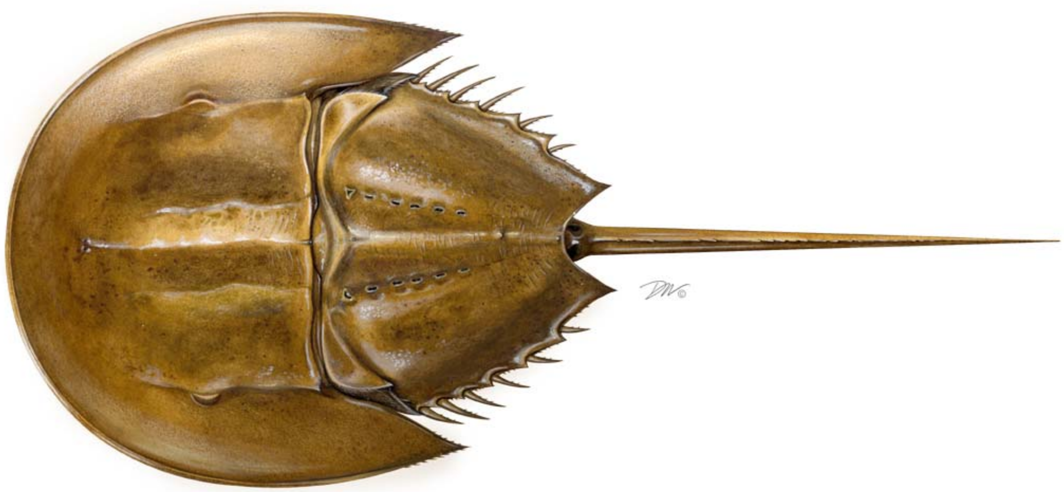
Stock Assessment Report No. 09-02
of the

Atlantic States Marine Fisheries Commission

Terms of Reference & Advisory Report to the Horseshoe Crab Stock Assessment Peer Review



November 2009

Healthy, self-sustaining populations for all Atlantic coast fish species or successful restoration well in progress by 2015

Stock Assessment Report No. 09-02
of the

Atlantic States Marine Fisheries Commission

Terms of Reference & Advisory Report to the Horseshoe Crab Stock Assessment Peer Review

Conducted on
November 17-20, 2009
Baltimore, Maryland

Prepared by the ASMFC Horseshoe Crab Stock Assessment Review Panel

Dr. Michael Jones, Panel Co-Chair, Michigan State University
Dr. Yong Chen, Panel Co-Chair, University of Maine
Dr. Erica Nol, Trent University
Dr. John Tremblay, DFO Bedford Institute of Oceanography

A publication of the Atlantic States Marine Fisheries Commission pursuant to National Oceanic and Atmospheric Administration Award No. NA05NMF4741025

Table of Contents

Preface

Summary of the Commission Peer Review Process

The Atlantic States Marine Fisheries Commission Stock Assessment Peer Review Process is designed to standardize the process of stock assessment reviews and validate the Commission's stock assessments. The purpose of the peer review process is to: (1) validate the credibility of the scientific basis for management; (2) ensure the quality of Commission stock assessments; (3) periodically conduct formal peer reviews of stock assessments for all species managed by the Commission; and (4) improve public understanding of fisheries stock assessments.

The Commission stock assessment review process includes evaluation of input data, model development, model assumptions, scientific advice, and review of broad scientific issues, where appropriate.

The first ASMFC horseshoe crab stock assessment was peer reviewed in 1998. In 2006, an assessment framework and methodology proposed for future horseshoe crab stock assessments was peer reviewed. In 2009, the Commission convened a Stock Assessment Peer Review Panel comprised of members with expertise in fisheries, stock assessment methods, adaptive resource management, and shorebird ecology. The review for the Horseshoe Crab Stock Assessment and Adaptive Resource Management (ARM) framework for Delaware Bay was conducted in Baltimore, Maryland from November 17-20, 2009. Prior to the Review Panel meeting, the Commission provided the Review Panel members with the 2009 Horseshoe Crab Stock Assessment Report, the ARM Report, and background materials.

The review process consisted of presentations describing the completed 2009 stock assessment and ARM modeling framework. Each presentation was followed by general questions from the Review Panel. The final two days involved a closed-door meeting of the Review Panel during which the documents and presentations were reviewed, conclusions drawn, and a report prepared.

The report of the Review Panel, hereafter referred to as the Panel, is structured to follow the Terms of Reference provided to the stock assessment and ARM teams.

Purpose of the Terms of Reference and Advisory Report

The Terms of Reference and Advisory Report provides summary information concerning the results of the external peer review to evaluate the accuracy of data and assessment methods. Details of the assessment are documented in a supplemental report entitled 'Horseshoe Crab Stock Assessment Report for Peer Review'. A copy of the supplemental report can be obtained via the Commission's website at www.asmfc.org on the Horseshoe Crab page or by contacting the Commission at (202) 289-6400.

Acknowledgments

The Peer Review Panel thanks all of the individuals who contributed to the review of the ASMFC Horseshoe Crab Technical Committee's report "Horseshoe Crab Stock Assessment Report" and the combined Horseshoe Crab and Shorebird Technical Committees' report "A Framework for Adaptive Management of Horseshoe Crab Harvest in the Delaware Bay Constrained by Red Knot Conservation". The Panel thanks members of the Horseshoe Crab Technical Committee, Horseshoe Crab Stock Assessment Subcommittee, Shorebird Technical Committee, and ARM working group for preparation of these reports. In particular, the Panel thanks David Smith, John Sweka, Michelle Klopfer, Richard Wong, and Conor McGowan for their informative presentations, for answering numerous questions, and participating in constructive discussions regarding horseshoe crab biology and past and current efforts to conduct horseshoe crab stock assessments.

The Panel also thanks Genny Nesslage, Patrick Campfield, and Brad Spear from ASMFC for coordinating the peer review and assisting with the preparation of this report.

I. Introduction

The Panel reviewed current efforts to analyze the status of the horseshoe crab (*Limulus polyphemus*) stock and develop a multispecies framework for the adaptive management of horseshoe crab harvest in the Delaware Bay. The status of the horseshoe crab population along the Atlantic coast is of great concern for a number of reasons. Horseshoe crabs play an important role in marine and estuarine ecosystems. In particular, the eggs of horseshoe crabs provide fuel for long-distance migrant shorebirds at their Delaware Bay stopover sites. Declines in horseshoe crabs have been implicated in the cause of sharp declines in the rufa population of the red knot (*Calidris canutus rufa*). In addition, the species serves as a primary bait source for several important commercial fisheries and as a source of Limulus Amebocyte Lysate, a valuable compound for biomedical usage.

Overall, the Panel commended the efforts of the Horseshoe Crab Stock Assessment Subcommittee (SASC) since the last stock assessment to develop alternative stock assessment models and an Adaptive Resource Management (ARM) modeling framework which explicitly links the Delaware Bay horseshoe crab population with red knot population dynamics. The Panel finds that the general trends described in the assessment report are broadly supported by the stock assessment data, although the inconsistency in observed trends among data sources in the New England and New York regions led to reduced confidence in the stock status assessment in these areas, particularly in light of the lack of information about whether these surveys represent distinct populations or samples from a common regional population. The Panel encourages the continued development of the catch-survey model and other models (e.g., size-structured and age-structured models, habitat modeling) to take full advantage of all the available data and to evaluate fishery-independent and fishery-dependent data quality and its impacts on stock assessment.

The Panel was impressed by the ARM work and finds that it comprises an excellent combination of a deliberative, stakeholder-sensitive process with a rigorous scientific assessment of the critical uncertainties surrounding the linkage between horseshoe crab harvest management and red knot conservation. The Panel endorses the shift towards a management strategy for horseshoe crab in Delaware Bay that attempts to balance potentially conflicting objectives for horseshoe crab exploitation and red knot conservation, while at the same time seeking to reduce uncertainty about the linkage between these two species.

In Sections II and III of this report, the Panel specifically addresses each Term of Reference recommended by the Horseshoe Crab Management Board for the coast wide horseshoe crab stock assessment and ARM modeling framework, respectively. In Section IV, the Panel provides an advisory report on the status of the horseshoe crab stock as a whole.

II. Terms of Reference – Stock Assessment

Term of Reference 1. Evaluate precision and accuracy of fishery-dependent and fishery-independent data used in the assessment, including the following but not limited to:

The Horseshoe Crab Stock Assessment Committee (SASC) presented and discussed both fishery-dependent and fishery-independent data. Although the SASC report discusses issues of data precision and accuracy, the Panel provides a number of suggestions below for further evaluation of the quality of these data that could improve future assessments. The SASC indicated the fishery-dependent data were not useful in assessing the HSC populations for a variety of reasons and the Panel concurs. Multiple sources of fishery-independent data combined with the Autoregressive Integrated Moving Average (ARIMA) analyses provide some confidence in these data for assessing accuracy of trends. The Panel recommends a number of approaches to strengthen the precision.

a. Discuss the effects of data strengths and weaknesses (e.g. temporal and spatial scale, gear selectivity, determining age class, sample size, standardization of indices) on assessment inputs and outputs.

The SASC noted commercial landings data are unreliable prior to 1998. Landings since 1998 are considered reliable particularly for Delaware Bay but the SASC noted that in some states (e.g., New York) landings are likely still underreported. Fishery-dependent data quality may be biased, in particular in early years, and rates of catch underreporting might vary spatially and temporally. The quality of catch statistics needs to be evaluated. Information on discards is not available. In some cases a survey of fishermen may yield estimates of underreporting rates. The sensitivity of assessment results to underreporting should be considered for plausible scenarios of underreporting, including the possibility of time-varying rates.

Data were presented suggesting prosomal widths were declining in some fisheries, but the SASC noted uncertainty with regard to whether protocols for measuring sizes in the commercial catch were followed consistently. The SASC also noted there was concern that harvesters may be selecting for larger horseshoe crabs, and in some cases juvenile crabs may be included in the harvest. The composition of catch for bait and biomedical uses may differ over time, which may make the temporal comparison of prosomal width data in the evaluation of impacts of fishing on size structure invalid. The Panel reiterates a recommendation from the 2006 stock assessment review: “The Panel strongly recommended improved characterization of the commercial catch and landings by fishery (bait, biomedical, and scientific) and by life stage” (ASFMC 2006).

The SASC noted that, due to the moratorium on HSC harvest in Delaware Bay, fishery-dependent data there will be unreliable, and because fishery effort may have been directed elsewhere as a result, this practice will also reduce the reliability of this CPUE data throughout the range.

Data from numerous fishery independent surveys were described in an appendix and a map of spatial extent of the surveys was provided at the review (Figure 1). The data were evaluated with trend analyses and ARIMA. All indices were not scaled in the same way (e.g., some with geometric means and others with stratified means) and the Panel recommends evaluation of whether this has any effect on the conclusions.

Most fishery-independent survey programs are not designed for capturing horseshoe crabs, which is likely to lead to large variability in survey catchability (and vulnerability) and may in turn result in biased representation of population structure. The Panel recommends that data from different survey programs with similar spatial coverage be compared for key population variables/parameters (e.g., abundance, sex ratio, and size composition). Such a comparative study may provide insight on differences in sampling catchability.

Current analyses only used the mean (arithmetic, geometric, and delta) of each survey program, and do not consider spatial variability (i.e., variability among sampling stations in a given program). An evaluation of among-station variability may provide insights about the quality of the data. Most survey programs are likely to have a large number of stations without horseshoe crab catch. A delta transformation might be better for analyzing these survey data.

The assumption of a constant 15% mortality rate for bled crabs returned in the biomedical fishery needs to be evaluated for accuracy. Some anecdotal evidence was presented at the review that it might be higher. Again, the sensitivity of the commercial harvest estimates and stock assessments to this assumption should be evaluated.

Limited biological data from fishery-dependent and fishery-independent programs were used in the stock assessment. The models used in the stock assessment do not utilize biological/fisheries information such as maturation, fecundity, molting frequency, molt increment, weight-length data, and size compositions of population and catch. The data used include survey abundance indices and reported catch, but none of the four approaches fully utilize the biological information available to the stock assessment. The Panel recommends the SASC review the literature and data from previous studies to identify growth-related information such as molting frequency, molt increment, and whether they differ with sizes and sexes, and among different regions. Such an analysis might allow estimation of the probability of an individual horseshoe crab in a given size class growing into a different size class in a defined time period, which could facilitate the development of a size-structured stock assessment model. The information can also be useful in determining the size composition of the juvenile stage in the ARM model.

The Maine/New Hampshire inshore bottom trawl survey (fall and spring from 2000- present) data are available, but were not included in this assessment. Also, data from the Northeast Area Monitoring and Assessment Program's (NEAMAP) bottom trawl survey (fall and spring from 2007-present) were not considered in this assessment but could provide useful trend data in the future given its broad inshore sampling range of coastal waters (approximately 20-90 feet) between Martha's Vineyard, Massachusetts and Cape Hatteras, North Carolina. Biological data from the NEAMAP survey include several hundred crabs sampled each fall for counts, widths, weights, and gender. The Panel recommends a request to NEAMAP to measure and record additional variables (e.g., maturity) and to consider tagging crabs.

b. Justify weighting or elimination of available data sources.

The numerous surveys were presented with equal weight even though some must give a better indication of horseshoe crab abundance than others. The multiple surveys for horseshoe crab at times give conflicting, or at least inconsistent signals, likely due to survey differences in gear, location, timing, and spatial extent. The Panel recommends that fishery-independent programs be ranked for their relevance to horseshoe crab spatial distributions and sampling efficiency. The ranking can then be considered in the stock assessment. The Panel recommends that the SASC then evaluate which surveys best represent trends in horseshoe crab abundance. Approaches outlined in Hata and Berkson (2004) might be valuable in this regard.

A habitat model - for example, a two-stage general additive model for horseshoe crab abundance data and environmental data - can be developed for horseshoe crab of different life history stages to identify critical habitats, which can then be used to predict potential habitats for horseshoe crabs of different life history stages. Such information can then be used in evaluating importance of various fishery-independent survey programs, and possibly their relative catchabilities.

Term of Reference 2. Determine most appropriate assessment analysis or analyses given management objectives, available data, and species life history.

The SASC is to be commended in this area. They followed the recommended framework in utilizing a surplus production model and eventually moving to the catch-survey model. The addition of the ARIMA modeling is welcome as it provides probabilities that current indices exceed certain benchmarks (e.g., 1998 level)

Overall, the trend analysis and ARIMA yielded similar conclusions about the status of horseshoe crab populations of the four regions. The surplus production model and catch-survey model yielded similar conclusions about the status of horseshoe crabs in Delaware Bay. This is not surprising because similar data sets were used in the trend analysis, ARIMA, and in the production model and catch-survey model.

The surplus production model can be used as a preliminary stock assessment tool. However, the long time period (~ 9 years) horseshoe crabs spend before they recruit to the fishable stock raises questions about the suitability of this model, particularly if an alternative is available (i.e., the catch-survey model). Also, the potential for this model to provide good estimates of stock status relative to reference points (e.g., F_{MSY}) in regions outside the Delaware Bay is not good because of a lack of contrast in the available time series data for these areas.

The catch-survey model has potential for Delaware Bay, and should be further developed and tested. Realistic estimates of natural mortality and the relative catchability of pre-recruit and recruited (primi- and multiparous) horseshoe crabs are critical to the use of the catch-survey model. Stock size estimates from this analysis can also be used in the ARM modeling.

In the future, a size-structured population dynamics model might be a good candidate for the horseshoe crab stock assessment model in Delaware Bay because it would likely better represent the biology of horseshoe crabs and more fully utilize the biological data available.

In addition, a more detailed population life history model (e.g., individual-based or age-structured) should be developed to use as an operating model for evaluating the performance of aggregated stock assessment models (e.g., surplus production) in assessing the dynamics of horseshoe crab.

Term of Reference 3. Evaluate methods used to evaluate population dynamics and determine stock status. Have the strengths and limitations of these methods been clearly and thoroughly explained?

The SASC followed the recommended framework for horseshoe crab. Overall, there have been substantial increases in the suite of approaches used to assess horseshoe crab. The strengths and limitations of these methods were in general well described. The additional sensitivity analyses related to the surplus production model (effect of landings uncertainty, shape of logistic, etc.) and presented at the review were greatly appreciated. Although, as noted in TOR 2 above, we recommend further exploration of the applicability of the surplus production model to horseshoe crab using an operating model.

Four methods were used in the assessment. Trend analysis and ARIMA were used for coast wide evaluation of temporal trends. A surplus production model and catch-survey model were developed based on recommendations made by the 2006 Horseshoe Crab Stock Assessment Review Panel and are only used in assessing the Delaware Bay population. These four approaches have their advantages and disadvantages, but like any assessment method their performance heavily depends on the quality and quantity of input data. In the future, a tabular comparison of the results from the two assessment models (surplus production and catch-survey) would contribute further to evaluation of the assessment.

Overall, the trend analysis and ARIMA yielded similar conclusions about the status of horseshoe crab populations in the four regions, and the surplus production model and catch-survey model yielded similar conclusions about the status of horseshoe crabs in Delaware Bay. This is not surprising because similar data sets were used in the trend analysis and ARIMA, and in the production model and catch-survey model.

Additional strengths/limitations of the different methods are listed below:

- Trend analysis
    - Simple and straightforward, but superseded by ARIMA which can be more informative and less susceptible to errors
    - Results may be influenced by process errors and observation errors within and among surveys.
- ARIMA modeling
    - Need to evaluate relative strength of different surveys
    - Need to evaluate effect of using indices generated in different ways (stratified means vs. geometric means) on ARIMA modeling
    - Possibility that some of the trends reflect changes in distribution of animals or timing of migration and thus availability to gear

- Surplus production
    - The Panel recommends further evaluation of violating the assumption that "the stock reacts instantaneously to changes in conditions" given only mature crabs are included in the current modeling approach and it appears that horseshoe crab take 9-11 years to mature.
    - For regions outside of Delaware Bay, the contrast in abundance time series may not be not great enough to fit models with confidence.
    - Need to clearly identify that <u>abundance</u> is being modeled, not <u>biomass</u>
- Catch-survey analysis
    - The Panel agrees this is a valuable approach for estimating abundance of horseshoe crab as the available life history and survey data appear to be fully adequate, and the model makes fewer assumptions than surplus production.
        - The model's fit in 2009 depends on an the assumption that the survey (Virginia Tech trawl survey) catchability of multiparous crabs is twice that of primiparous crabs. Survey catchability needs to be measured. If such measurements validate this assumption, the model should be able to provide useful estimates of abundance and fishing mortality.
        - This model is also sensitive to natural mortality; a range of M's should be evaluated.

Term of Reference 4. Evaluate the current practice of conducting assessments, including methods and data used, at a regional or sub-regional (estuary-specific) level rather than coastwide.

The SASC summarized data by region: Southeast, Delaware Bay, New York, and New England. The SASC focused on the Delaware Bay region because it is the center of horseshoe crab abundance, the most important area for red knot feeding, and has the most data. Analyses for the other regions (Southeast, New York, and New England) were limited to the trend and ARIMA analyses of catch rate data from fishery-independent surveys. The ARIMA analyses for each region included a probabilistic evaluation of whether the 2009 horseshoe crab indices were likely to be above certain benchmark levels.

This approach makes sense given the evidence for regional or sub-regional scales of population structure and the available data. Evidence that the horseshoe crab population has regional structure includes the restricted spatial scale of horseshoe crab early life history stages, the apparently limited exchange among regions from tagging studies, and genetic differentiation among the Atlantic coast horseshoe crab population.

While the regional nature of horseshoe crab population dynamics needs to be addressed in assessments, the Panel thinks the ability to compare regional trends across the coast is important. This is difficult with the variety of existing survey methods. One approach to developing a comparable survey index would be to fit generalized linear/additive models to the existing survey data, including environmental covariates and survey parameters. Ideally, a more robust alternative would be to implement coast wide surveys directed at horseshoe crab using the methods of the Virginia Tech trawl survey.

Term of Reference 5. State and evaluate assumptions made for all methods and explain the likely effects of assumption violations on results.

The SASC listed most assumptions but did not always evaluate the effects of violations. The assumption of equal weight/importance of all the survey programs in a given region is explicit, but not tested in the trend analysis and ARIMA.

Limited test runs have been conducted to evaluate possible impacts of violating assumptions for the surplus production model and catch-survey model. There was some evidence presented during the review that the surplus production model results were sensitive to the data sources (e.g., Delaware 30-ft trawl). This should be further explored.

In particular, the assumption of the surplus production model that the stock reacts instantaneously warrants further evaluation. The Panel recommends an operating model be developed to simulate a horseshoe crab fishery in order to test the performance of stock assessment models of different complexities.

Term of Reference 6. Evaluate biological or empirical reference points.

Empirical reference points, based on survey abundance index quartiles and a reference year (1998) were developed and evaluated using the ARIMA approach.

Both abundance- and F-based biological reference points (BRPs) were estimated using the surplus production model for Delaware Bay. Appropriately, this analysis included consideration of the uncertainty associated with these reference points and with stock status relative to the reference points. However, we advise against adoption of these reference points for management prior to a more systematic evaluation of the suitability of the surplus production model for horseshoe crabs (see TOR 5).

The Panel recommends the development of other model-based BRPs such as $F_{0.1}$ and F_{max} estimated from a yield-pre-recruit model, and $F_{10\%}$, $F_{20\%}$, and $F_{40\%}$ from an egg-per-recruit model for future stock assessment. There is a need to consider both limit and target reference points.

Term of Reference 7. Evaluate the status of each sub-stock as related to reference points, and summarize the relative status of the horseshoe crab stock throughout its range. State uncertainties associated with this evaluation.

The SASC used empirical reference points to evaluate sub-stock status. No overfishing or overfished assessment was made based on these empirical reference points. The Panel felt that the historical reference point (1998) was more useful than the quartile reference points, particularly because of the sensitivity of the latter to time series length. The Panel recommends development of a multiple-year average (rather than a single year) for the historical reference point that would represent a period of acceptably high horseshoe crab abundance. The years included in this multiple-year average should be determined by expert judgment of the SASC. Assuming a reference period of acceptably high abundance can be determined, this reference point should be used as a target. If the available time series for a survey only includes periods where abundance was believed to be below desirable levels, the reference point should be considered as a limit. We suggest an evaluation of the effects of different lengths of the time series on the ARIMA analysis of current stock status relative to reference points.

Term of Reference 8. Develop detailed short and long-term prioritized recommendations for needed research, data collection, and assessment methodology. Highlight improvements to be made by next benchmark review.

The SASC identified six research and assessment priorities, all of which the Panel agrees will move the horseshoe crab assessment forward. It would be useful to rank these priorities to facilitate decisions about allocation of scarce resources. This is discussed further in the final section of the Advisory Report, Section IV.

III. Terms of Reference – Adaptive Resource Management Framework

Adaptive Resource Management (ARM) has been employed to determine an appropriate level of horseshoe crab harvest such that energetic needs of migratory shorebirds, namely red knot in Delaware Bay, are not compromised. The purpose of this external review is to decide if the ARM framework and the predictive modeling developed to support ARM are appropriate to make this determination.

Term of Reference 1. Complete an explicit objective statement to reflect societal values (including policies and stakeholder interests) relevant to the Delaware Bay region horseshoe crab/red knot issue.

The ARM team has developed an explicit objective statement that represents the trade-off between horseshoe crab harvest goals and red knot conservation goals.

The objective was developed with input from representatives from contrasting stakeholder interests, although for the most part it was assumed that the membership of the two Technical Committees involved in the process adequately represented the diversity of stakeholder interests. The Panel observed that in other situations, government agency biologists would not be viewed by stakeholder groups as necessarily representing their interests.

Term of Reference 2. Assign an objective function that accurately represents the objective statement, addresses competing objectives, and is expressed in terms that can be evaluated using monitoring data.

The objective (reward) function that was developed by the ARM team accurately represents the objective statement.

The ARM team used knife-edge utility functions to represent the value of horseshoe crab harvest associated with differing levels of both female horseshoe crab and adult red knot abundance. The Panel is concerned that a knife-edge function might obscure some of the uncertainty surrounding the relationship between both horseshoe crab and red knot abundance and the value (utility) associated with abundance.

Term of Reference 3. Produce management alternatives that: result in a range of costs and benefits to all parties, are limited, are designed to remain static until expected results can be evaluated, can be implemented in a timely manner through the current management system, and are political feasibility.

The ARM Team developed and revised a set of management alternatives that represent wide contrasts in tactics ranging from a complete moratorium on horseshoe crab harvest to a relatively high rate of harvest on both male and female crabs.

The policy scenarios resulting from the optimization do not necessarily result in a static management option over time until expected results can be evaluated, but the Panel expects that the scenarios could be modified to operate in this way.

More important, the adaptive decision process described in the ARM plan is explicitly designed to provide a feedback loop between management actions and outcomes, with the evidence for alternative models being revised in this feedback loop. The Panel views this as consistent with the notion that "expected results can be evaluated".

The Panel is not in a position to judge whether (a) the management alternatives can be implemented in a timely manner, or (b) they are politically feasible. We do not feel they are unreasonable or impractical alternatives, in principle, and the process used by the ARM team to develop the alternatives ensures some accommodation of stakeholder/political realities.

Term of Reference 4. Evaluate precision and accuracy of data used in the assessment, including the following but not limited to:

a. **Discuss the effects of data strengths and weaknesses (e.g. temporal and spatial scale, sample size, standardization of indices) on model inputs and outputs.**
b. **Report statistical distributions of inputs where available and use them to inform the model if possible.**
c. **Justify weighting or elimination of available data sources.**

The ARM team provided detailed discussion of the empirical basis for the alternative models, where data were available to inform model structure or parameters. In many cases this discussion was limited to reference to other studies, and thus did not include many of the details listed in this TOR. However, the Panel finds that the ARM team has done a very thorough and appropriate job of using available data and published models/analyses to inform the development of alternative models

The Panel was particularly impressed with the development and analysis of the mark-recapture models to support their "weight-based multistate survival analysis". This methodology has already yielded very useful insights regarding an empirical link between horseshoe crab abundance and red knot condition. The Panel views this methodology as very promising for future estimation of model parameters.

The Panel found that most data sources were appropriately weighted. The Panel would like to have seen a distribution of values provided for the parameter representing survival of lower weight red knot birds (see below) given its importance to the population trajectory of red knots. We note that the ARM report incorrectly summarizes the probability distribution of horseshoe crab spawning times in May used in the optimization model.

Term of Reference 5. Evaluate models used to estimate population parameters (e.g., biomass, abundance).

a. **Establish that the model theory and framework has been demonstrated and documented in the peer-reviewed literature.**
b. **Test the model using simulated data.**
c. **Describe whether the models found a stable solution. Conduct sensitivity analyses for starting parameter values, priors, model assumptions.**
d. **Explain the model strengths and limitations.**

The ARM report contains very little background information on models used, other than for the multistate mark-recapture model. The general modeling approaches (theory and framework) are not novel.

We did not see any results of model tests using simulated data – it was not evident whether such analyses have been conducted. However, the panel does not view this as a limitation of the modeling work, but rather as a tool that can help evaluate the performance of the model under various assumptions. There was very little reporting of the results of sensitivity analyses, although it was acknowledged that this was a future priority for the ARM team. In general, there was limited discussion of the strengths and limitations of the alternative models.

The ARM report does not include parameter estimates of the best multi-state capture-recapture models for red knot survival.

The current fecundity-survival model produced a declining red knot population regardless of harvest intensity. The adult light-weight survival component of this model was based on the Baker et al. (2004) paper and the fecundity component based on the expert opinion of Humphrey Sitter. We suggest considering alternative parameterizations that use the lower confidence limits of the survival of light adults derived directly from more recent data.

In general, the Panel concluded that the process followed by the ARM team for model development was logical and appropriate for a participatory structured decision making project. Nevertheless, the Panel has concerns that the three models currently being proposed as alternatives may not be the most suitable candidates for the optimization analysis. In the advisory report we provide a number of suggestions for additional strategies to assist the selection of models for the adaptive management process. Specifically, insofar as the models represent a limited set of alternative hypotheses about system structure (i.e., crab – knot interactions) the Panel believes exploration of a wider range of model structures and sources of uncertainty would be beneficial.

Term of Reference 6. Evaluate the use of multiple models as a means of elucidating uncertainty or uncertainty in the mechanisms that determine system dynamics.

This is the essence of the ARM process. The Panel strongly supports this process and commends the ARM team and ASMFC for conducting and supporting this activity. As discussed above and in the advisory report, the Panel believes there are opportunities for complementary analyses that could further enhance the potential impact of this process, by supporting selection of the best possible set of candidate models and uncertainties to include in the ARM process.

Term of Reference 7. State and evaluate assumptions made for all models and explain the likely effects of assumption violations on synthesis of input data and model outputs. Examples of assumptions may include (but are not limited to):

- **a. Populations are at equilibrium.**
- **b. Constant ecosystem (abiotic and trophic) conditions.**
- **c. Form of the functions that link species dynamics in multi-species models.**

The assumptions of neither the demographic horseshoe crab stage-based model nor the multi-state capture-recapture analysis for red knot were stated. These include (but are not limited to): assumptions of (1) a closed population, (2) each individual has similar probability of capture and resighting, and (3) animals do not lose their marks or are affected by their marks (bands). A violation of these assumptions was discussed in the presentations (e.g., the probability of capturing > 180 g birds was less than that for capturing < 180 g birds) but the implications for the model parameter estimates was not mentioned.

Assumptions of constant ecosystem conditions for the projection, management based optimization models were not addressed. A potential violation is non-constant conditions of horseshoe crab food that will play out in changing population and individual growth of horseshoe crab. Additional uncertainty might be introduced by changes in the abiotic conditions of Delaware Bay (e.g., tidal patterns, temperature).

The approach used to link red knot survival to horseshoe crab abundance seemed appropriate given the extremely limited data on this relationship. In fact the derivation of an empirical basis for this relationship represents a significant advance.

Term of Reference 8. Evaluate uncertainty of model estimates.

Much thought was given to which model estimates could indeed incorporate uncertainty. The choice of which and how many model estimates to evaluate for uncertainty was to a great extent determined by computational limitations. Sensitivity analyses are suggested using single species approaches (See Advisory Report).

Term of Reference 9. Perform retrospective analyses, assess magnitude and direction of retrospective patterns detected, and discuss implications of any observed retrospective pattern for uncertainty in population parameters and/or management measures.

There was no retrospective analysis conducted. In principle this could have been conducted by using the horseshoe crab egg information to back-calculate weight gain in the pre-peak harvest period.

Term of Reference 10. Establish model weights that reflect relative credibility and sum to 1 for all members of the model set.

The process whereby the ARM team established initial weights was good and reflected the diversity of goals of individual team members.

Term of Reference 11. Establish procedures for updating model weights based on new observations.

This was achieved through use of the ARM double-looped program. The program would converge to the model with the greatest weight. This approach is commended.

Term of Reference 12. Develop of list of ongoing monitoring programs that provide data to:

a. **Determine system state for state-dependent decisions**
b. **Evaluate management performance toward objectives**
c. **Learn about system dynamics via comparison of monitoring data with model-based predictions**

a. The ARM team provided excellent suggestions for monitoring methods for the two major state variables, adult horseshoe crab abundance and red knot abundance. Specifically, the use of capture data (older and new) to assess the proportion of newly banded birds and the addition of survey methodology to determine marked to unmarked ratios are both much improved methods for assessing abundance over the use of aerial surveys.
b. To evaluate management performance, the same two state variables are measured in addition to the other six state variables (horseshoe crab juveniles, pre-recruits, adult males, adult females, and red knot immature and adult abundance). There continue to be issues in monitoring all but adults of both species but the ARM team certainly recognizes these constraints and has put thought into how these other life stages can be adequately monitored. The sensitive variable (horseshoe crab egg mortality) has been singled out as one that can be re-evaluated experimentally using the techniques of Botton et al. (2003). The ARM team has proposed developing models that will essentially allow estimation of recruits into adult populations (of both species) that will forego the need to have better estimates of the earlier life stages.
c. The ARM team provided good suggestions to improve model parameters, especially adult red knot population size, juvenile to adult transitions which could then be used to assess recruitment rates, and similarly for horseshoe crab, the suggestions for assessing recruitment into the population by foregoing the need to use egg mortality, juvenile mortality, etc., and using recruitment rates (a stage-structured model).

Term of Reference 13. Develop a list of gaps where monitoring activities are needed to provide data for achieving TOR 12 a-c.

A list of monitoring gaps was provided. For some variables the ARM deemed that effort should no longer be given to improving estimates. Further sensitivity analyses will assist in prioritizing variables for future monitoring,

Term of Reference 14. Provide a list of recommended monitoring programs to fill those gaps.

Much thought was put into this aspect of the ARM framework. Table 1 summarizes these recommendations together with the Panel's assessment.

IV. Advisory Report

The Panel commends the SASC for the advances they have made in the assessment of horseshoe crab since the previous review. The introduction of ARIMA modeling and the implementation of stock assessment models for Delaware Bay constitute real improvements over the previous assessment. The development and preliminary application of the catch-survey method is particularly encouraging.

Horseshoe Crab Stock Assessment presently faces two important challenges that make both assessment and management difficult: (1) heavy reliance on fishery-independent surveys which do not target horseshoe crab, especially outside of Delaware Bay; and (2) important hypothesized linkages between horseshoe crab abundance and red knot in Delaware Bay that require consideration of a multi-species management strategy.

At least in the short term, non-targeted surveys are likely to be the primary source of fishery-independent data for areas outside of Delaware Bay. At the same time, the stock assessments in Delaware Bay are likely to become more sophisticated because of the importance of the multispecies interaction. Nevertheless, because there is some evidence of a link between actions to control harvest on Delaware Bay and horseshoe crab dynamics elsewhere, the Panel warns against too much separation. In particular, coast wide assessments should continue despite potentially growing differences in assessment methods.

Status of Stock

- We find the general trends described in the assessment report are broadly supported by the stock assessment data, although the inconsistency in observed trends among data sources in the New England and New York regions lead to reduced confidence in the stock status determinations in these areas.
- The declining trends in some surveys in these northern regions are a source of concern, and analyses over the next few years should carefully monitor changes relative to empirical reference points.

- The lack of discussion in the assessment report on the relative strengths (accuracy) of the different surveys further exacerbates the uncertainty regarding the significance of the reported trends.
- Horseshoe crab abundance in the Southeast and Delaware Bay appears to have increased in recent years, but may still be below the 1998 reference point, and are almost certainly below levels of the early 1990s.
- Exploitation rate estimates in Delaware Bay appear to be low, especially in recent years; exploitation rates in other regions are unknown.

Overfished/overfishing determination

- Because exploitation rates are unknown, it is not possible to determine whether overfishing is occurring in the stocks outside of Delaware Bay. In Delaware Bay, the surplus production model results (and the survey trends) suggest that this population is not experiencing overfishing, and is likely not overfished at the present time, at least relative to the B_{MSY} and F_{MSY} reference points.
- For the Southern region, the survey results do not suggest the stocks are overfished, at least relative to the 1998 reference point.
- For the New York and New England regions, the survey results are more equivocal, and low recent catches in some surveys relative to the 1998 reference point suggest some of these populations may be overfished.
- The panel does not believe that a re-assessment of the historical reference points based on a range of years, as discussed below in the Biological Reference Points section, will change the overall assessment of current status.
- Lack of explicitly defined limit and target abundance-based and F-based reference points in the fishery makes it difficult to yield a more conclusive assessment as to whether the fishery is in the status of “overfishing” and whether the stock is “overfished”.

Stock Identification and Distribution

- The assessment program effectively treats the coast wide horseshoe crab population as if it were four stocks (since the times series analyses are considered collectively by region). Assessment at this scale, rather than coast wide (Florida to New England) is sensible given available biological data on stock structure.
- There are insufficient data on stock structure to evaluate whether the current four regions are the most appropriate assessment units. Evaluation of whether there are sub-region units that should be indexed independently is warranted.
- In light of the limited knowledge of movement among possible subpopulations we have concerns, not about the division of the coast wide population into regions, but about the implicit treatment of data from all surveys in a region as if they represent a single population.

Management Unit

- As increased knowledge of stock structure and subpopulations accrues, the development of management units at a finer scale, consistent with the spatial scale of ecological processes may be warranted. Based on the current assessments, management of horseshoe crabs at a unit finer than the entire Atlantic coast is warranted.

Landings

- The landings data since 1998 are believed to be quite reliable, especially for Delaware Bay. However, some concern was raised about possible current underreporting of harvest, particularly in the New York region.
- Because these data are not used in the stock assessment (except in the Delaware Bay models), this does not appear to be a large source of concern. The Delaware Bay stock assessment models do not appear sensitive to consistent but modest underreporting, but the Panel notes this could be more of an issue if there have been temporal trends in underreporting.
- There is concern with the lack of accurate data on the sizes of horseshoe crab in the commercial catch, and whether (i) juveniles are harvested by some sectors, and (ii) there has been a decline in prosomal width over time.
- This concern would obviously become greater if further evidence of stock depletion in NY and NE is obtained.

Data and Assessment

- The fishery dependent data are not used to assess trends in the population. The reasoning behind this choice should be more clearly articulated (i.e., why not look at commercial CPUE data, recognizing the well-known limitations of these data for assessing population trends?).
- The fishery independent data, particularly outside of Delaware Bay, suffer from being “bycatch” surveys, making them particularly vulnerable to biases introduced by where they are conducted relative to horseshoe crab distribution in each region.
- Some evaluation of the relative value (accuracy) of the various surveys is warranted. This could be done subjectively and reported in the interpretation of trend analysis results or by more formal methods possibly using covariate models that shed light on the factors (e.g., habitat) influencing vulnerability of horseshoe crab to the surveys.
- The Panel considers the ARIMA method superior to the linear trend analysis, and recommends focusing on this approach in the future in areas where more sophisticated modeling is not possible. The Panel concluded that the ARIMA method could supersede the linear trends analysis, provided the unsmoothed (input) index estimates are reported along with the smoothed (output) estimates.
- We are concerned the surplus production model for Delaware Bay is not suitable, given the life history of horseshoe crab and the presumed mechanism of density dependence. As noted in the report, surplus production models assume an instantaneous response of the stock to changes in conditions, which seems unrealistic given the late age of maturity of horseshoe crab and the belief that density dependence operates at the egg stage. We urge that the sensitivity of the production model to this assumption be explored more thoroughly if it is to be used further. A simple age-structured operating model (e.g., Sweka *et al.* 2007) could be used to generate simulated data that are then fit to the surplus production model and the biomass/exploitation rate estimates compared to true values to test for biases.
- The catch-survey methodology appears to be a promising tool for assessment in Delaware Bay, but will require further examination of the evidence for differential catchability of primiparous and mulitparous horseshoe crab. As a first step we suggest a spatial analysis

of the catch data, using habitat variables as covariates that may explain differences in the distribution and thus catchability of the two life stages.
- Commercial catch does not report juveniles. Additional biological data could be collected. There were insufficient fishery data available on harvest sizes and on reproductive states from trawl or dredge harvests. The Panel reiterates a recommendation from 2006*:* "The Panel strongly recommended improved characterization of the commercial catch and landings by fishery (bait, biomedical, and scientific) and by life stage" (ASFMC 2006).

Biological Reference Points
- No biological reference points have been agreed upon for horseshoe crab management. In view of the limited ability to assess stock abundance or fishing mortality outside of Delaware Bay, the utility of such reference points as a management tool is questionable.
- Nevertheless, we recommend development of plausible biological reference points using life history information for horseshoe crab, comparisons to other species with similar life histories (e.g., long-lived, late maturing invertebrate species), and development of yield per recruit or egg per recruit models.
- We also suggest empirical reference points based on an estimated historic state are preferable to percentile-based reference points because of the vulnerability of the latter to the influence of the period for which past data are available. This is especially true when the reference point analysis is being used in an aggregated manner (i.e., across multiple surveys). Rather than basing the historical reference point on a single year, we recommend using the average across a range of years that represent, in the SASC's judgment, a period of relatively high abundance.

Fishing Mortality
- Fishing mortality estimates are only available for Delaware Bay and both the surplus production and catch-survey analyses suggest the fishing mortality is currently low. We see no reason to expect that current fishing mortality rates in Delaware Bay might be substantially higher than these analyses suggest. Nevertheless, we recommend, if practical, monitoring of the presence (and proportion) of juvenile horseshoe crab in commercial catch.
- We are concerned that estimates of mortality of horseshoe crab released after bleeding may be low, and thus the exploitation mortality in the biomedical fishery may be underestimated.

Recruitment
- The stock assessment report does not include any analyses of recruitment, per se, other than the treatment of primiparous horseshoe crab as recruits in the catch-survey model. This is discussed above. Stock assessments would benefit from a clearer definition of recruitment.

Spawning Stock Biomass
- See status of stock section above.

Bycatch

- Horseshoe crab harvested in the hand fishery have no bycatch. No information was reported on the bycatch of horseshoe crab in other fisheries or the bycatch of other species in horseshoe crab trawl and dredge fisheries. More assessment information on bycatch and discards in trawl and dredge fisheries would be useful, possibly via a sea sampling program.

Adaptive Resource Management

In Section III (TOR Report for the ARM model), we summarized our evaluation of this effort. Overall, the Panel was greatly impressed by this work, which we believe comprises an excellent combination of a deliberative, stakeholder-sensitive process with a rigorous scientific assessment of the critical uncertainties surrounding the linkage between horseshoe crab harvest management and red knot conservation. The Panel endorses the shift towards a management strategy for horseshoe crab in Delaware Bay that attempts to balance potentially conflicting objectives for horseshoe crab exploitation and red knot conservation, and at the same time seeks to reduce uncertainty about the linkage between these two species. As noted in Section III, the ARM process is ideally suited for this purpose. Here in the advisory section of the report we focus on a recommendation for additional simulation analyses that we believe will **supplement**, but should **not replace** the modeling and optimization work that has already been completed.

We recommend that the ARM team develop new models or use existing models that allow a richer exploration of (1) the population dynamics of horseshoe crab, (2) their interaction with red knots, (3) a variety of uncertainties not limited to model structure and parameters; and (4) a wider range of policy options. We recommend this not because we believe the optimization/ARM framework they are currently using is wrong or inappropriate, but rather because the framework – as is frequently noted in the ARM report – imposes severe constraints on model complexity (dimensionality) for computational reasons. This inescapably leads to compromises on model complexity that raise difficult questions about whether the choices made for the optimization and model updating (ARM) procedure are the ideal ones for learning about the system and making good decisions in the face of uncertainty. Our view is that many of these choices can be “vetted” outside of the optimization framework and then used to improve the actual ARM model and optimization.

We advocate an approach resembling recent work in fisheries management that is sometimes referred to as “Management Strategy Evaluation” (MSE: Cooke 1999, Punt 2006). MSE involves developing a simulation model of the complete management system, including the process of data collection (assessment) and the implementation of management, in addition to the system dynamics themselves. This enables explicit consideration of the influence of both partial observability and partial controllability on the performance of so-called “management procedures.” A management procedure consists of an assessment process (a stock assessment) combined with a control rule (e.g., a harvest policy). The MSE model is not embedded within an optimization framework and thus only requires forward simulations, although many replicate simulations are required due to the stochastic nature of the model. The goal is to compare the relative (expected) performance of alternative policy/assessment combination (the management procedure) based on a suite of performance measures that represent the relevant set of management objectives for a particular situation.

In this case the development of an MSE model to complement the ARM optimization model would allow:

1. Explicit examination of the relative importance of different sources of uncertainty to policy performance and the decision process. The MSE model can be used in a decision analysis framework to assess the expected value of reducing uncertainty (cf. Morgan and Henrion 1990).

2. Comparison of more "realistic" models of system dynamics (e.g., an age-structured model) to the aggregated model used (of necessity) in the optimization to determine whether the aggregation results in a relevant loss of realism (measured by a contrast in the relative performance of a suite of policies between the aggregated and more complex model).

3. Consideration of wider range of policy options, although without being able to determine the optimal policy.

4. Consideration of policy performance relative to a variety of possible objectives, rather than a single objective function, again with the cost being that optimization is not possible.

A challenge of MSE analysis is determining whether you have identified a "good" range of policies to compare, *a priori*. The great advantage of having the MSE analysis complement the optimization is that the latter can inform the former about a set of policies that appear to be optimal, within the constraints imposed by the optimization process. This creates the opportunity for an iterative process of optimization to generate a set of candidate policies, followed by an MSE analysis to determine whether the success of those policies is robust to a broader consideration of uncertainty and more complex and arguably realistic models, followed (if necessary) by a refinement of the optimization models to account for what appear to be critical processes or uncertainties.

To our knowledge, this "marriage" of the optimization approach to adaptive management pioneered in waterfowl management (Williams 1997) and used by the ARM team, and the MSE approach pioneered in marine fisheries (Butterworth 2007, Smith et al. 1999) has not been attempted previously. Consequently the insights gained from adding MSE to the ARM process for Delaware Bay horseshoe crab/red knot management could extend well beyond this case study.

Summary of Research Recommendations

The TOR sections of this report include a number of recommendations for research activities that could improve horseshoe crab stock assessment and the models that are used in the ARM optimization. In those sections we also comment on the research recommendations included in the stock assessment and ARM reports. Here we summarize our key research recommendations and provide our assessment of relative priority.

Research/assessment with available data:

1. ARM model sensitivity to:
    - egg survival model – density dependence relationship to habitat (beach size, etc)
    - operational sex ratio threshold
    - age zero survival
    - juvenile and adult red knot lightweight survival

2. Develop MSE framework for evaluation of alternative policy and sources of uncertainty

3. Use statistical modeling (GAM, GLM, etc.) to examine fishery-independent surveys (including spawning surveys) with respect to regional differences in timing, gear, sampling intensity, etc.

4. Further develop catch-survey analysis and explore application of Bayesian inference for catch-survey model

5. Life history model (e.g., individual-based or age-structured) as an operating model which can be used to test the performance of a stock assessment model and can be used for the risk analysis of alternative management strategies with respect to management objectives

6. Develop habitat models to quantify the relationships between horseshoe crab abundance (by size or stage class) and key habitat variables, and develop potential habitat maps to quantify potential spatial distribution of horseshoe crabs of different sizes or life history stages

7. Develop size-structured population model for the Delaware Bay stock

8. Use existing USFWS mark-recapture data to assess horseshoe crab adult demographics.

Research/assessment requiring new or additional data or significant modeling:

1. Assess the relative catchability of different horseshoe crab stages in the Virginia Tech benthic trawl survey. This could be accomplished with an experimental approach combined with analyses of existing survey data and habitat information.

2. Estimate the proportion of the Delaware Bay population that is available in time and space within the existing Virginia Tech benthic trawl survey area. This estimation should take horseshoe crab age into account. These two objectives could be met with a coordinated research program.

3. Expand or implement fishery-independent surveys (e.g., spawning, benthic trawl,

tagging) to target horseshoe crabs throughout their full range, including estuaries. Highest priority should be given to implementing directed surveys in the New England and New York regions. The Panel recommends using the Virginia Tech trawl survey as a model.

4. Develop research methodology to evaluate the stock-recruitment (adult-juvenile) relationship for horseshoe crab. This would require developing an index of juvenile abundance.

5. Characterize the proportion of states' landings that comprise crabs of Delaware Bay origin. This can be done through a directed tag/release study, a genetics/microchemistry study, or both.

6. Test efficacy of digital photography to remotely identify "lean" and "fat" red knots to increase the accuracy of transition probabilities between these two condition states.

IV. References

Atlantic States Marine Fisheries Commission (ASMFC). 2006. Terms of reference report for the stock assessment of horseshoe crab: a proposed framework. Special report No. 86 of the Atlantic States Marine Fisheries Commission. Washington D.C. 8pp.

Baker A. J., P. M. Gonzalez, T. Piersma, L. J. Niles, I. do Nascimento, P. W. Atkinson, N. A. Clark, C. D. Minton, M. K. Peck, G. Aarts. 2004. Rapid population decline in red knots: fitness consequences of decreased refueling rates and late arrival in Delaware Bay. Proc. R. Soc. Lond. B 271: 875-882.

Botton, M. L., R. E. Loveland, A. Tiwari. 2003. Distribution, abundance, and survivorship of young-of-the-year in a commercially exploited population of horseshoe crabs *Limulus polyphemus*. Marine Ecology Progress Series 265: 175–184.

Butterworth, D. S. 2007. Why a management procedure approach? Some positives and negatives. ICES Journal of Marine Science 64:613-617.

Cooke, J. G. 1999. Improvement of fishery management advice through simulation testing of harvest algorithms. ICES Journal of Marine Science 56:797-810.

Hata, D. and J. Berkson. 2004. Factors affecting horseshoe crab *Limulus polyphemus* trawl survey design. Transactions of the American Fisheries Society 133(2): 292-299.

Morgan, G. and M. Henrion. 1990. Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. Cambridge University Press, Cambridge, UK. pp. 56-68

Punt, A. 2006. The FAO precautionary approach after almost 10 years: have we progressed towards implementing simulation-tested feedback-control management systems for fisheries management? Natural Resource Modeling 19(4):441-464.

Smith et al. 1999. Implementing effective fisheries management systems – management strategy evaluation and the Australian partnership approach. ICES Journal of Marine Science 56:967-979.

Sweka, J. A., D. R. Smith, and M. J. Millard. 2007. An age-structured population model for horseshoe crabs in the Delaware Bay area to assess harvest and egg availability for shorebirds. Estuaries and Coasts 30(2): 277-286.

Williams, B.K. 1997. Approaches to the management of waterfowl under uncertainty. Wildlife Society Bulletin 25(3): 714-720.

V. Tables and Figures

Table 1. Summary of SASC and Peer Review Panel's opinions on monitoring needs.

Model State Variables/Parameters	SASC Suggested Monitoring Needs	Panel Findings and Suggestions
Red Knot: Total stopover population	Marked-to-unmarked ratio	Agree
Immature abundance	Use of model-averaged predictions	Agree
Adult annual survival and mass state transition rates	Multi-state open robust design survival analyses	Agree. Pursue digital photographic methods of obtaining physiological condition, upon release (known weights) to improve accuracy of transition rates.
Immature survival	No hypothesized link to HSC spawning so low priority. Will continue to use 85% of heavy adult survival (by convention)	Agree. Encourage the banding effort on southward fall migration (by Canadian red knot researchers) to refine this estimate and increase probability of these birds showing up in Delaware Bay surveys.
Juvenile survival	As per immatures	Agree
Fecundity/productivity	Use marked-unmarked ratios to estimate recruitment	Agree
Horseshoe crab: Adult male and female abundance and pre-recruit abundance	VT off shore trawls and comparison of catchability	Agree
Juvenile abundance	Model averaged juvenile abundance estimates	Agree. Encourage development of size or age-based juvenile abundance indices from existing surveys (e.g. Delaware 16' trawl) and possibly new surveys.
Male and female adult survival	Use USFWS mark-recapture data from Delaware Bay	Agree
Pre-recruit survival	Need local estimates as per male and female adult survival	See footnote[1]
Juvenile survival	DE Bay studies on juvenile stage	See footnote[1]
Age zero survival	Spatial and temporal replicates of Botton et al. 2003	See footnote[1]

Egg mortality	Continued use of simulation study	See footnote[1]
Fecundity	Current estimates sufficient	Agree
Sex ratio linked fertility function	Suggestion to conduct further studies on relationship between OSR and fertilization rate. Use spawning survey and benthic trawl surveys to monitor ratios	Agree
Spawning survey	High priority on continuing survey, suggestion to improve by sampling at different times	Strongly agree with continuing survey. Consider using GLM approach to improve quality of index based on environmental covariates.
Egg survey	Not used because data are so variable	Agree

[1] Separate estimates of these life-stage survival rates will be very difficult, if not impossible to obtain. Alternatively, effort could be devoted to developing an index of recruitment (i.e., for age 1 juvenile crabs based on a targeted survey and size information) that could be eventually used to estimate a stock-recruitment relationship and eliminate the need for life-stage survival estimates (egg → juvenile).

Figure 1. Location of fishery independent surveys used in the horseshoe crab assessment.