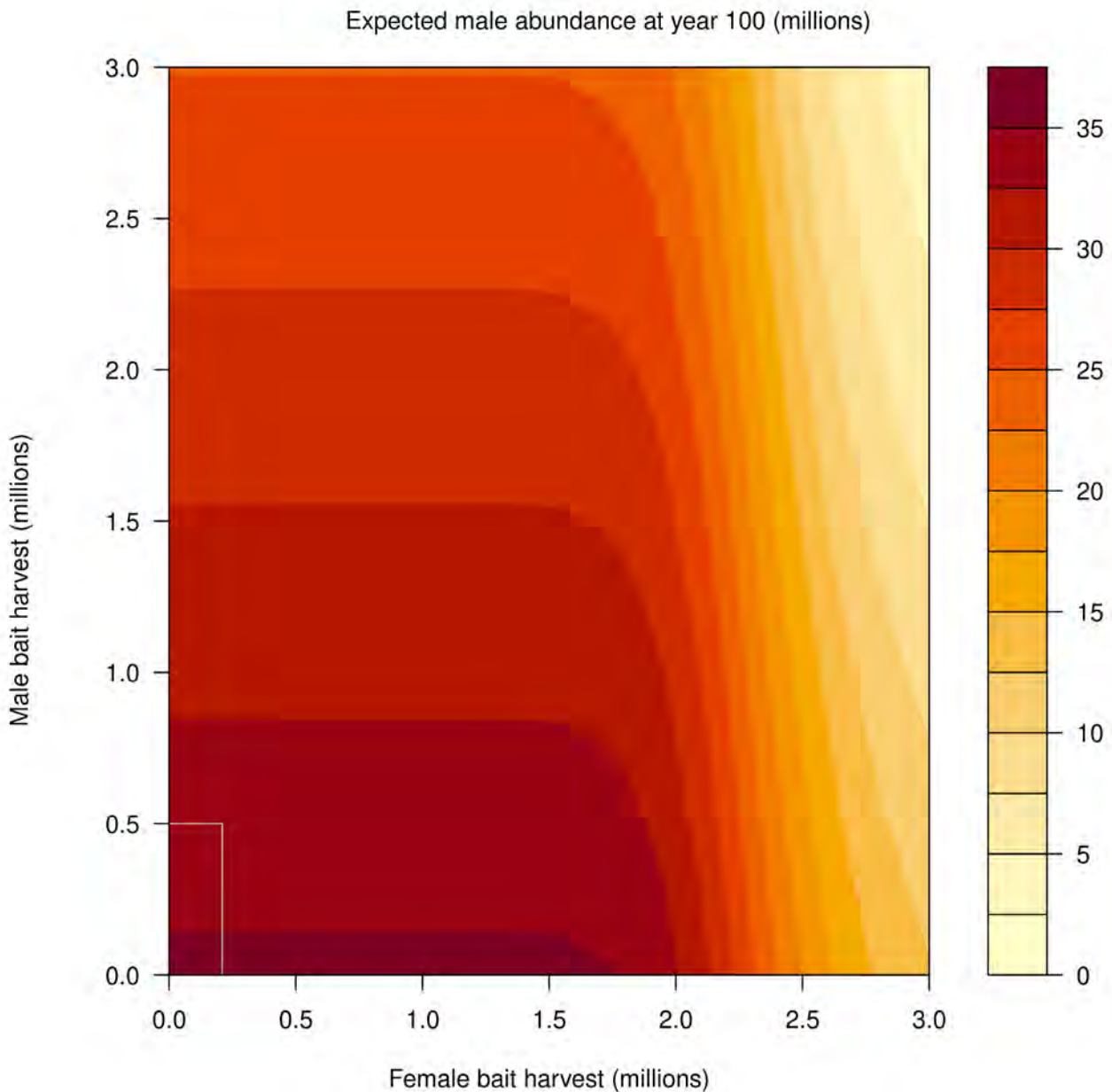


Figure 35. Expected male HSC abundance in projection year 100, over varying values of annual female and male harvest. Mean recruitment parameters μ were at their nominal values (Table 1). Each point in the graph represents the median abundance in year 100, over 5,000 simulations. Note that although harvest varied across scenario, it was constant through time. The gray lines represent the maximum harvest limits considered under the ARM framework.

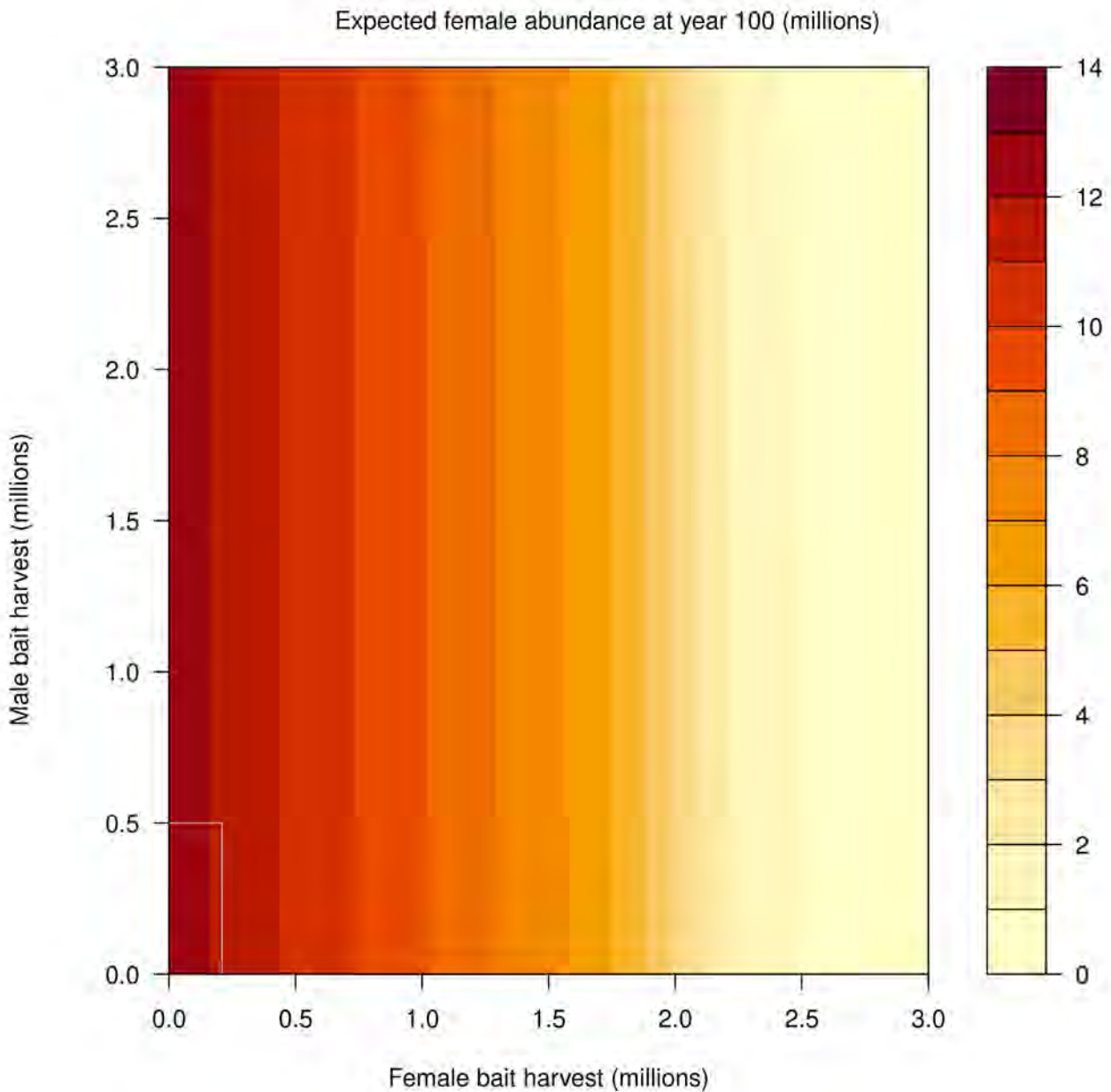


Figure 36. Expected female HSC abundance in projection year 100, over varying values of annual female and male harvest. Mean recruitment parameters μ were reduced such that median recruitment was reduced by 5%: $\exp(\mu) \times 0.95$. Each point in the graph represents the median abundance in year 100, over 5,000 simulations. Note that although harvest varied across scenario, it was constant through time. The gray lines represent the maximum harvest limits considered under the ARM framework.

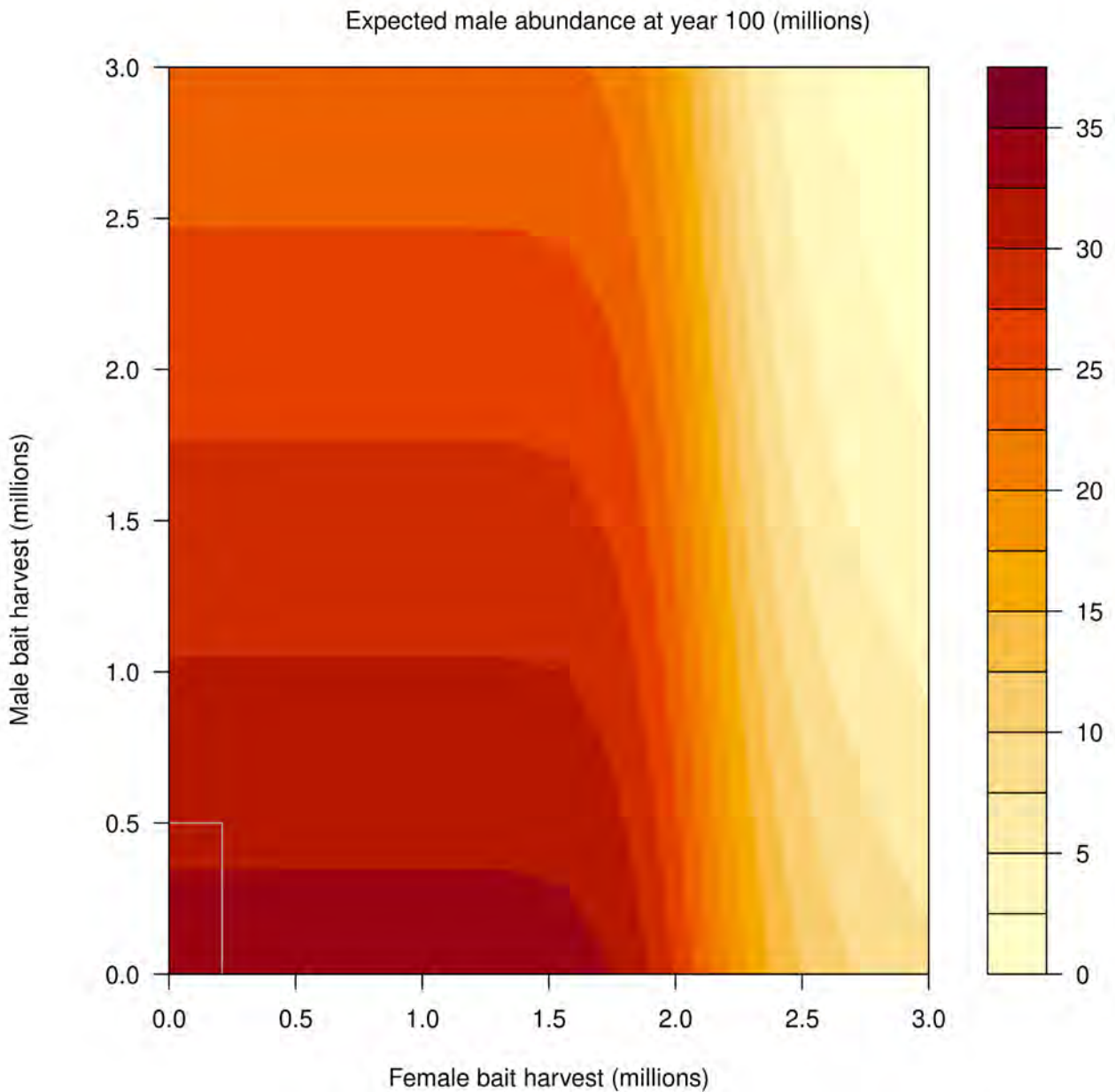


Figure 37. Expected male HSC abundance in projection year 100, over varying values of annual female and male harvest. Mean recruitment parameters μ were reduced such that median recruitment was reduced by 5%: $\exp(\mu) \times 0.95$. Each point in the graph represents the median abundance in year 100, over 5,000 simulations. Note that although harvest varied across scenario, it was constant through time. The gray lines represent the maximum harvest limits considered under the ARM framework.

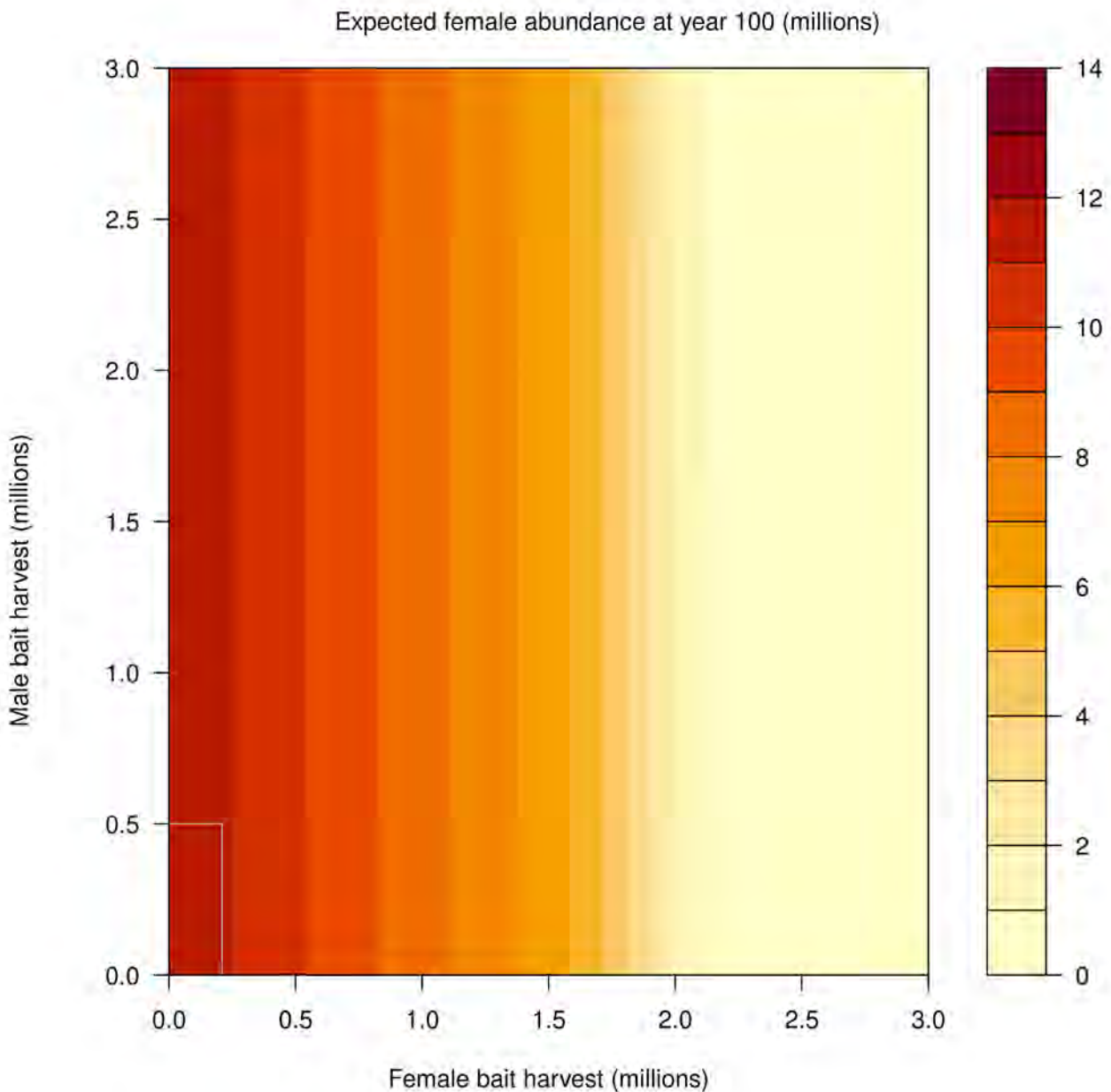


Figure 38. Expected female HSC abundance in projection year 100, over varying values of annual female and male harvest. Mean recruitment parameters μ were reduced such that median recruitment was reduced by 10%: $\exp(\mu) \times 0.90$. Each point in the graph represents the median abundance in year 100, over 5,000 simulations. Note that although harvest varied across scenario, it was constant through time. The gray lines represent the maximum harvest limits considered under the ARM framework.

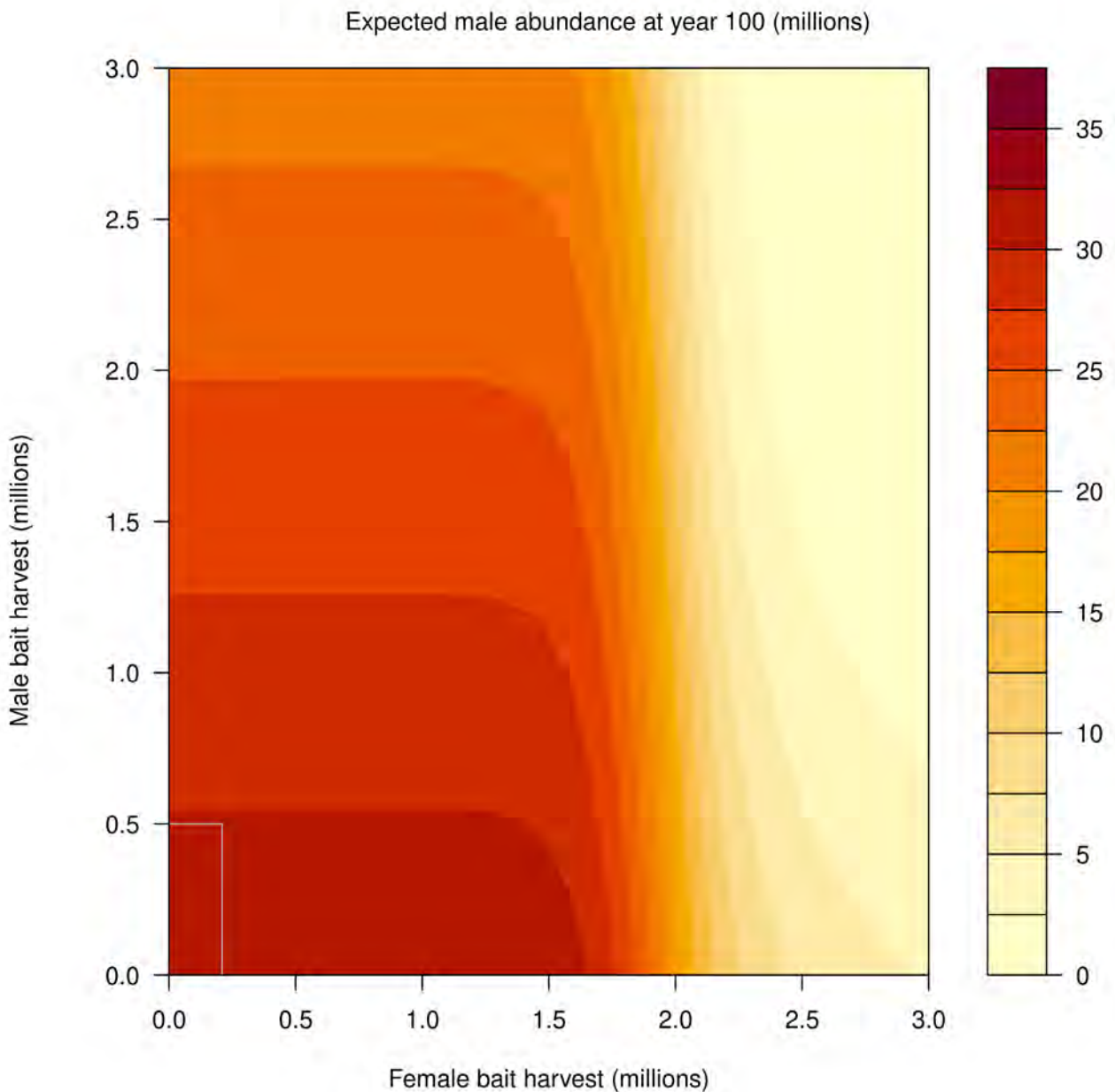


Figure 39. Expected male HSC abundance in projection year 100, over varying values of annual female and male harvest. Mean recruitment parameters μ were reduced such that median recruitment was reduced by 10%: $\exp(\mu) \times 0.90$. Each point in the graph represents the median abundance in year 100, over 5,000 simulations. Note that although harvest varied across scenario, it was constant through time. The gray lines represent the maximum harvest limits considered under the ARM framework.

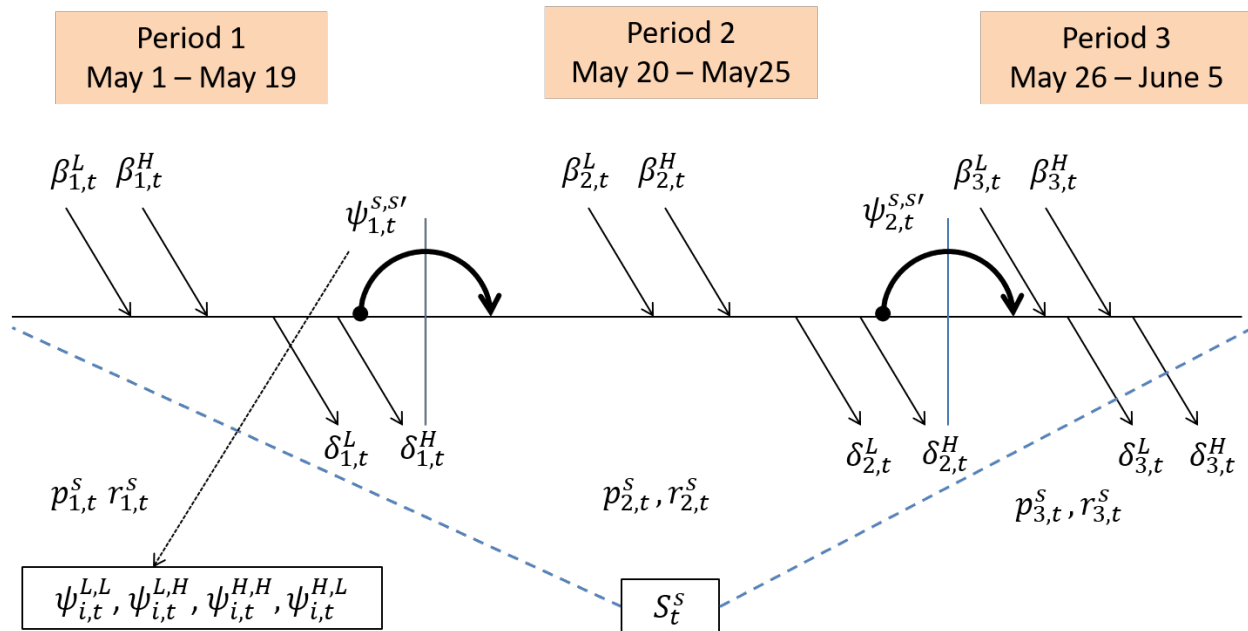


Figure 40. Schematic showing the primary period (stopover year) divided into three secondary periods to estimate survival and weight gain probabilities in a multistate open-robust-design analysis.



Figure 41. Example encounter histories for the multistate open robust design.

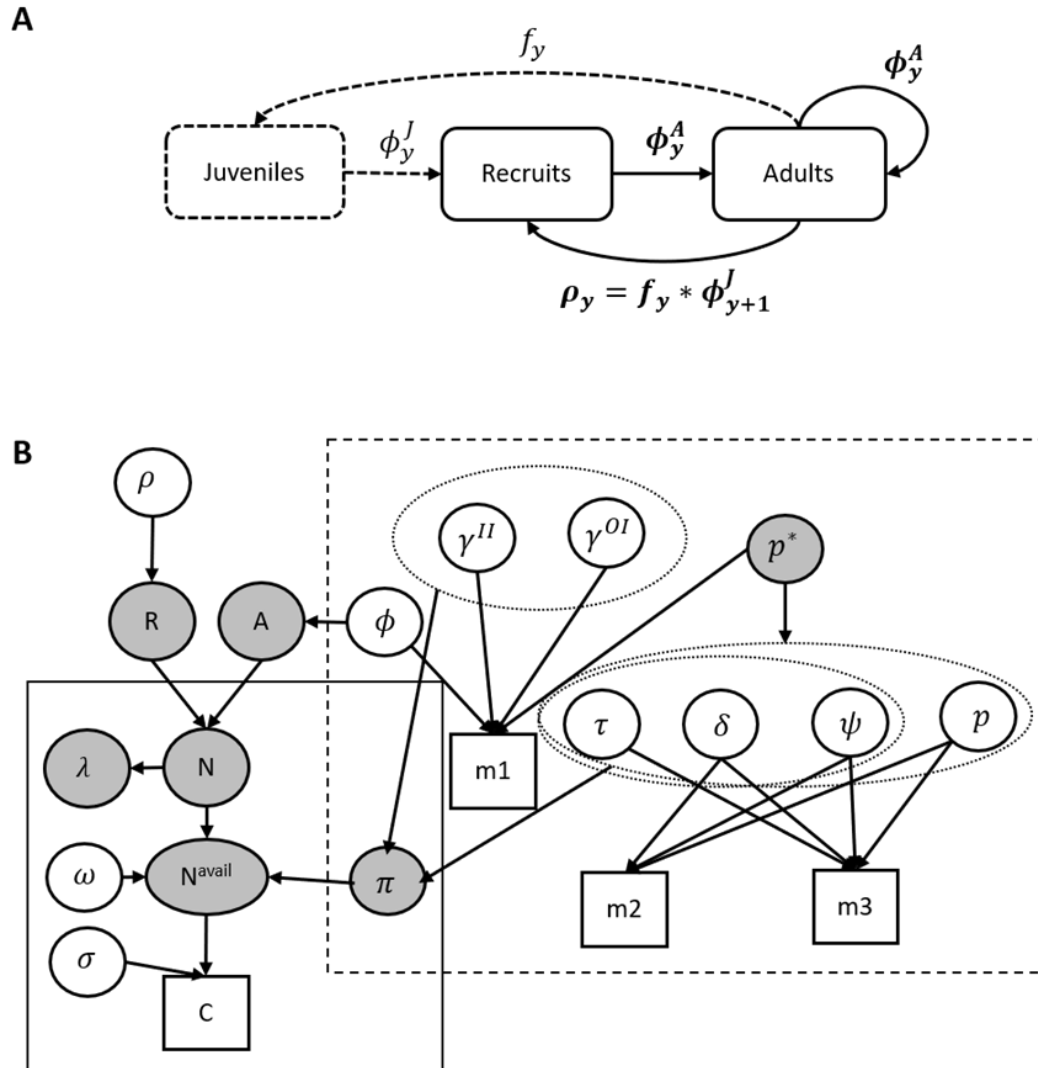


Figure 42. Conceptual diagram of the integrated population model. This model is based on a two-stage life cycle with a pre-breeding census (A) in which individuals do not breed until their second year. A recruitment rate, ρ , was estimated which is a product of fecundity and juvenile survival and assume that new recruits have the same survival probability as returning adults. The integrated population model (B) uses an open robust design sub-model to estimate annual survival probability, ϕ , while accounting for temporary emigration and the proportion of the population available to be counted, π , based on estimated within-season dynamics of arrival and departure. In this diagram, white circles indicate estimated parameters, gray circles indicate derived parameters, and squares indicate data (C = counts, $m1$ = m-array for the primary periods, $m2$ = m-array for new encounters within secondary periods, and $m3$ = m-array for subsequent encounters within secondary periods). The open robust design sub-model components are in the dashed box and the state-space sub-model for counts is in the solid box. All parameters are defined in Table 23.

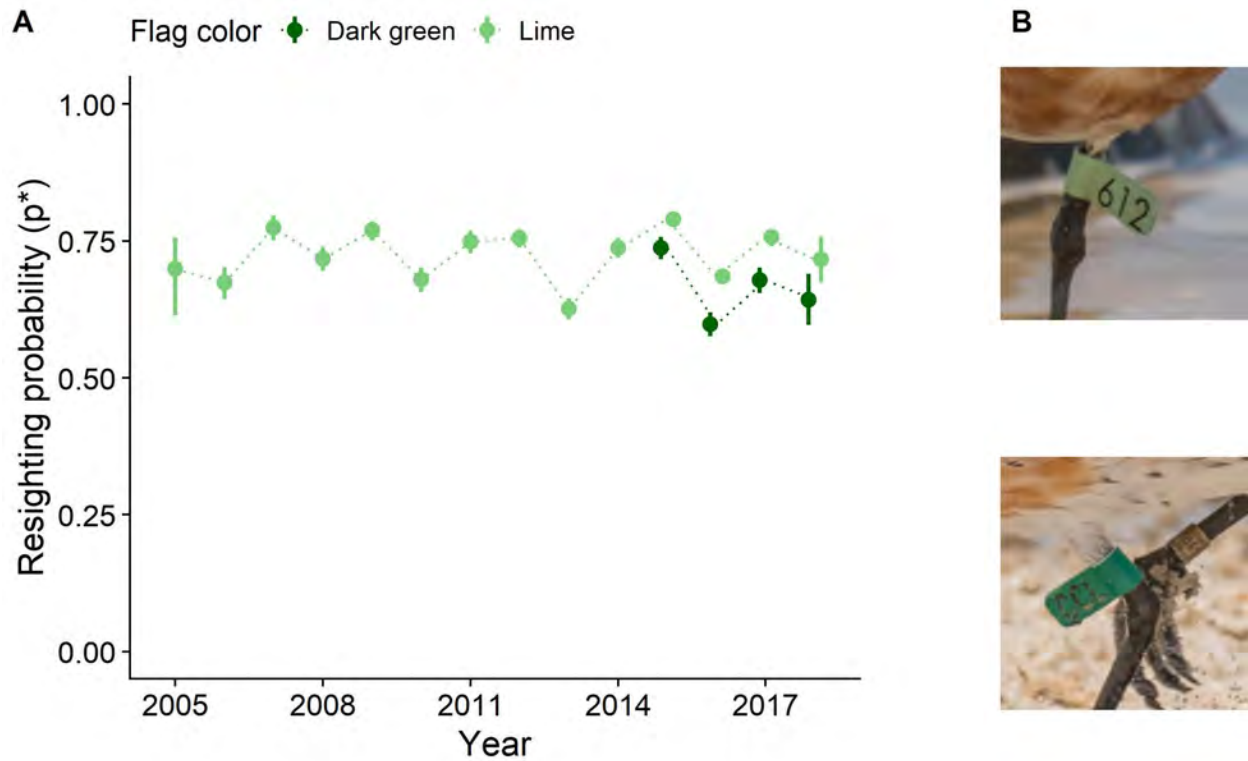


Figure 43. Estimated resighting probability of red knot marked with field-readable plastic leg flags , 2005-2018 (A). Dark green flags (B, bottom) were first deployed in 2014, and birds marked with these flags had a lower resighting probability than birds marked with light green (lime) flags (B, top).

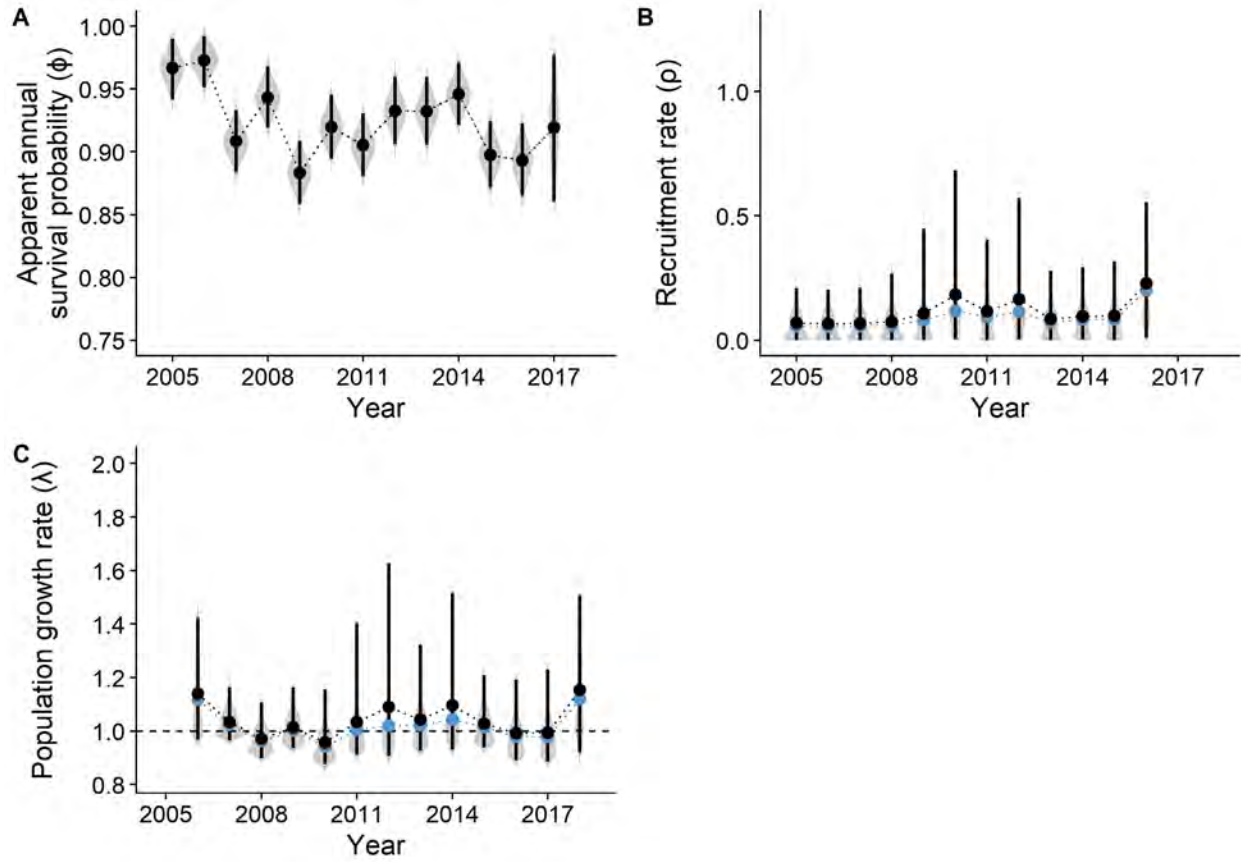


Figure 44. Estimates of survival (A), recruitment (B), and population growth rate (C) over time for red knot, 2005-2018. Gray shaded regions show the full posterior distributions. Black points and vertical lines represent posterior means and 95% credible intervals. Blue points represent the medians of the posterior distributions.

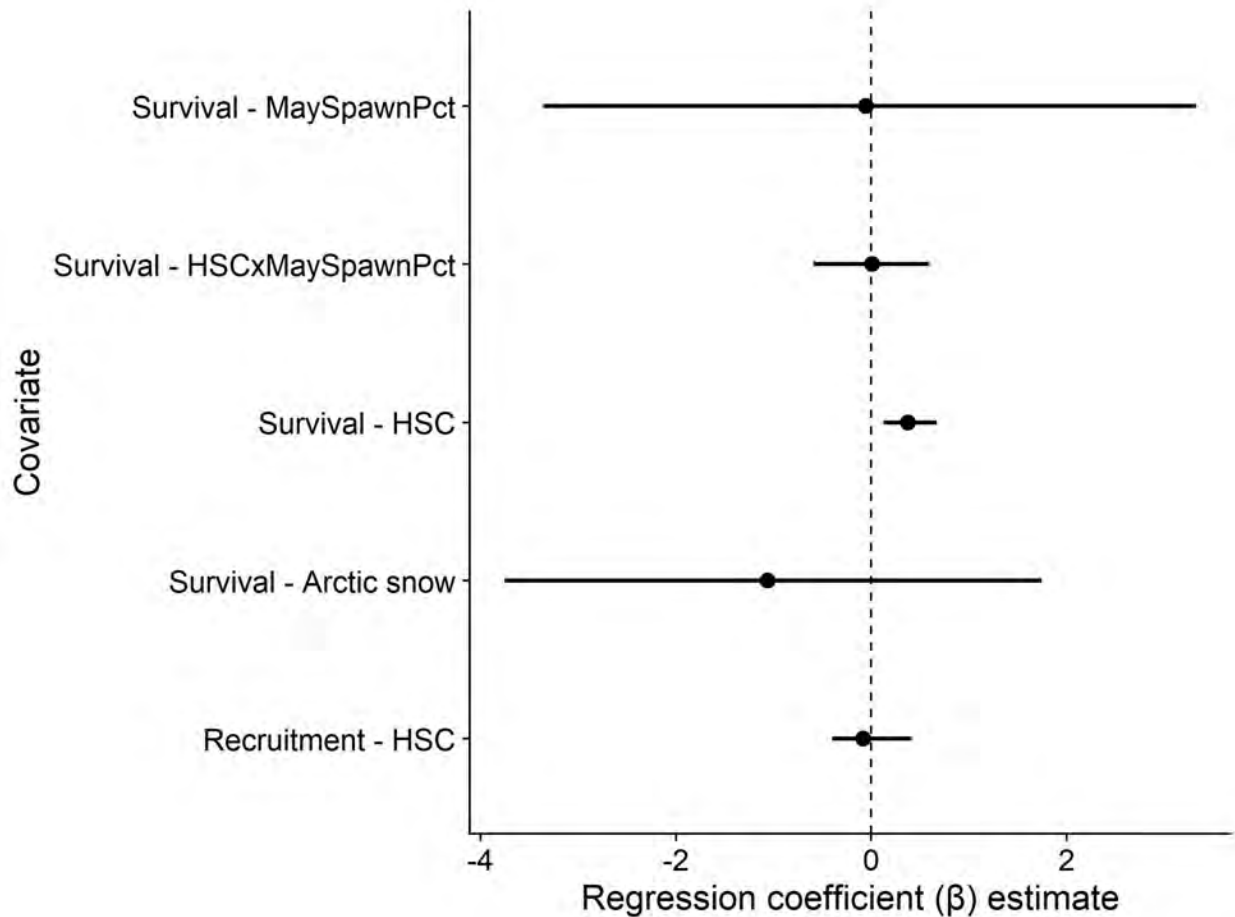


Figure 45. Estimated effects of horseshoe crab abundance, spawn timing, and Arctic snow on red knot survival probability and recruitment rate. Points represent posterior means of the standardized regression coefficients and vertical lines represent 95% credible intervals.

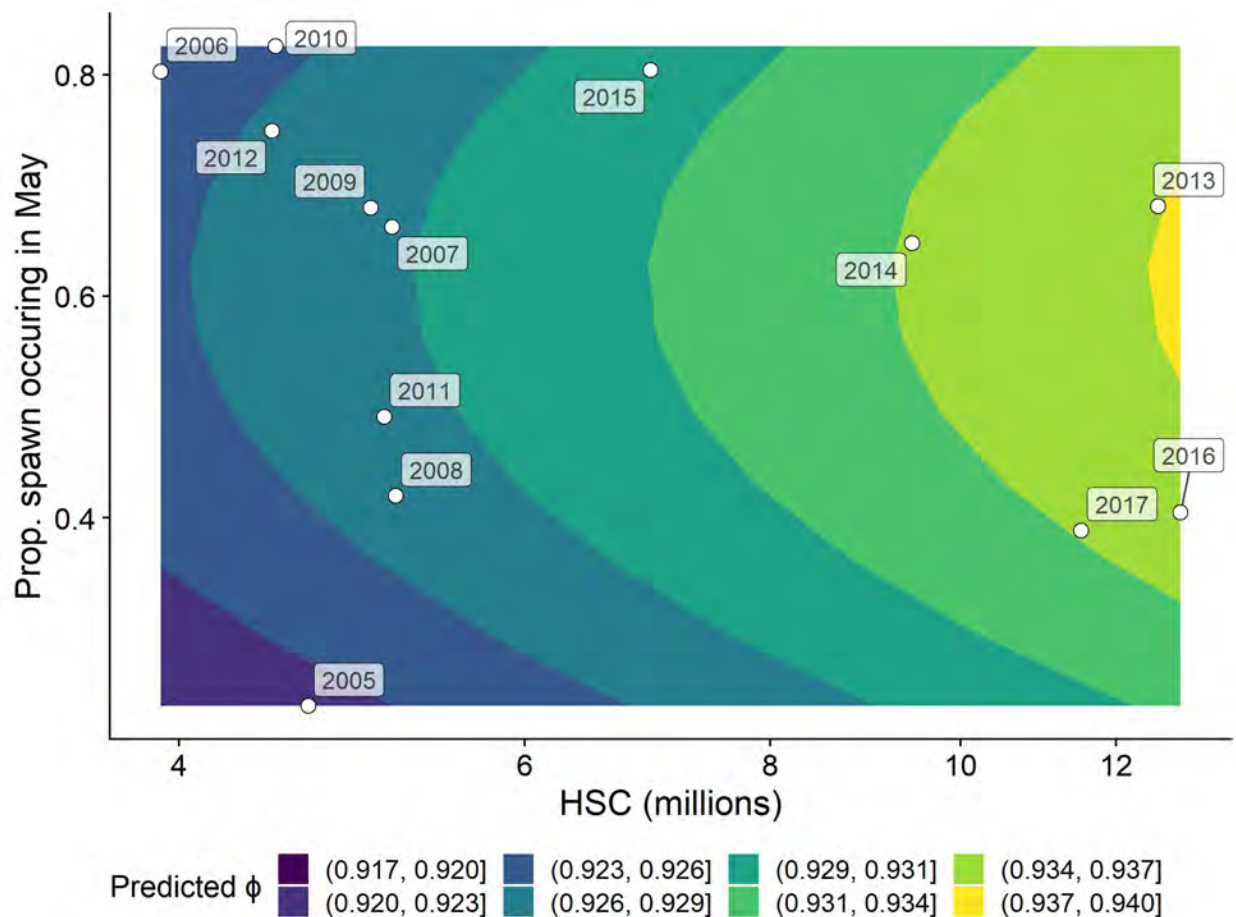


Figure 46. Interactive effects of horseshoe crab abundance and timing of spawn on predicted annual survival probability for red knot. The x-axis represents horseshoe crab abundance and the y-axis represents the proportion of spawning activity that occurred in May. Shaded regions indicate the predicted annual survival probability, and points show observed data. Horseshoe crab abundance was log-transformed for analysis, but values on the natural scale are presented here for ease of interpretation.

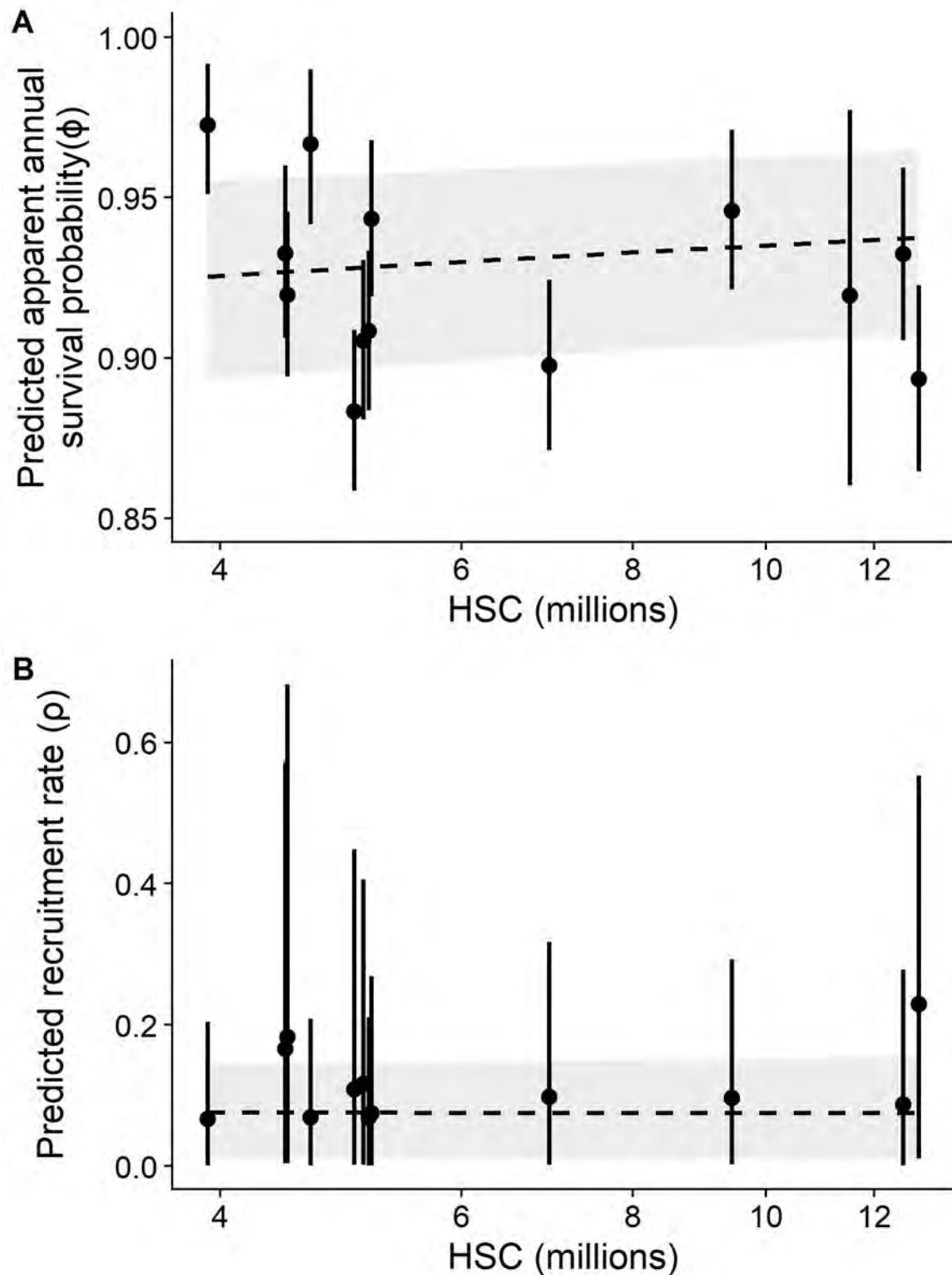


Figure 47. Estimated relationship between horseshoe crab abundance and red knot demographic rates. The black dashed line and gray shaded region show the mean and 95% credible interval of the predicted values. Points and vertical lines show the mean and 95% credible interval of model estimates.

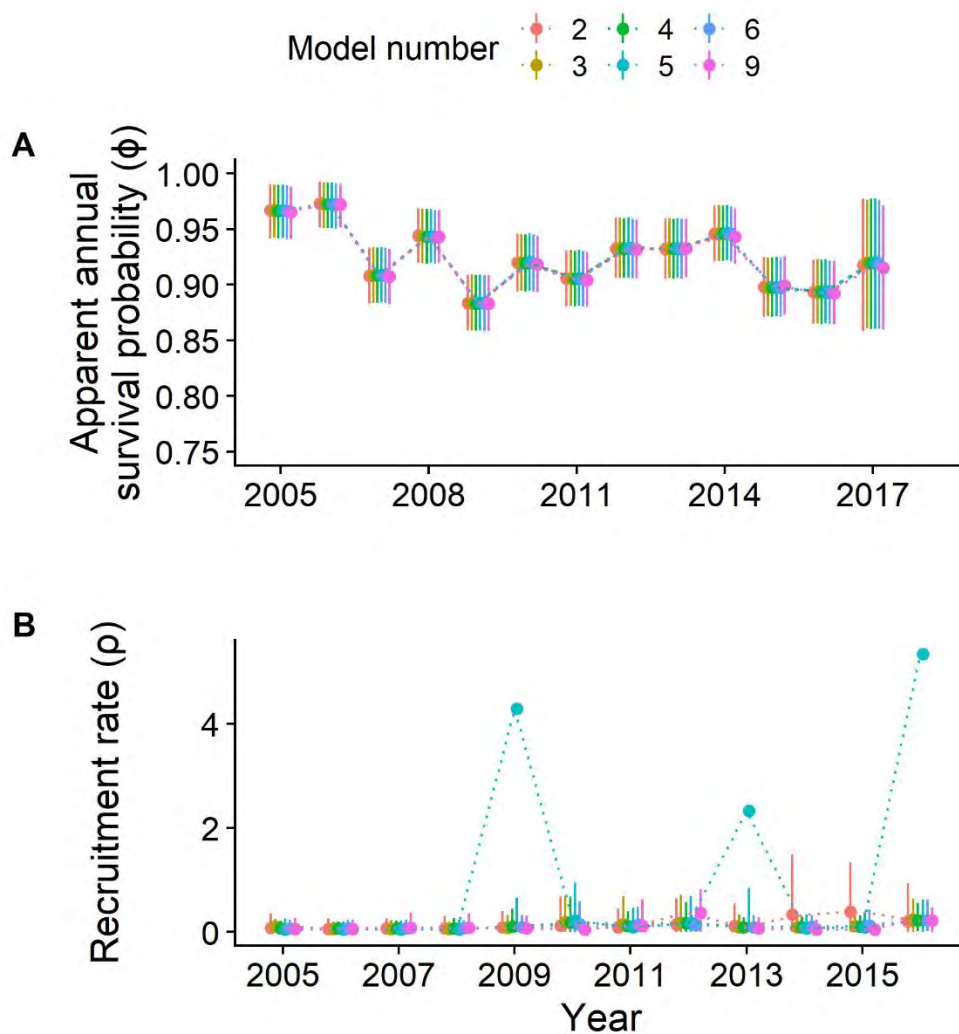


Figure 48. Results of the IPM sensitivity runs to evaluate the influence of the prior distributions for availability, average recruitment rate, and variance in recruitment rate on demographic parameter estimates. Solid points represent posterior means and vertical lines are 95% credible intervals. Model versions are described in Table 27.

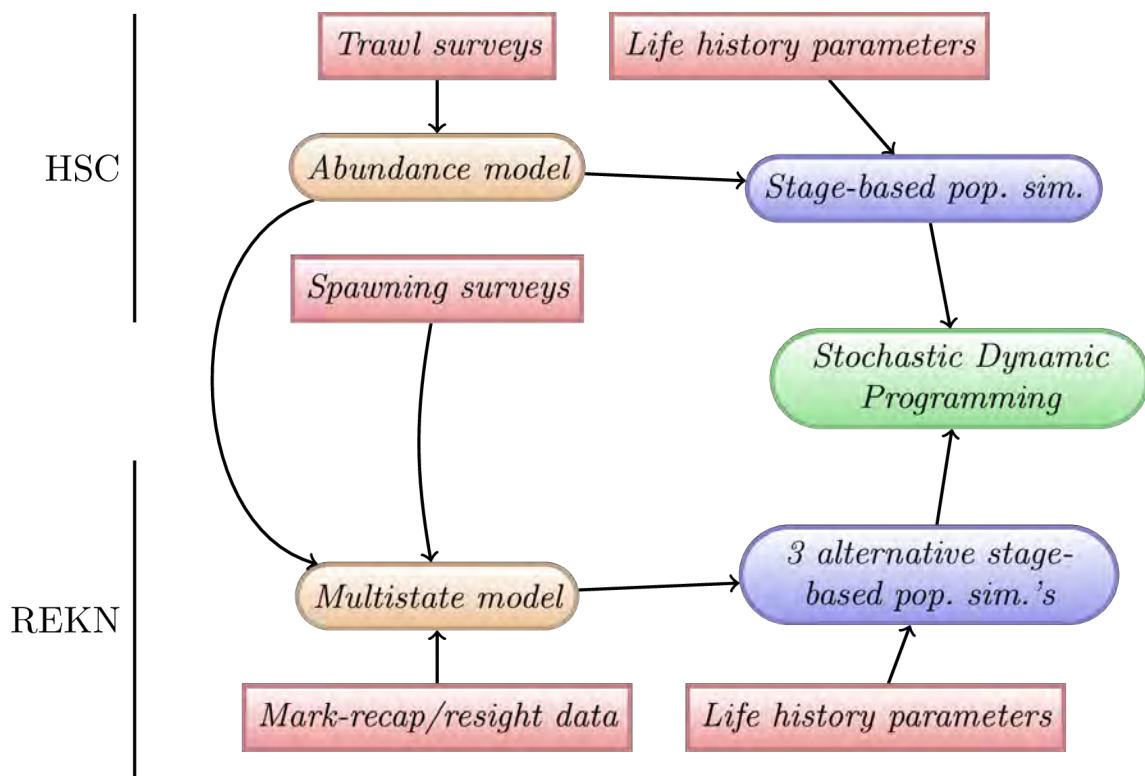


Figure 49. Components of the original ARM framework described by ASMFC (2009) and their relationships. Empirical datasets in red; estimation models shown in yellow; simulation models in blue; optimization algorithm in green. Components in the upper part of the diagram relate primarily to horseshoe crabs (HSC); those in the lower to red knots (REKN).

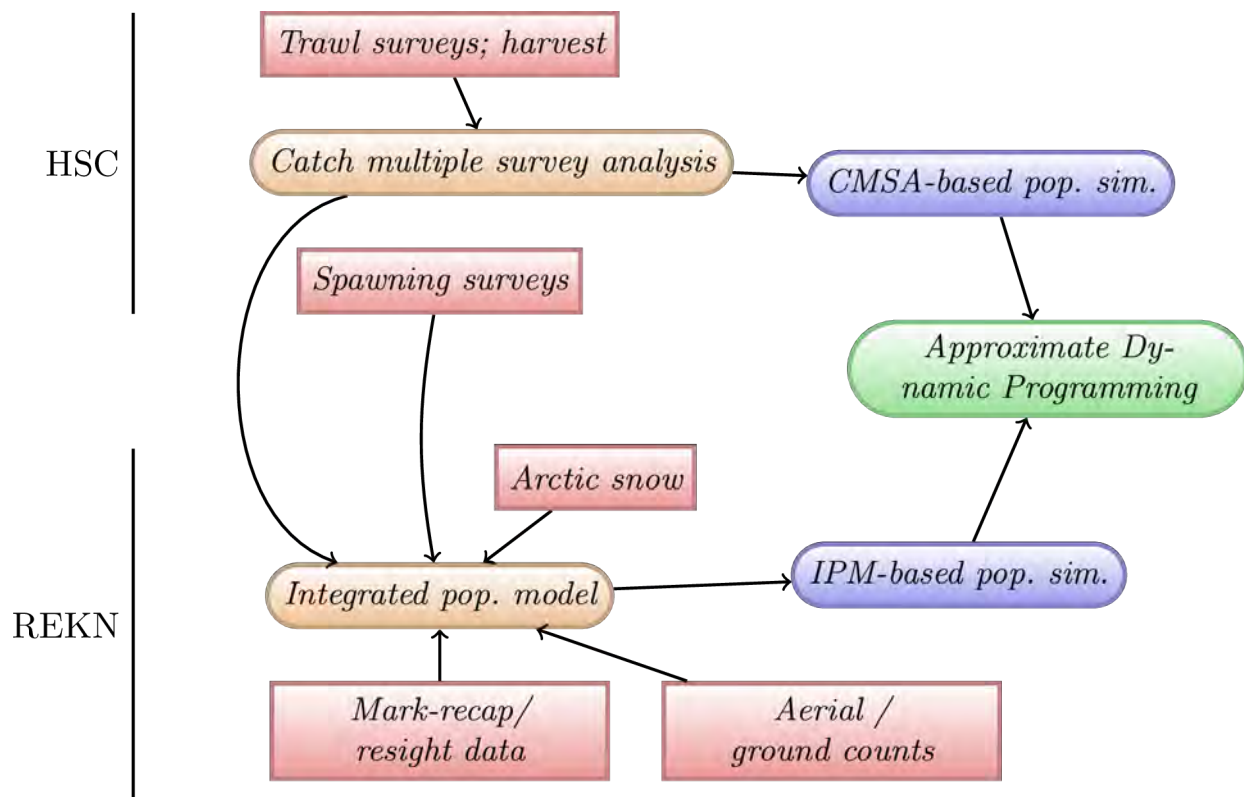


Figure 50. Components of the revised ARM framework described by ASMFC (2009) and their relationships. Empirical datasets in red; estimation models shown in yellow; simulation models in blue; optimization algorithm in green. Components in the upper part of the diagram relate primarily to horseshoe crabs (HSC); those in the lower to red knots (REKN).

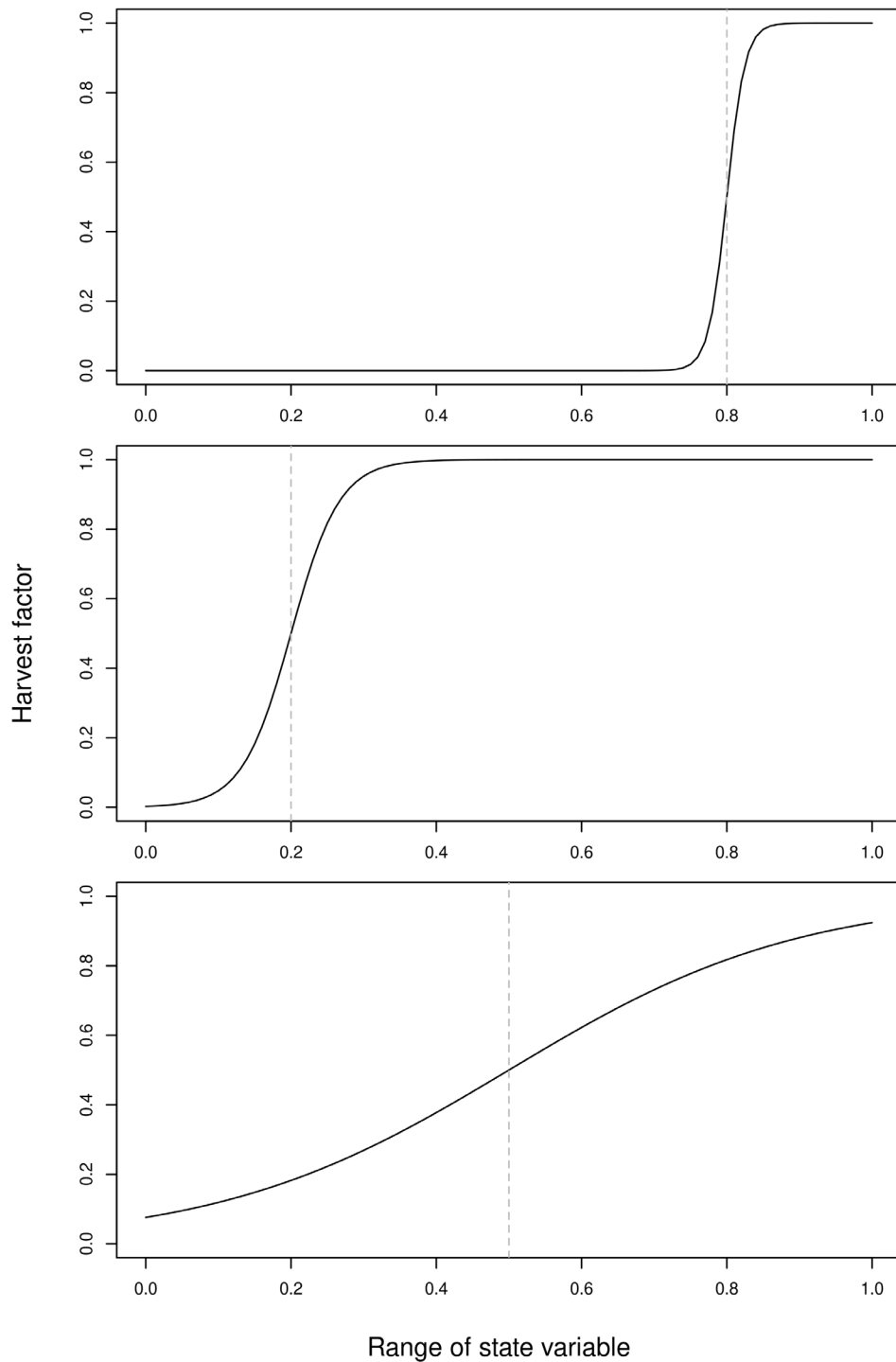


Figure 51. Examples of harvest factor curves produced by Equation 5. The x-axis shows the reasonable range of a hypothetical state variable; dashed lines show the inflection points. The top panel shows a curve with high slope (large α value) and high inflection point (large β); the middle panel one with relatively low inflection

point and moderate slope; the lower panel a moderate inflection point and shallow slope.

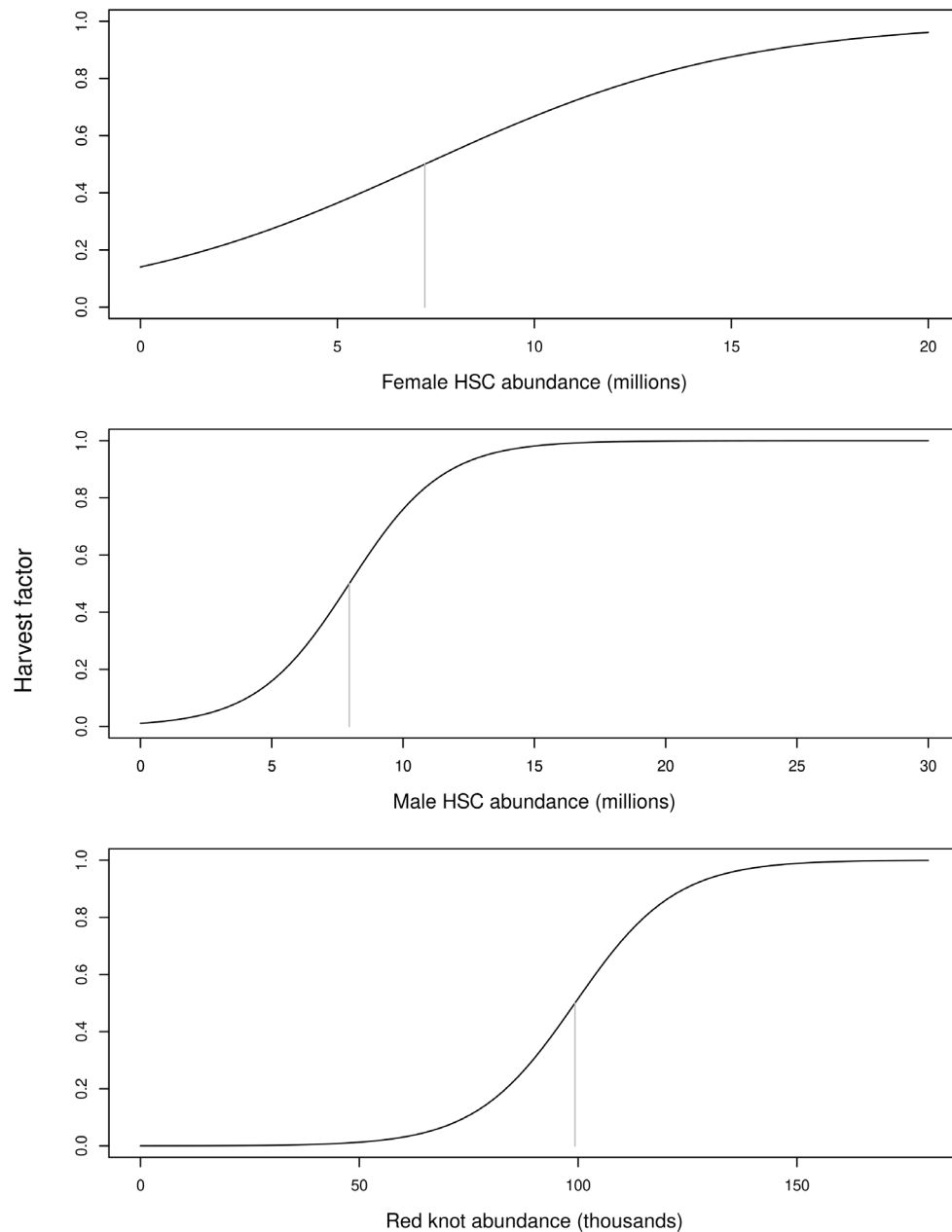


Figure 52. Optimal harvest factor curves (Table 31; Section 8.4.3). Each x-axis shows the possible range of the corresponding inflection point parameter (β) for that state variable. Gray line segments indicate the optimal inflection point.

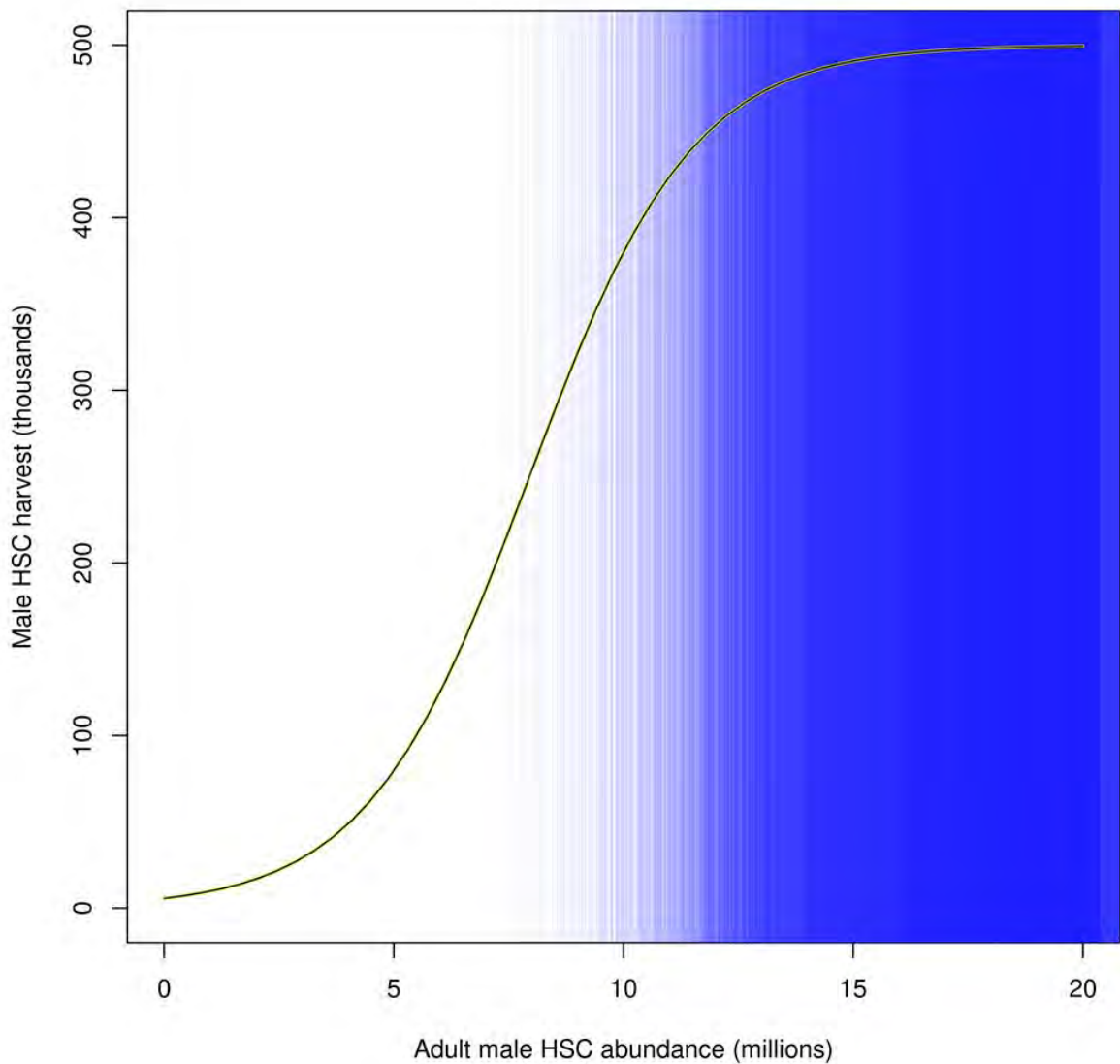


Figure 53. Optimal male bait harvest function for the canonical version of the revised ARM model , with $H_{\max}^f = 210,000$ and $H_{\max}^m = 500,000$. Vertical blue lines indicate actual male abundance values in a particular year, in one of 10,000 simulated horseshoe crab populations; many of these values are larger than the upper limit of the x-axis used here and thus are not shown.

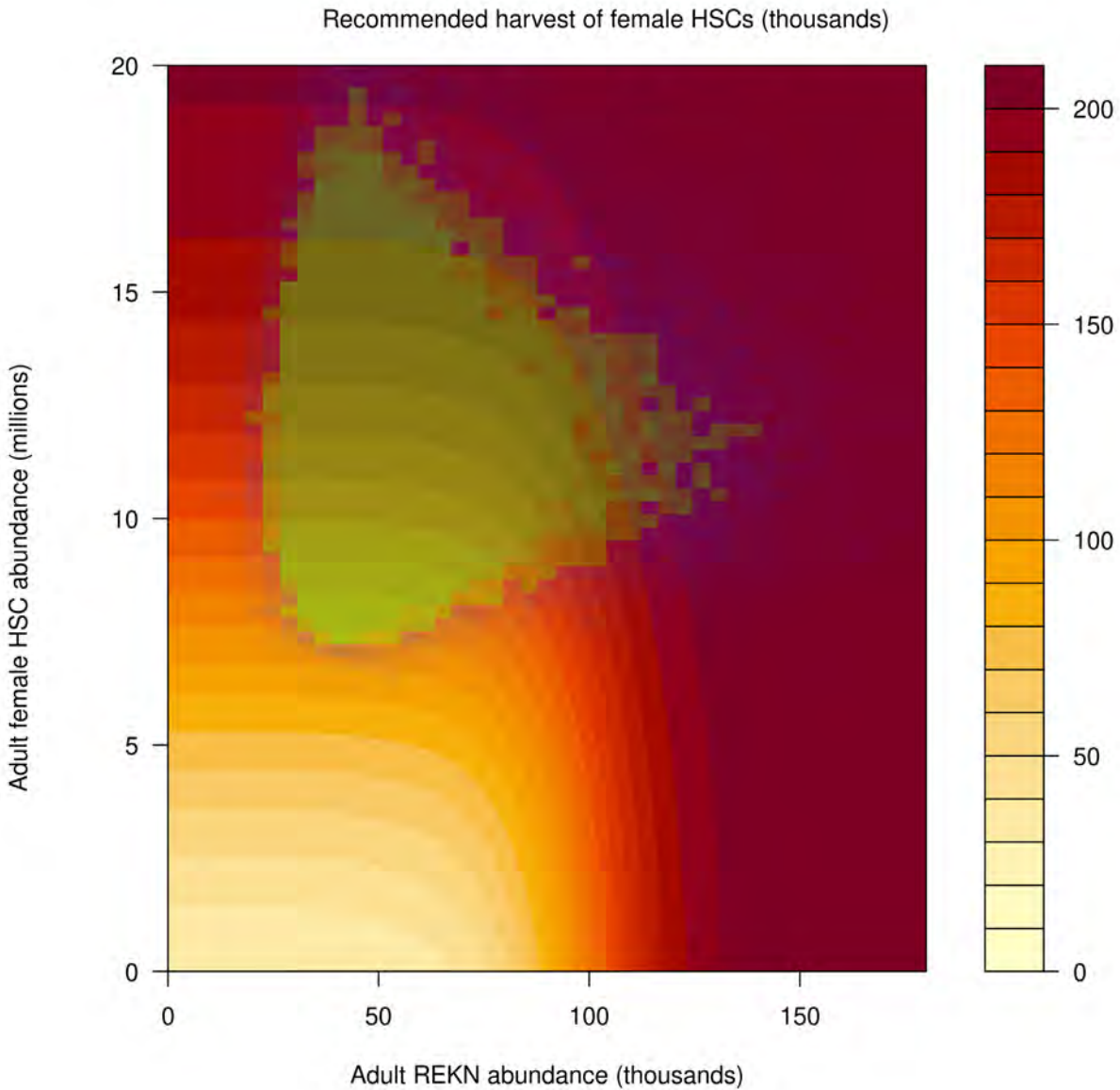


Figure 54. Optimal female bait harvest function for the canonical version of the revised ARM model , with $H_{\max}^f = 210,000$ and $H_{\max}^m = 500,000$. Recommended harvest depends on both female horseshoe crab (HSC) and adult red knot (REKN) abundances. Transparent green and blue overlay represents a non-parametric kernel, indicating where the bulk of the values of HSC and REKN abundances for the first 10 years of 10,000 simulations over 100 years: the green cells collectively contain 75% of the observations, the blue an additional 20%.

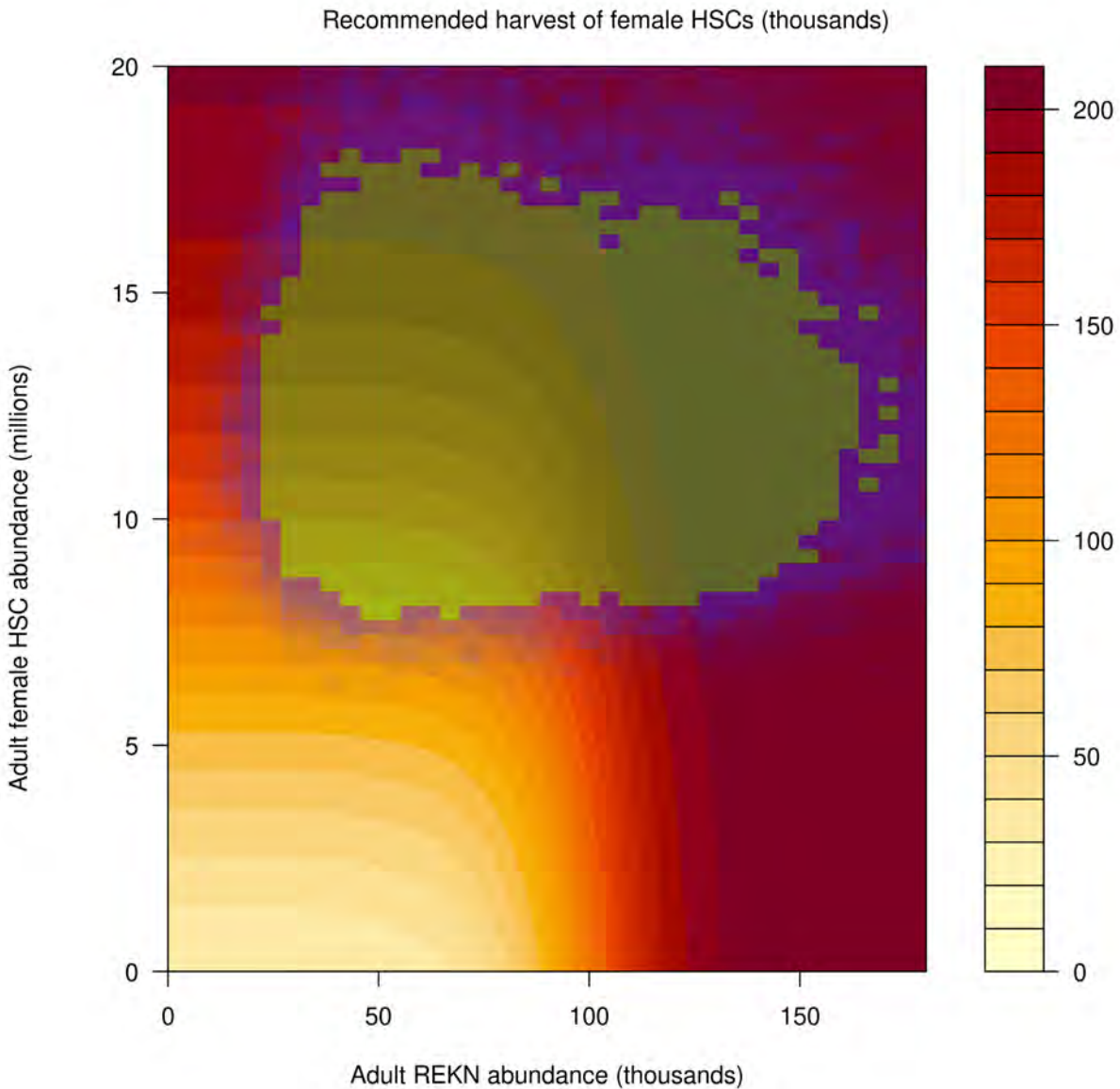


Figure 55. Optimal female bait harvest function for the canonical version of the revised ARM model , with $H_{\max}^f = 210,000$ and $H_{\max}^m = 500,000$. Recommended harvest depends on both female horseshoe crab (HSC) and adult red knot (REKN) abundances. Transparent green and blue overlay represents a non-parametric kernel, indicating where the bulk of the values of HSC and REKN abundances for years 11-20 of 10,000 simulations over 100 years: the green cells collectively contain 75% of the observations, the blue an additional 20%.

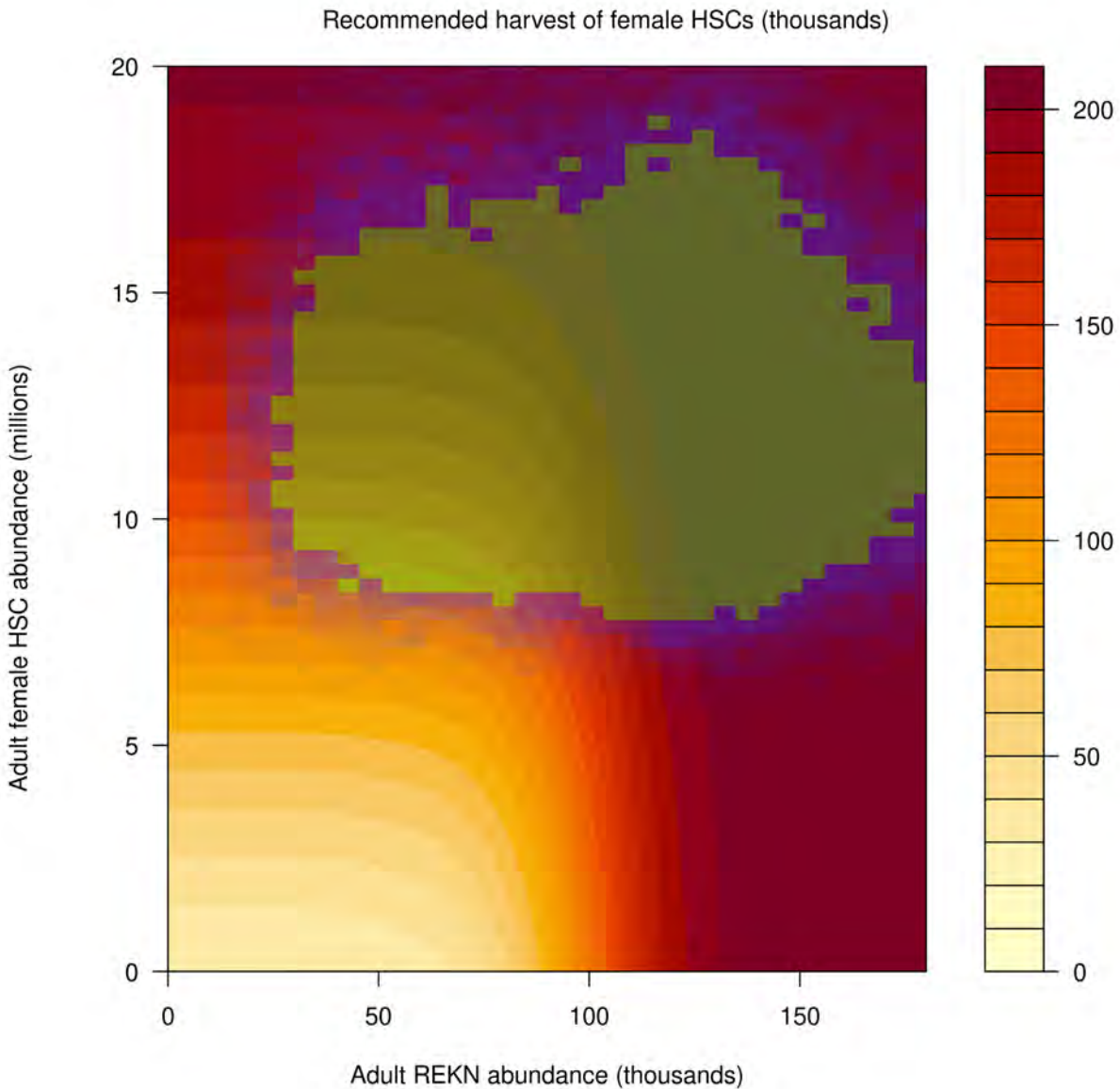


Figure 56. Optimal female bait harvest function for the canonical version of the revised ARM model , with $H_{\max}^f = 210,000$ and $H_{\max}^m = 500,000$. Recommended harvest depends on both female horseshoe crab (HSC) and adult red knot (REKN) abundances. Transparent green and blue overlay represents a non-parametric kernel, indicating where the bulk of the values of HSC and REKN abundances for years 21-30 of 10,000 simulations over 100 years: the green cells collectively contain 75% of the observations, the blue an additional 20%.

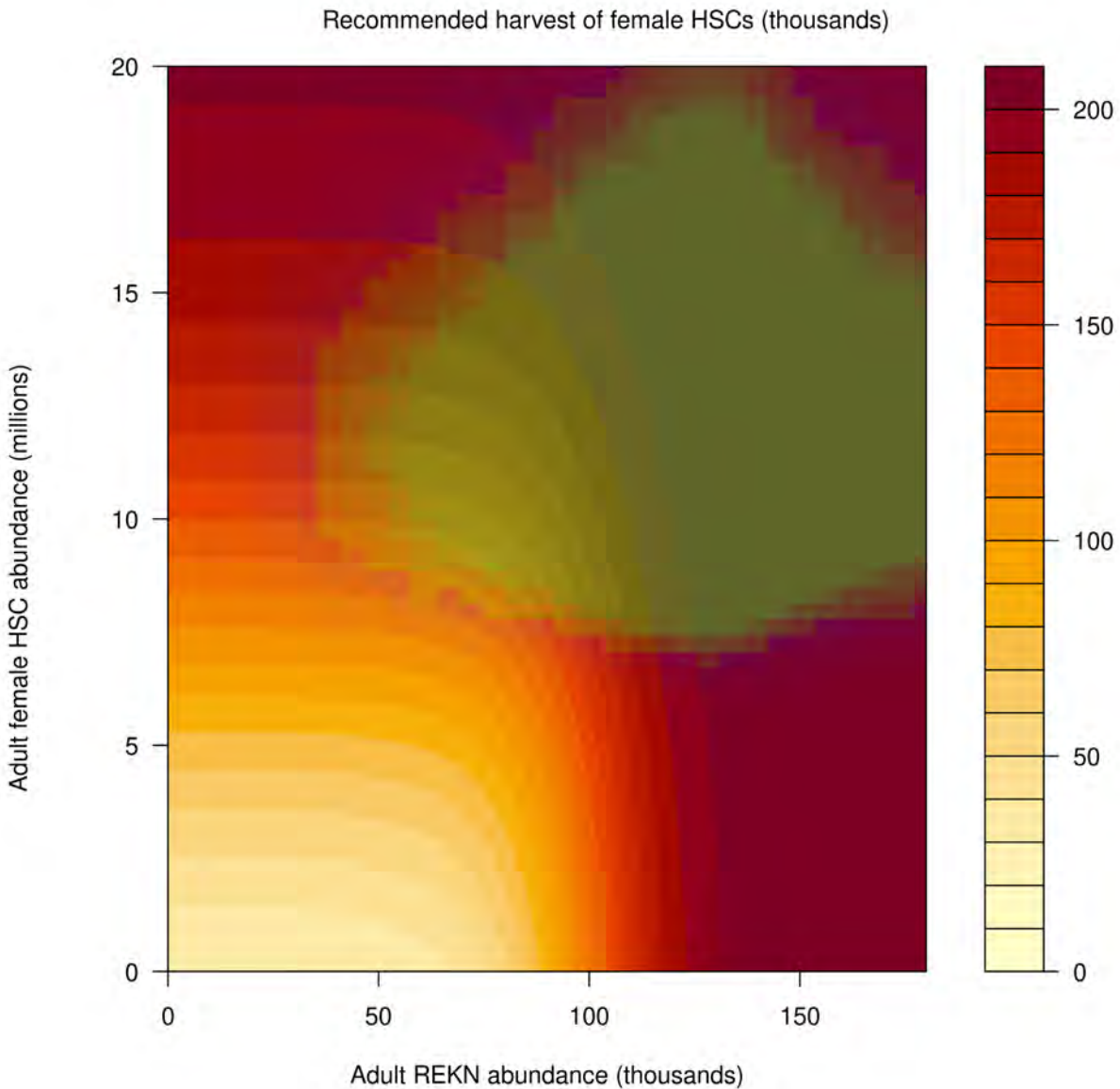


Figure 57. Optimal female bait harvest function for the canonical version of the revised ARM model, with $H_{\max}^f = 210,000$ and $H_{\max}^m = 500,000$. Recommended harvest depends on both female horseshoe crab (HSC) and adult red knot (REKN) abundances. Transparent green and blue overlay represents a non-parametric kernel, indicating where the bulk of the values of HSC and REKN abundances for years 31-100 of 10,000 simulations over 100 years: the green cells collectively contain 75% of the observations, the blue an additional 20%.

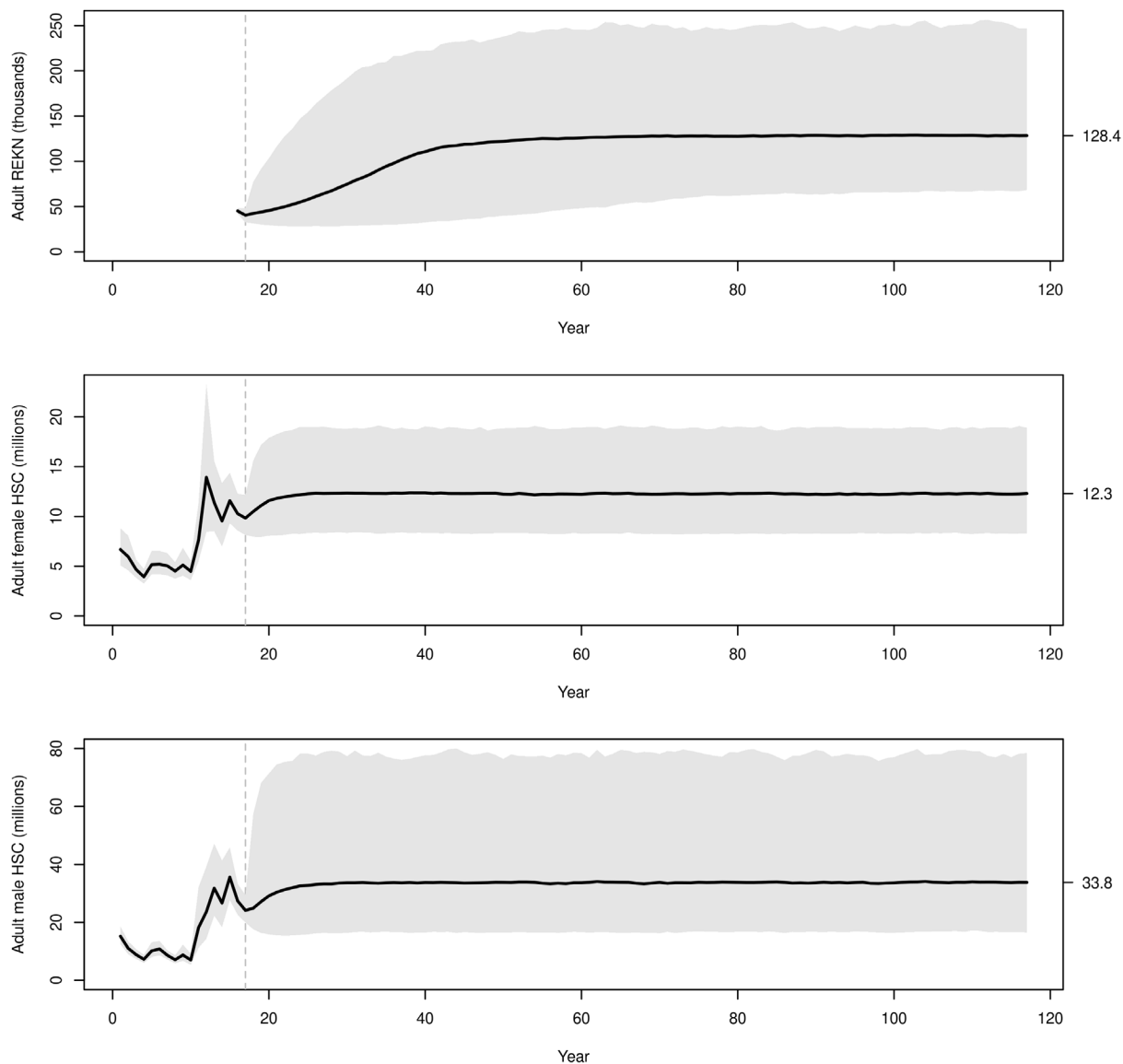


Figure 58. Summary of population trajectories for 10,000 simulated populations of horseshoe crabs and red knots under the optimal harvest policy for the canonical ARM model. Curves to the left of the vertical dashed gray line shows random draws from distributions based on actual estimates; simulated values begin to the right of the line. Black line shows the median; gray region is bounded by the 2.5th and 97.5th percentiles. Value in the right margin is the median at year 100 of the simulation (year 118 of the time series). Year 1 corresponds to 2003; dashed line is at 2019.

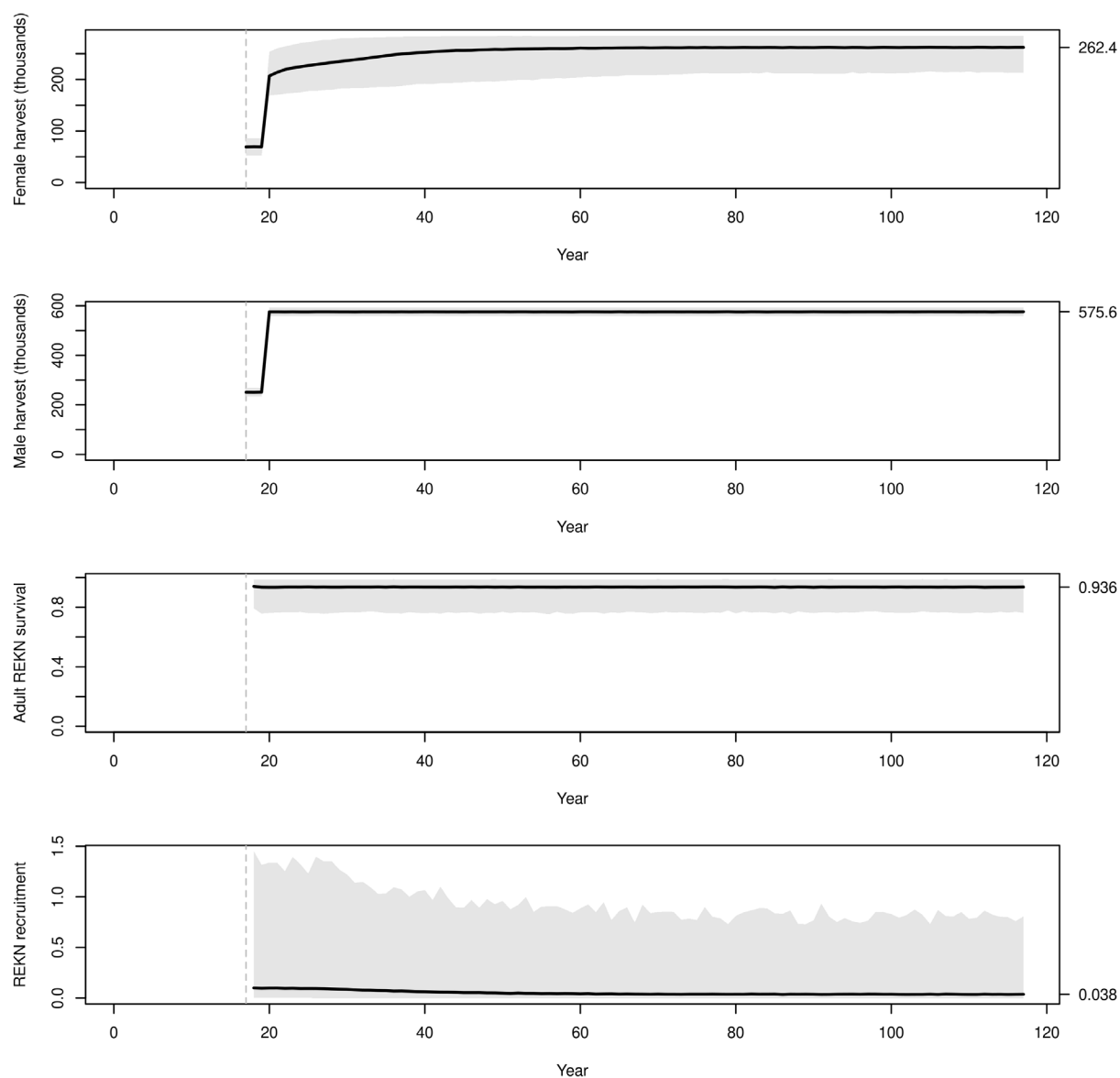


Figure 59. Summary of female and male horseshoe crab bait harvest and red knot (REKN) population parameters for 10,000 simulated populations under the optimal harvest policy for the canonical ARM model. The vertical dashed gray line lies at 2019; year 1 is 2003. Black line shows the median; gray region is bounded by the 2.5th and 97.5th percentiles. Value in the right margin is the median at year 100 of the simulation (year 118 of the time series). Year 1 corresponds to 2003; dashed line is at 2019. Note that female and male harvest here include the ‘background harvest’ due to biomedical use and bycatch.

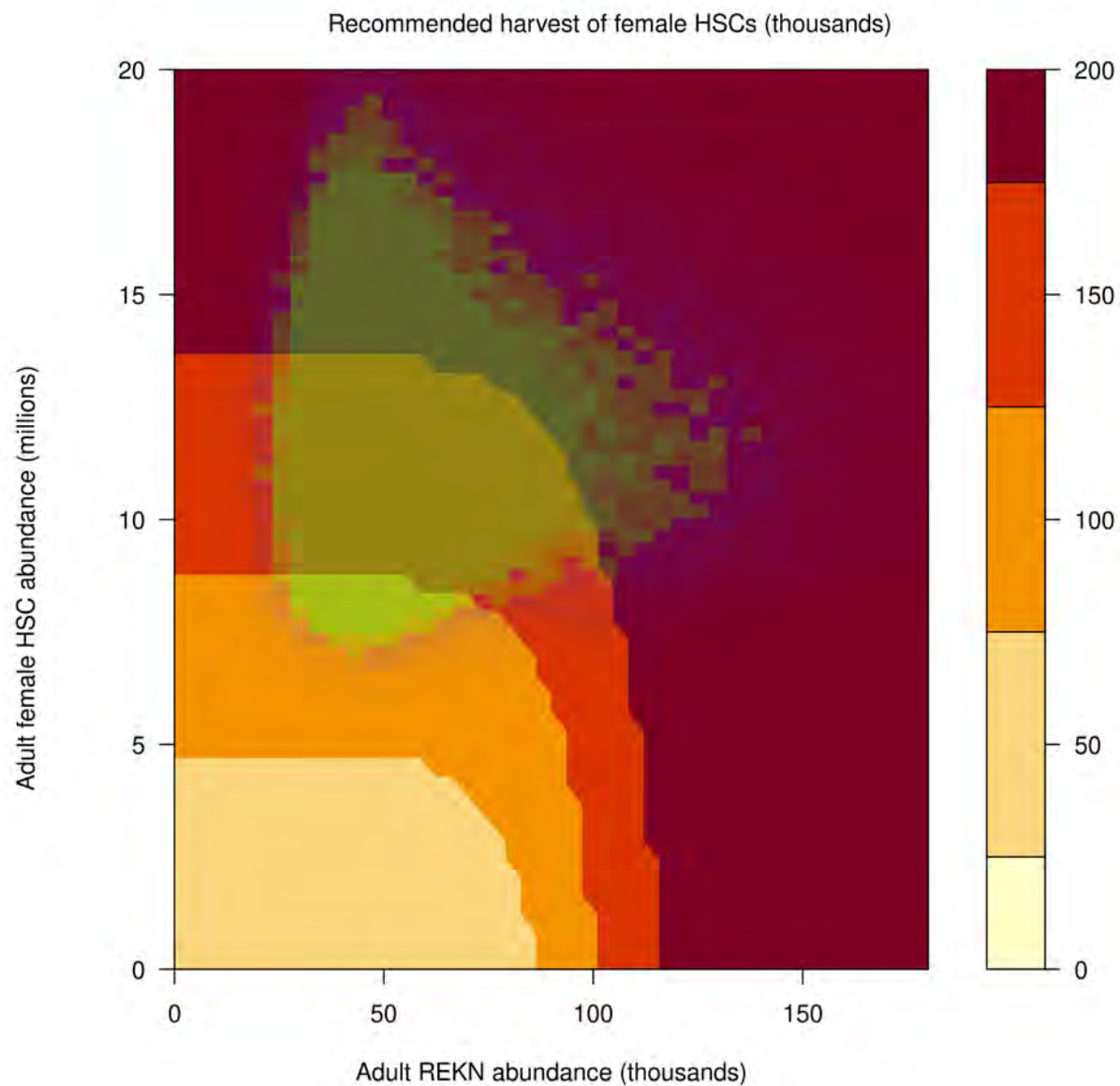


Figure 60. Optimal female bait harvest function for the canonical version of the revised ARM model but with harvest recommendations rounded to the nearest multiple of 50,000. Otherwise, the plot is the same as in Figure 54: non-parametric kernel summarizes the first 10 years of the simulation time period.

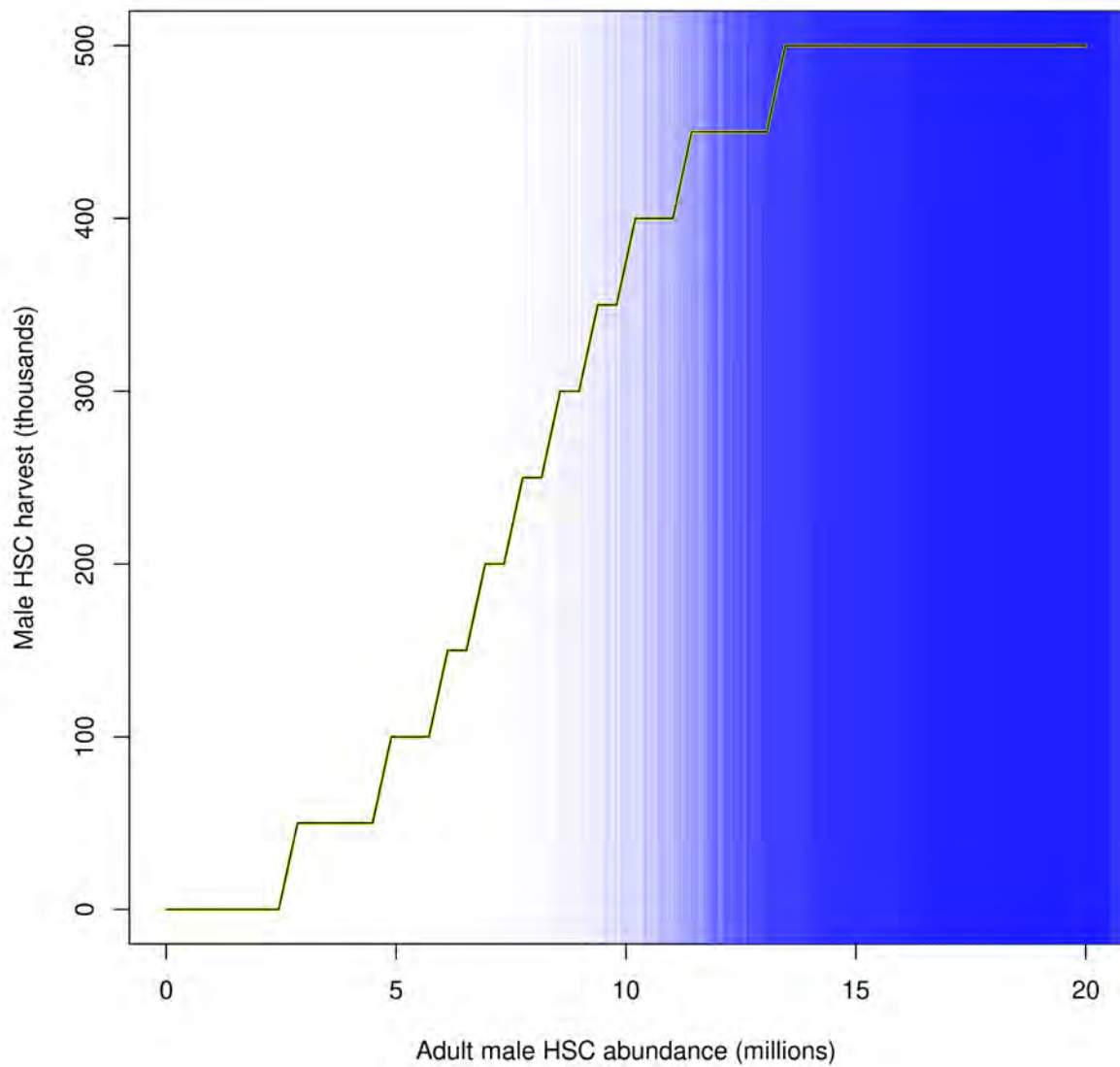


Figure 61. Optimal male bait harvest function for the canonical version of the revised ARM model but with harvest recommendations rounded to the nearest multiple of 50,000. Otherwise, the plot is the same as in Figure 53.

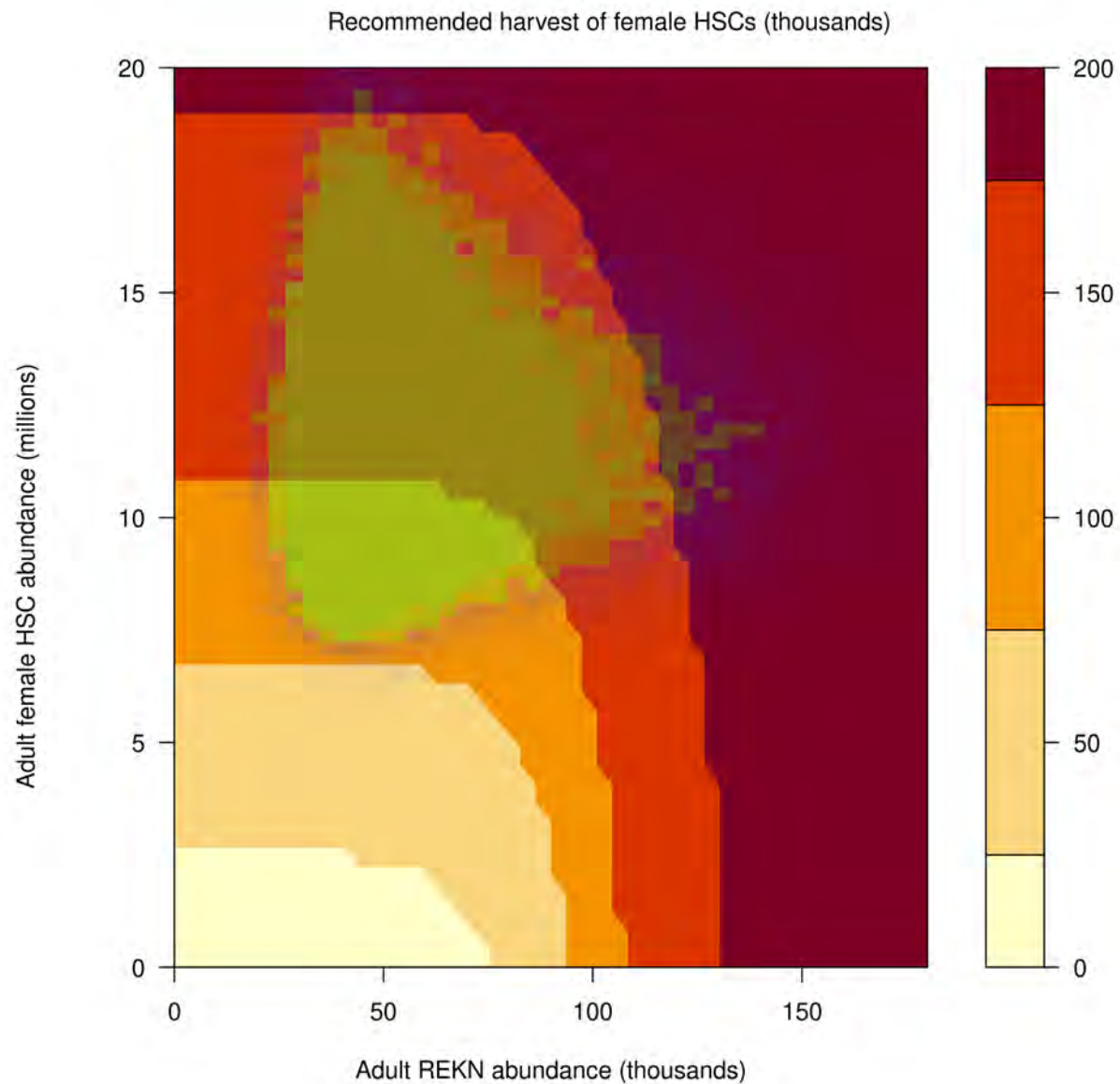


Figure 62. Optimal female bait harvest function for the canonical version of the revised ARM model but with harvest recommendations rounded down to the nearest multiple of 50,000 they exceed. Otherwise, the plot is the same as in Figure 54 and Figure 60: non-parametric kernel summarizes the first 10 years of the simulation time period.

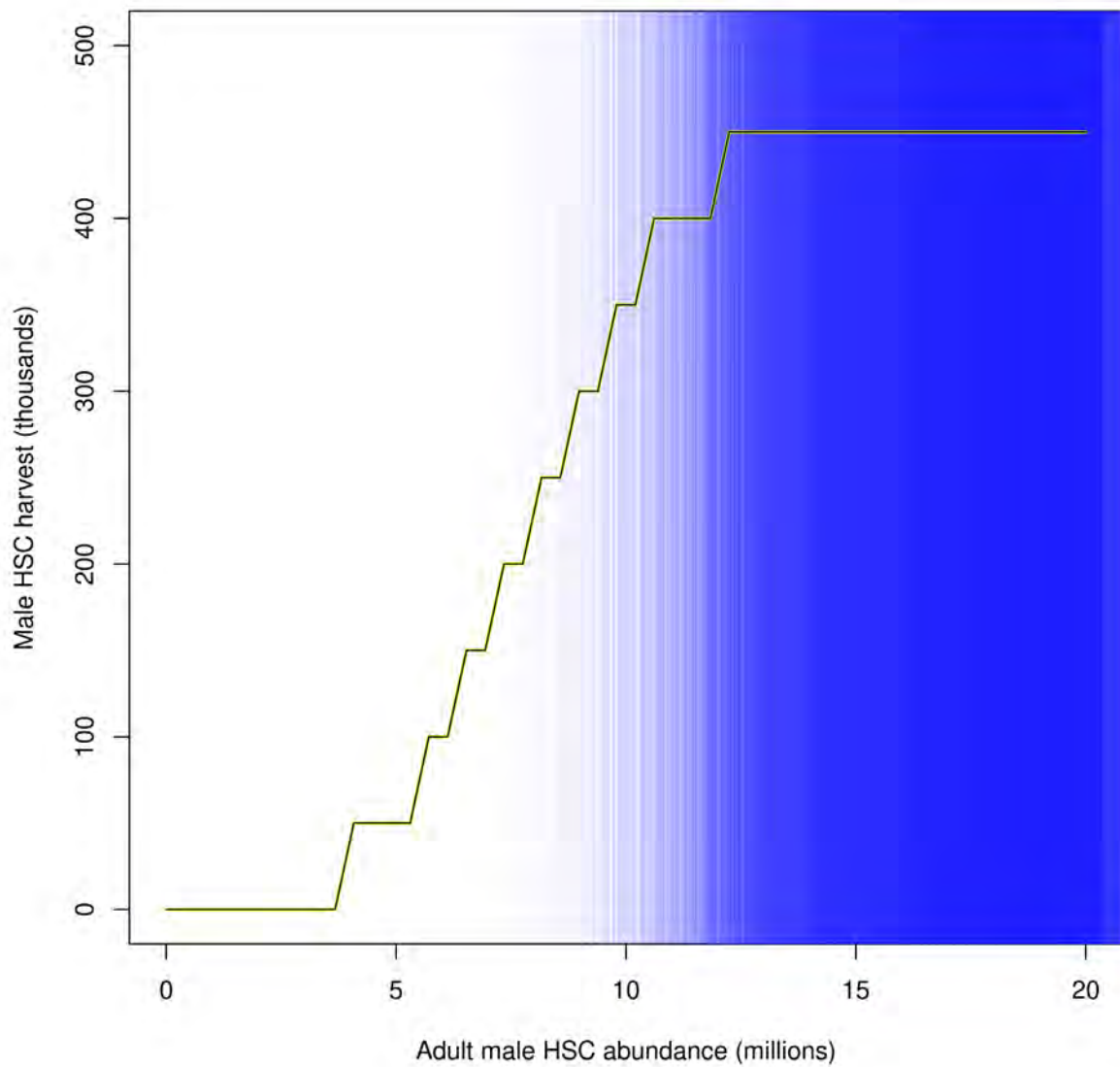


Figure 63. Optimal male bait harvest function for the canonical version of the revised ARM model but with harvest recommendations rounded down to the nearest multiple of 50,000 they exceed. Otherwise, the plot is the same as in Figure 53 and Figure 61.

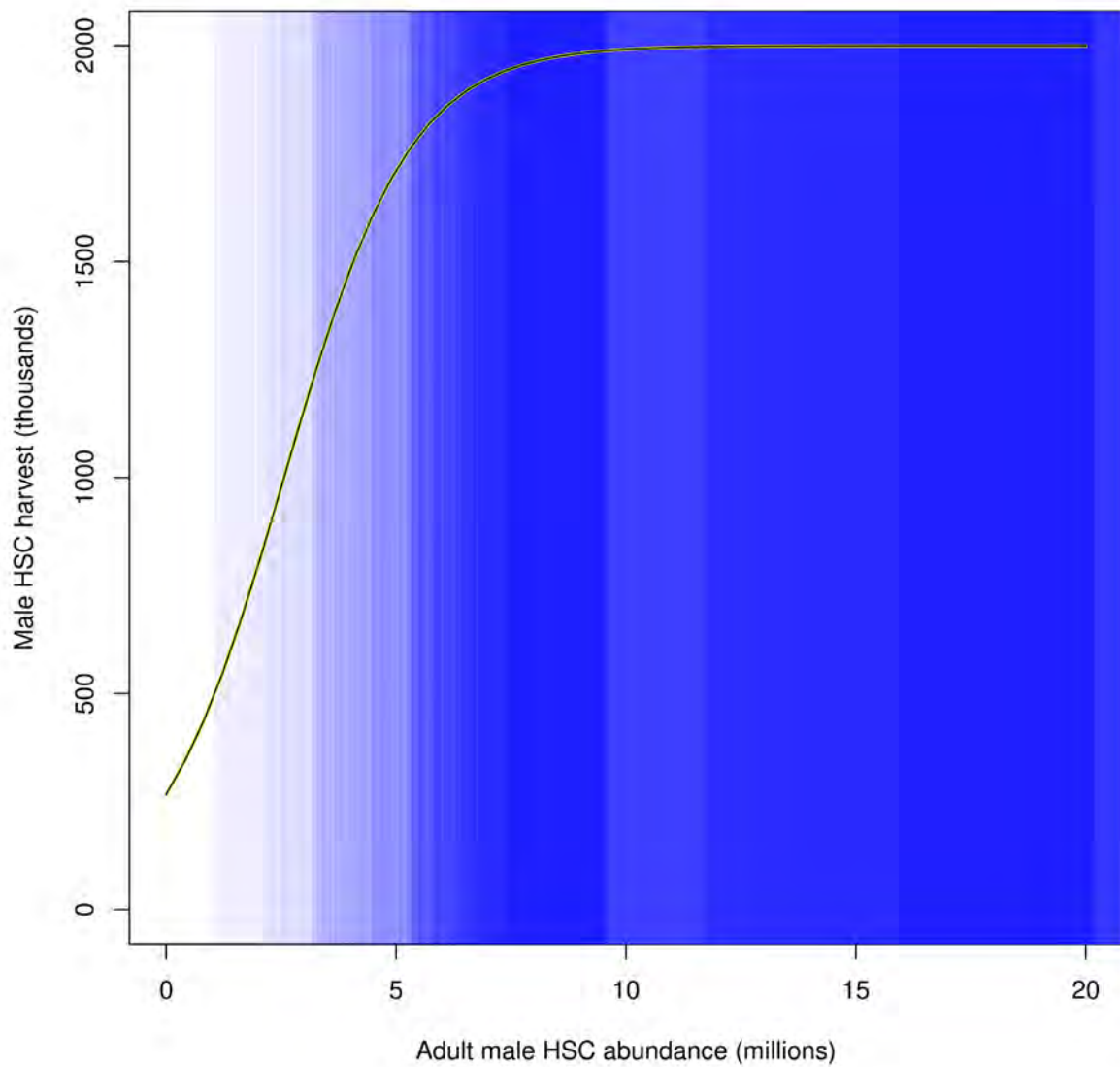


Figure 64. Optimal male bait harvest function for a version of the revised ARM model with $H_{\max}^f = 2$ million and $H_{\max}^m = 2$ million. Compare to Figure 53.

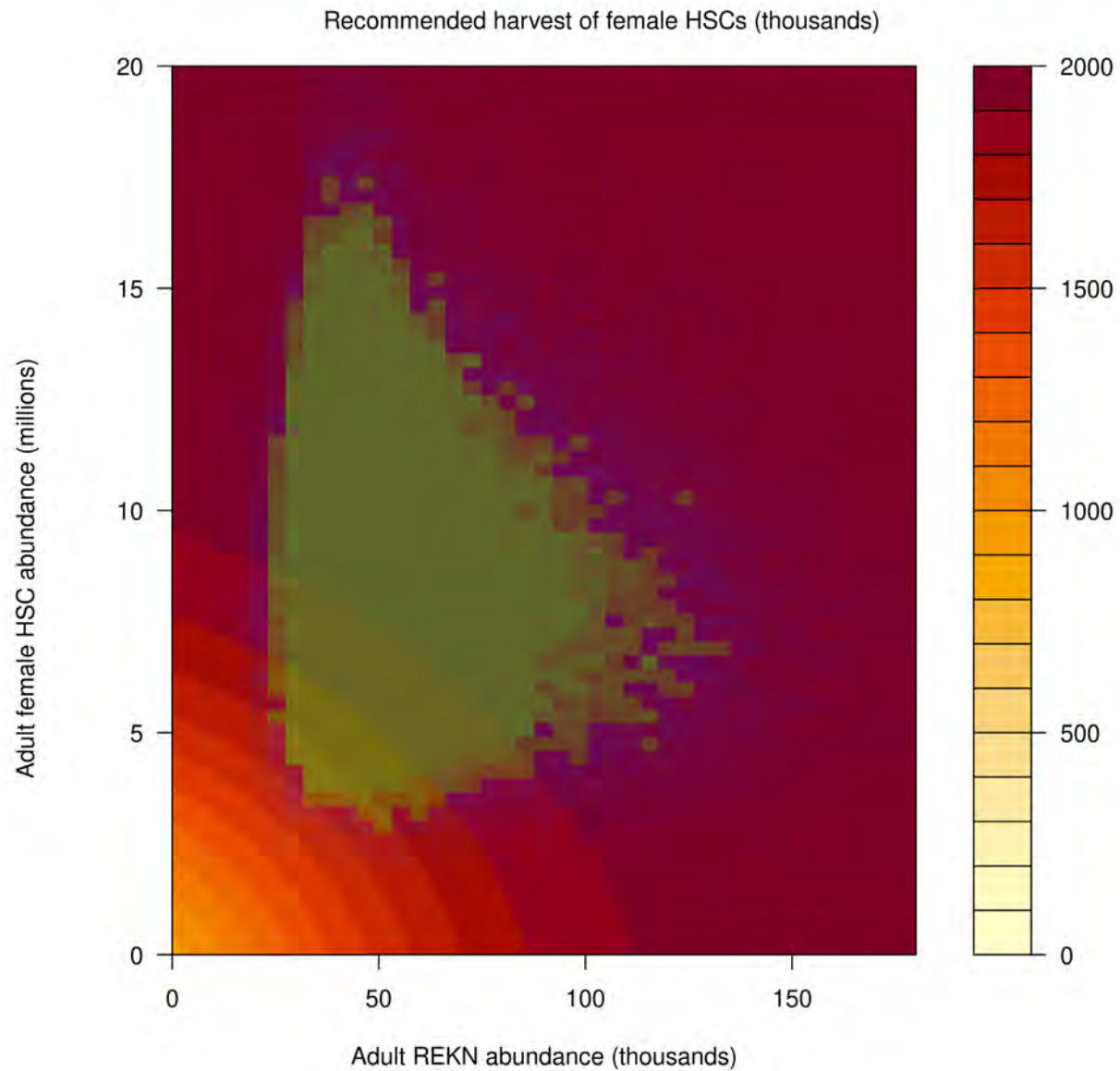


Figure 65. Optimal female bait harvest function for a version of the revised ARM model with $H_{\max}^f = 2$ million and $H_{\max}^m = 2$ million. Transparent non-parametric kernel indicates where the bulk of the values of HSC and REKN abundances for the first 10 years of 10,000 simulations over 100 years. Compare to Figure 54.

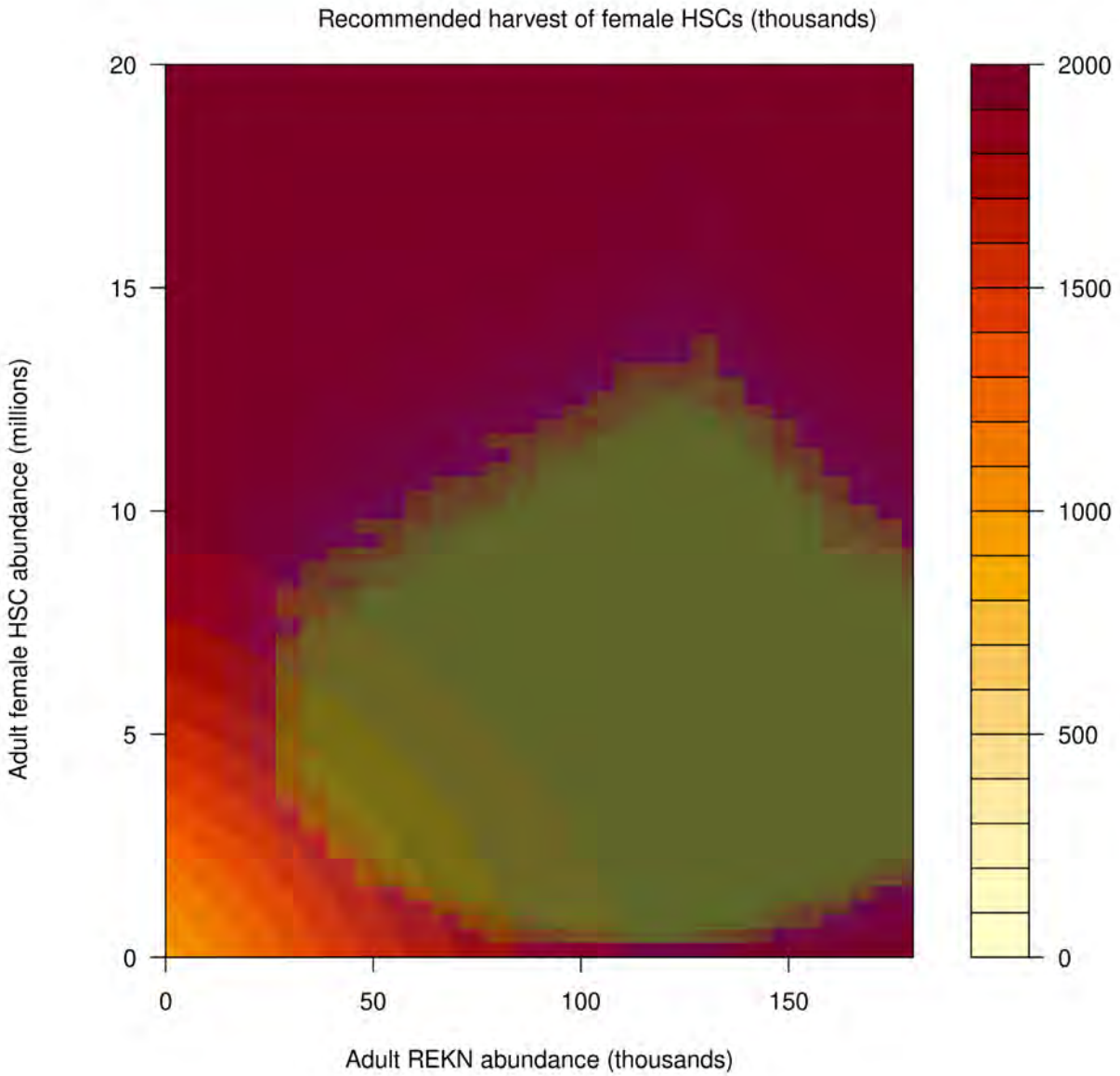


Figure 66. Optimal female bait harvest function for a version of the revised ARM model with $H_{\max}^f = 2$ million and $H_{\max}^m = 2$ million. Transparent non-parametric kernel indicates where the bulk of the values of HSC and REKN abundances for years 31-100 of 10,000 simulations over 100 years. Compare to Figure 57.

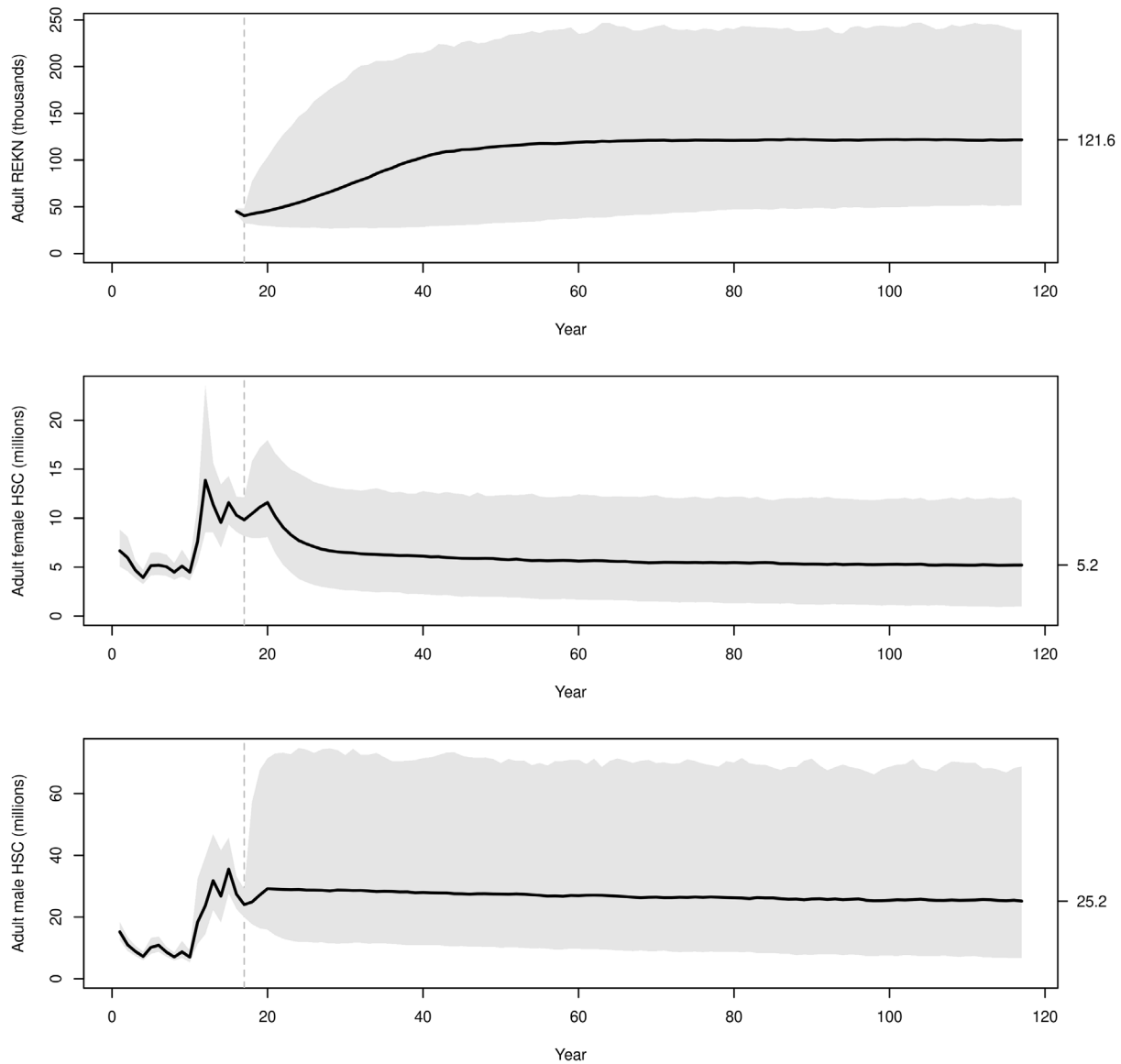


Figure 67. Summary of population trajectories for 10,000 simulated populations of horseshoe crabs and red knots, under the optimal harvest policy for a version of the ARM model with $H_{\max}^f = 2$ million and $H_{\max}^m = 2$ million. Compare to Figure 58.

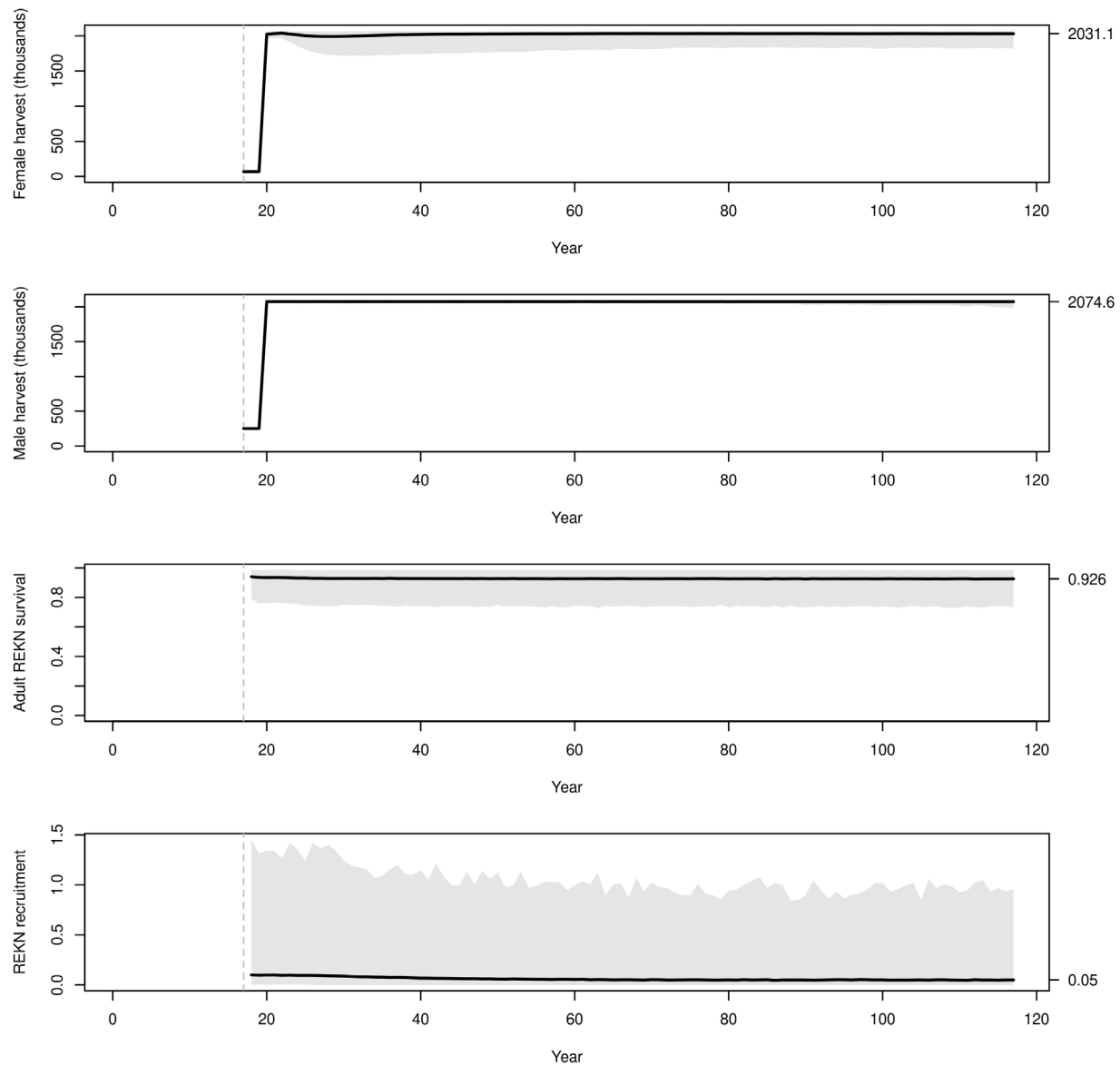


Figure 68. Summary of female and male horseshoe crab bait harvest and red knot (REKN) population parameters for 10,000 simulated populations, under the optimal harvest policy for a version of the ARM model with $H_{\max}^f = 2$ million and $H_{\max}^m = 2$ million. Compare to Figure 59.

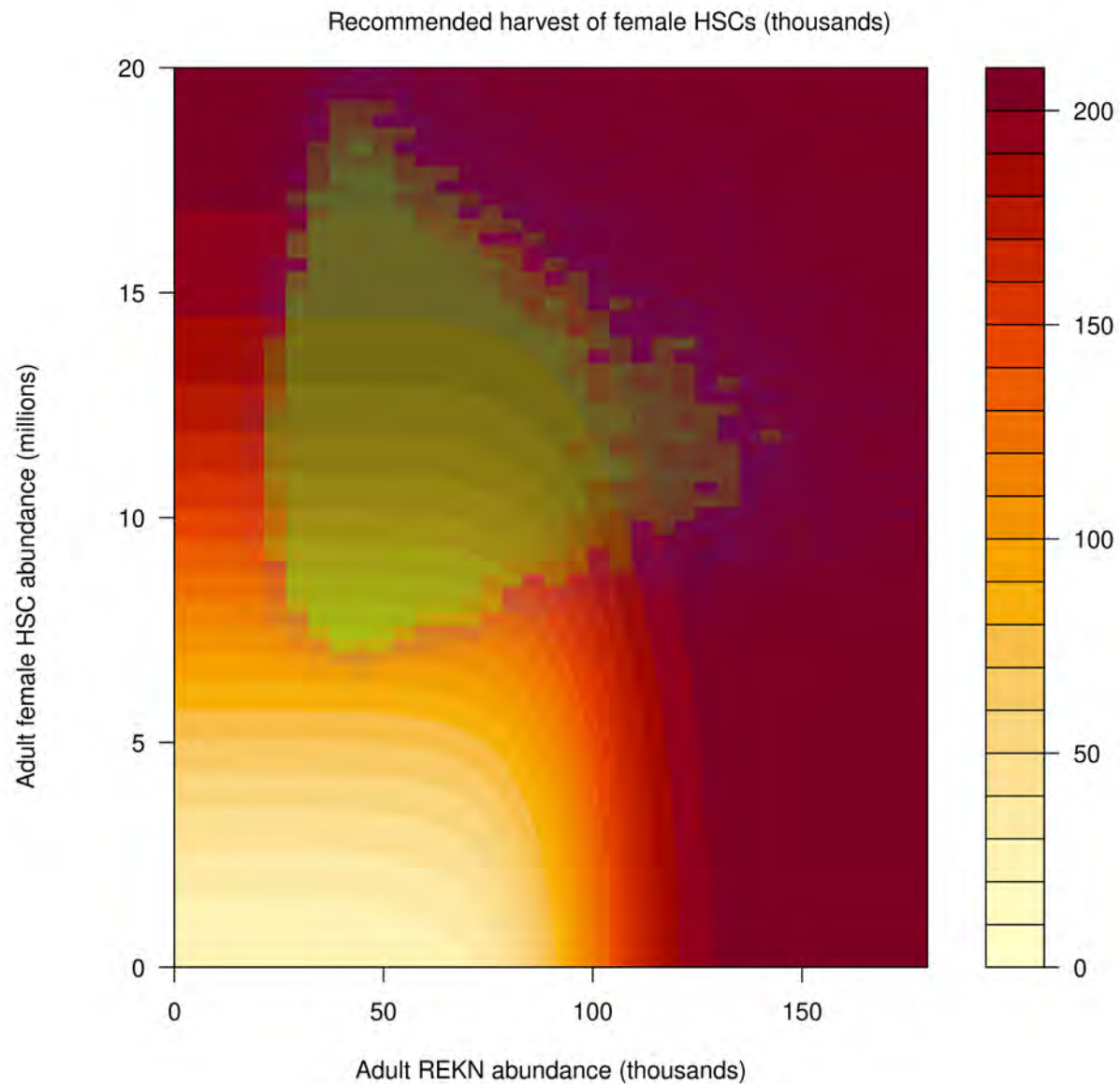


Figure 69. Optimal female bait harvest function for the canonical version of the revised ARM model with added variation in expected recruitment. In this version, median recruitment for males and females is allowed to vary $\pm 5\%$. Non-parametric kernel depicts simulation values over the first ten years. Compare to Figure 54 and Figure 70.

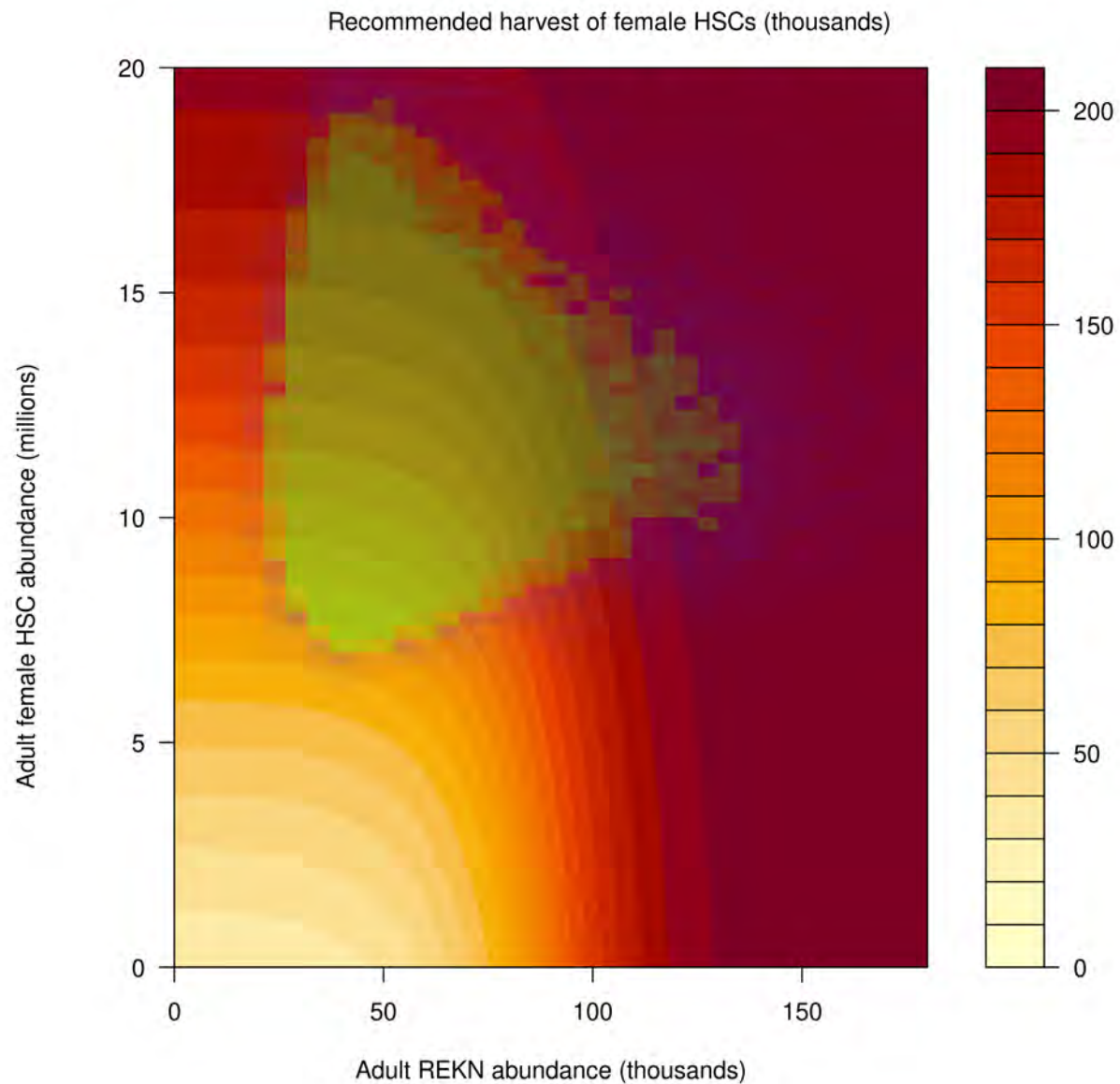


Figure 70. Optimal female bait harvest function for the canonical version of the revised ARM model with added variation in expected recruitment. In this version, median recruitment for males and females is allowed to vary $\pm 10\%$. Non-parametric kernel depicts simulation values over the first ten years. Compare to Figure 54 and Figure 69.

15 APPENDIX A : A Field Protocol to Estimate Marked Proportion in Mark-resight Studies

A scan sampling protocol (Martin and Bateson 1986) was used to record the ratio of marked to unmarked birds in all areas that are searched for flagged birds, with certain precautions to avoid bias in the scan samples.

For large flocks (e.g. >100 birds):

1. Determine the general area in front of the observer that is visually accessible (i.e. the area within which the birds can be viewed well enough to determine whether birds are marked or not). This is the “scan area” in front of the observer.
2. Visually divide the scan area into four equal segments and number them from one to four, e.g. left to right.
3. Using a table of random numbers between 1 and 4 (see below), randomly select a segment of the scan area.
4. Without looking through the scope, which might bias scan results if the observer begins the scan with a conspicuous (i.e. marked) bird, aim the scope at the selected segment.
5. Looking through the scope and beginning with a bird at the edge of the field of view, scan birds in the flock, and 1) tally the number of marked birds, and 2) tally the number of birds checked for marks. When a predetermined number of birds has been checked for marks, say 50 birds, record the number of birds with alphanumeric flag codes and the number of birds checked for flags. A hand-held tally counter may be helpful here.
6. If the flock flies off before the scan sample is complete (e.g., before you check 50 birds), the data are still useful. Record the number marked and the number checked, as usual.
7. Only those birds whose legs are visible are counted as checked for marks. In some cases, certain individual birds cannot be checked for marks (e.g., when roosting on one leg, with only one leg visible). If it is not possible to clearly determine whether or not a bird has an alphanumeric flag, the bird is not tallied in the total number checked for birds.
8. Only those birds with legible alphanumeric flags should be counted as marked birds.
 - a. Birds that are marked with a combination of color bands only, without an alphanumeric flag, are not tallied as “marked” birds. Birds with color band combinations only are not counted as marked birds in this protocol because many color band combinations are not unique to the individual bird and therefore will not be part of the analysis using the resighting data; even birds that are marked with a unique combination of color bands are not included in the analysis with alphanumeric codes.

- b. Similarly, engraved flags that are illegible because they have lost ink (or are otherwise unreadable) should not be counted as marked; they should be counted as unmarked.

For small flocks (i.e., when it is possible to quickly check every bird present in the scan area):

1. Scan the entire flock for marks and recorded the number of birds checked for flags and the number of marked birds.
2. In the case of a small flock, it is unlikely that the observer will require more than one hour to record alphanumeric flags of individual marked birds, but in the event that the resighting session is longer than one hour, it is not necessary to conduct more than one scan-sample of the same small flock.

Random numbers table. Cut on dotted line and place in field notebook.

Random numbers table for use
in the field to select birds
for scan samples.

1	1	3	4	3	3	2	2	3	4
4	1	2	1	1	1	1	3	4	1
3	2	1	1	3	4	4	3	3	2
2	3	4	4	3	1	1	1	4	4
3	1	3	2	2	1	4	3	2	4
3	2	3	2	1	4	2	1	3	1
4	2	1	3	3	4	2	2	3	4
4	4	1	2	1	2	3	3	1	1
3	1	1	1	1	1	1	1	4	1
1	1	4	1	2	3	4	2	4	4
4	2	3	2	2	2	4	4	3	3
1	2	2	4	4	4	1	3	3	2
3	4	3	3	2	3	2	2	3	3
3	2	2	3	2	1	4	1	1	1
2	1	1	1	1	3	1	2	2	1
3	4	2	4	4	4	1	4	4	4
4	2	2	4	4	3	2	1	1	3
2	3	1	4	3	1	2	2	4	2
4	2	3	3	3	1	1	4	1	3

References

Martin, P., and P. Bateson. 1986. Measuring behaviour: an introductory guide. Cambridge University Press, Cambridge.