<u>Horseshoe Crab Stock Assessment and Technical Committees Report</u>

January 3 – 6, 2006

The Stock Assessment Subcommittee (SAS) held a workshop on January 3rd, 4th, and 5th to review and discuss models used to estimate horseshoe crab population status and trends. The Technical Committee (TC) met immediately after the SAS on January 5th and 6th to discuss the results of the SAS workshop and management options for draft Addendum IV. Both meetings were held at the Renaissance Hotel near the Philadelphia Airport. The following is a summary of those meetings.

Attendees

Committee Members

Andrew Draxler (NMFS)
Larry DeLancey (SC), TC Vice Chair-elect
Tina Moore (NC)
Sue Gerhart (FL)
Greg Breese (USFWS), Chair
Jeff Brust (NJ)
Stew Michels (DE)
Steve Doctor (MD)
Carl Shuster (VIMS)
Penny Howell (CT)
Lewis Gillingham (VA)
Robyn Burgess (NY)
Frank Germano (MA)
Kim McKown (NY
Dave Smith (USGS), SAS Chair
Michelle Davis (Virginia Tech)
Peter Himchak (NJ)
Mike Millard (USFWS), TC Chair-elect
Joanna Burger (Rutgers)
Brad Spear (ASMFC), Staff

Others

Jon Brodziak, NMFS NEFSC
Rich Wong, DE
Eric Stiles, NJ Audubon
Maya Von Rossom, DE Riverkeeper
Constance Campanella, American Bird Conservancy
Jason Rylander, Defenders of Wildlife
Sandy Bauers, Philly News
Bruce Freeman, NJ, HSC Board Chair
Michael Oates, Anew, Inc.
Frank Eicherly, Waterman
John Sweka, USFWS
Rick Robins, Ches. Bay Packing, HSC AP
Perry Plumart, American Bird Conservancy
Greg Butcher, Audubon

SAS Review of HSC Models
The Horseshoe Crab Management Board directed the SAS to conduct a review of models recently published to estimate population status and trends. Because several authors of the models sit on the SAS, ASMFC brought in two external assessment experts to help the committee in an objective review. The workshop participants updated and adjusted model runs conducted since the models were submitted for publication in peer reviewed scientific journals. The workshop report is enclosed as Attachment I. It was reviewed, modified, and accepted by the TC and is now submitted for the Board's consideration. The SAS review report will also be forwarded to the USFWS Shorebird Technical Committee.

There was the suggestion at the TC meeting to have the work of the SAS peer reviewed before the February Board meeting. Due to time restrictions, this was not possible. A possible alternative for the Board's consideration is for ASMFC to hold an external peer review between the February and May Board meetings. Another alternative is to postpone external peer review until 2008 or 2009 when the next benchmark stock assessment for horseshoe crab is tentatively scheduled.

SAS Stock Assessment Research/Work Agenda
The SAS also prepared a document (Attachment II) that lists research and work that should be completed in short term and long term horizons. The lists were compiled after discussing model review results mentioned above, the peer review panel report regarding the SAS's Assessment Framework (2000), and 2004 Stock Assessment Report. The exercise of creating a short term work agenda underscored the importance of being able to effectively identify female pre-recruits on a large scale. This information is needed to run the Collie-Sissenwine Model (catch survey analysis, CSA) effectively. The SAS and TC should be make a determination soon as to whether the SAS will continue to work toward the CSA (as proposed in the SAS Assessment Framework, 2000) or to go down a different path for HSC stock assessment. A possible lead for determining a standardized methodology for identifying pre-recruits is with the Virginia Tech benthic trawl survey.

Funding to Address SAS Research Agenda
Members of the committees and audience stressed the importance of moving forward as quickly and effectively as possible with the HSC stock assessment. Several audience members that represent the birding community offered their assistance to ASMFC, states, and HSC Board and committees in finding and securing funds to help accomplish the SAS's research agenda.

HSC TC and SAS Leadership Changes
Greg Breese is stepping down as TC chair after many years of service. The Committee praised Greg for his efforts to advance the understanding of horseshoe crab and shorebird dynamics. It presented Greg with a copy of The American Horseshoe Crab (Shuster et al.) that will be distributed and signed by TC and SAS members. Mike Millard (USFWS, Lamar, PA) was elected to fill Greg's position as chair. Mike has served on the TC and SAS for about seven years. Larry DeLancey (SC DNR) who was been active on the committee for many years was elected as vice chair. Finally, after Jim Berkson's resignation from the SAS, Dave Smith (USGS, Leestown, WV) took over as SAS chair this summer.

Brief Review of VT Trawl Survey, DE Bay Spawning Survey, and HSC Tagging
At its prior meeting, the TC requested a review of VT trawl and DE Bay spawning survey results once they were completed. Results were not available for discussion at this meeting. TC members stressed the importance of reviewing these results before they are used to make management decisions. Often times the public and managers do not take into account the limitations and variability inherent in these surveys before they are used to inform policy recommendations. The TC requested the opportunity to hear a presentation and review the results of these surveys once they are available. Currently funding is not budgeted for a face-to-face meeting and a conference call is not an appropriate forum for review. The TC agreed that a web conference might be an appropriate option.

The TC requested a presentation from VT on progress or results of projects funded by Congress through NMFS, Department of Commerce. The Virginia Tech Horseshoe Crab Research Center (HCRC) has recently undergone leadership changes as has the HSC technical committees (see above). The committee chairs plan to reestablish a working relationship with the VT HCRC to facilitate frequent exchange of information.

The TC stressed the importance of receiving a report on four years of results of the benthic trawl survey. TC members had questions about the future of the survey (i.e. funding, long term prospects, design changes, goals). Some members had suggestions for changes or additions to the survey design (i.e. focusing less on 'coastwide' and extend survey into DE Bay, adding a tagging component, ground-truthing results with benthic sled underwater video [see below]).

Both the SAS and TC recommended reconvening the HSC Tagging Subcommittee. Significant tagging studies have been conducted since its last meeting in January 2003. The committees suggested inviting Benjie Swann (Limuli Laboratories), discussing the collaborative work of USGS, Cornell Cooperative Extension, NJ, and DE, revisiting the USFWS tagging database, and most urgently, to assist the HSC Plan Development Team (PDT) in defining the phrase "crabs of DE Bay origin" (as used in a motion by the Board at its November meeting). As noted above, there may be opportunity to add a tagging component to the VT trawl survey. In addition, Great South Bay (NY) has infrastructure in place that may allow for piggybacking of a HSC radio tagging study. Another possible study is using PIT tags in juveniles to get a better handle on early life history and age data. The use of PIT tags is currently being explored in the lab at USGS.

Benthic Sled Underwater Video
Mike Oates was contracted by New Jersey through ASMFC to construct and test an underwater video sled that could be used to observe HSCs underwater. He presented his findings and underwater video for the Board at its November meeting. He gave a similar presentation to the TC. The TC was impressed with the work that Mike and others had done to build a lightweight and energy-efficient tool that can be used to observe HSCs in the benthic environment. Potential uses discussed by the TC included testing state trawl survey efficiency to make qualitative observations and ground-truthing other surveys such as the VT trawl survey. TC members also saw applications of the sled for other fisheries.

Addendum IV Management Options
The Board provided the PDT the following guidance for options to include in draft Addendum IV:

1) A two-year moratorium on harvest of horseshoe crabs from the states of New Jersey and Delaware with an exemption for existing biomedical needs. Any biomedical needs that could not be returned alive to the general area of capture shall be made available to the bait industry.
2) Restrictions on harvest of horseshoe crabs outside of Delaware Bay as necessary to restrict harvest of horseshoe crabs of Delaware Bay origin.

The PDT is clear on (1) and will include this option in the draft Addendum. It needed guidance from the TC on how to interpret (2), specifically the phrase mentioned above ("horseshoe crabs of Delaware Bay origin"). The TC offered that tagging data from USFWS database could be used to help. It suggested one specific option, which is to propose a male-only harvest with a delayed season in Maryland and Virginia. This option is similar to one proposed by others for Delaware and New Jersey.

Rick Robins presented to the TC an alternative to option (1) above. The alternative is the following combination:

1) Moratorium on the directed harvest of female HSC in Delaware and New Jersey for two years.
2) Moratorium on harvesting horseshoe crabs in Delaware, New Jersey and Maryland from January 1 through June 7 for two years.
3) Allow delayed harvest in Delaware and New Jersey of MALES ONLY from June 8 – December 31, at Addendum III harvest quotas.
4) Limited male harvest would be accompanied by a sex-ratio threshold and monitoring provision as precautionary measure.
5) Re-evaluate after 2-year period to assess effectiveness of management strategy, define triggers for re-opening.

A Board member proposed a similar option prior to the TC meeting. The PDT was looking for guidance from the TC as to whether this option had merit for inclusion into the draft Addendum.

There were a number of concerns voiced at the meeting. Concern was raised about the impact of a male-only harvest on the sex ratio of the population. There was also unease about the impact to egg abundance if female crabs are caught as bycatch in mobile gear. Further concerns were in regard to the disproportionate impact to the conch and eel fisheries with a male-only harvest. Males are not a very effective bait for catching eels while they are the preferred bait in conch traps. Another concern was that a moratorium of harvest through June 7 might not be late enough to allow for maximum egg availability for late-migrating red knots.

Despite the concerns mentioned above, the TC agreed that the proposed alternative is reasonable and recommended that the PDT include it or something similar in the draft Addendum. Support for including the option was also illustrated by identifying the precedent of management through differential harvest pressure on males and females in deer and lobster. These species have been successfully managed using a strategy focused on maximizing the survival of mature females while harvesting the biological surplus of males.

An audience member proposed a coastwide moratorium. After a brief discussion by the TC, the proposal was withdrawn.

TC members raised a couple other questions regarding proposed action by the Board:

If a two-year moratorium is imposed, what is the trigger for reevaluation at the end of two years? (It was noted that the next benchmark stock assessment might coincide with the two-year time frame.)

What are enforcement issues associated with the proposed options?

ATTACHMENT I

Review of Horseshoe Crab Population Models

Presented to the
Horseshoe Crab Technical Committee

Prepared by the
Horseshoe Crab Stock Assessment Subcommittee

Jeff Brust, New Jersey Division of Fish and Wildlife
Michelle Davis, Virginia Tech University
Kim McKown, New York Department of Environmental Control
Stew Michels, Delaware Department of Natural Resources and Environmental Control
Mike Millard, U.S. Fish and Wildlife Service
Dave Smith, Chair, U.S. Geological Survey
Brad Spear, Staff, Atlantic States Marine Fisheries Commission

with assistance from
Jon Brodziak, National Marine Fisheries Service
Rich Wong, Delaware Department of Natural Resources and Environmental Control

January 2006

Terms of Reference for Review of

I. Davis, M. L., J. Berkson, and M. Kelly. *In press*. Delaware Bay horseshoe crab population assessment using a surplus production model. Fishery Bulletin.

II. Smith, D. R., M. J. Millard, S. Eyler. *In press*. Abundance of adult horseshoe crabs in Delaware Bay estimated from a bay-wide mark-recapture study. Fishery Bulletin.

III. Sweka, J. A., D. R. Smith, and M. J. Millard. An age-structured population model for horseshoe crabs in the Delaware Bay area to assess harvest and egg availability for shorebirds. *In review*.

1. Evaluate adequacy and appropriateness of the models presented in papers *I – III* and data used in the models for estimating stock biomass and fishing mortality rates or evaluating population dynamics.

2. Identify important assumptions of the models and evaluate validity of the assumptions given horseshoe crab life history, characteristics of input data, and design and objectives of the study.

3. Evaluate whether or not it is appropriate at this time to use the results of the models, based on the most recent data available, as a basis for management decisions considering the multiple-use fishery management goal specified in the Interstate Fishery Management Plan for Horseshoe Crab (FMP).

4. Provide recommendations for improving the models.

5. Summarize the status of the horseshoe crab population that spawns in Delaware Bay in light of best available assessments. Provide explanations for any inconsistent or contradictory results from recent modeling efforts.

1.0 Introduction

At the request of the Horseshoe Crab Management Board, the Horseshoe Crab Stock Assessment Subcommittee convened a workshop on January 3rd and 4th to review the aforementioned papers and models. Because of time-constraints, this was not an external peer review. Review participants were members of the stock assessment subcommittee, some of whom had authored the papers to be reviewed. To achieve a measure of independent review within the time-constraints, outside participants who had expertise in stock assessment methodology were invited.

The subcommittee critiqued the models and explored possible improvements. The review also included discussion of additional model adjustments and runs conducted since the papers were submitted for publication. Section 2 provides the subcommittee's responses to Terms of Reference 1 through 4 for each model. Section 3 outlines the subcommittee's summary of Delaware Bay region horseshoe crab population status addressing Term of Reference 5.

The review resulted in a thorough and balanced technical review of the proposed models. Also, a number of important recommendations were made on ways to move the assessment of horseshoe crabs forward.

2.0 Models

Following a brief introduction, terms of reference 1-4 are addressed for each model. Each model is organized by subsection.

2.1 Surplus Production Model (Davis et al.)

The Davis et al. paper applied a surplus production model (spm), which is a traditional fishery model, using the program ASPIC (Prager, 1994). Data inputs in the published ASPIC runs included NMFS spring trawl survey, DE Del Bay 30 ft trawl survey, DE Del Bay 16 ft trawl survey YOY and ≤ 160 mm, MD Coastal Bays, NJ Ocean trawl, and Hand and Dredge CPUE from DE harvest. NMFS fall trawl survey, NJ Del Bay trawl, and Del Bay Spawning Survey were not included in the published ASPIC runs. Data outputs included B/Bmsy (relative biomass), F/Fmsy (relative F), estimates of absolute B and F, and population projections.

The subcommittee discussed appropriate index selection for use as data inputs in ASPIC. The discussion resulted in an ASPIC model run that differed from the model runs presented in the Davis et al. paper. Terms of reference refer to the updated analysis rather than the published ASPIC runs. The updated analysis is presented in Appendix A.

To select indices for input into ASPIC the subcommittee considered model assumptions, life history of horseshoe crabs, and temporal and spatial coverage of the survey. Correlation of indices was treated as a secondary criterion. The subcommittee agreed on the following criteria for index selection.

At a minimum,

1) the index should adequately represent population biomass,
2) the survey design should sample the target population adequately over space and time, and
3) if the index is a measure of harvest CPUE, it should not be confounded by regulatory change.

The subcommittee was concerned about mixed metric units. Original runs used landings in weight and indices in numbers. Having the same units for the landings and indices is preferable in production models. Also, there was discussion whether the fall surveys (e.g., the NMFS fall trawl survey) should be advanced one calendar year to coincide with the spring surveys.

The subcommittee believed that the following surveys would best represent the exploitable population in the Delaware Bay region. Indices for the baseline ASPIC run consisted of NMFS fall trawl (advanced one calendar year to match with subsequent spring surveys), DE 30 ft (April – July), NJ Del Bay trawl (adults; May – July), DE 16 ft trawl (adults; Apr – July), and the Del Bay Spawning Survey.

TOR #1: Evaluate adequacy and appropriateness of the models presented in paper and data used in the model for estimating stock biomass and fishing mortality rates or evaluating population dynamics.

The subcommittee felt that the updated ASPIC run was adequate and appropriate for determining trends in relative F and relative abundance. There was consensus that the updated ASPIC run provides valuable information for a qualitative assessment of current F relative to F_{MSY} and current abundance relative to B_{MSY} (i.e., are the ratios above or below 1). There were questions regarding the accuracy of quantitative estimates of absolute F and biomass due to the short time series relative to the generation time of horseshoe crabs and the validity of applying a production model to horseshoe crabs, which are long-lived and require a long-time to reach reproductive maturity. Prager (1994) also cautions against using absolute estimates of current and target values, but recommends using relative values. Also, the magnitude of estimates of absolute F and biomass change depending on the time period and set of horseshoe crab indices that are included in the ASPIC run.

There was considerable reservation on the use of ASPIC for projections of horseshoe crab population dynamics. The committee reached consensus that it was inappropriate to develop projections due to a mismatch between horseshoe crab life history and the assumptions used in ASPIC. In particular, the lack of a recruitment time lag in ASPIC causes concerns regarding the use of ASPIC for horseshoe crab population projection. Simulation studies should be conducted to evaluate the appropriateness of ASPIC projections for horseshoe crabs.

TOR #2: Identify important assumptions of the models and evaluate validity of the assumptions given horseshoe crab life history, characteristics of input data, and design and objectives of the study.

Assumptions regarding the underlying model:

1) Age-aggregated model: Assumed that size or age structure of the population does not greatly affect population dynamics. Estimation of production model parameters assumes that annual changes in age-aggregated indices are determined by annual changes in population size and growth. Estimation procedures assume that catchability is equal for all ages that contribute significantly to population biomass.
2) Constant carrying capacity: Assumed that there were no changes in the biotic or abiotic environments during the model period that would impact horseshoe crab carrying capacity or intrinsic population growth rate.
3) Logistic population growth: Assumed Graham-Schaefer form of the surplus production model, or logistic growth. Population growth rate is low when population size is near zero and near the carrying capacity. The population grows fastest (and has the highest surplus production) when biomass is at B_{MSY}, or half of the carrying capacity.
4) Non-equilibrium model: Assumed that harvest did not have to be equal to surplus production, and that the population was not at equilibrium conditions.
5) $B_{MSY}=0.5K$: Assumed that the biomass that would produce maximum sustainable yield (B_{MSY}) was equal to half of the carrying capacity (K). This model form is often used

because of its theoretical simplicity, and because it is central among possible production model shapes.

Assumptions regarding the data:

1) Conditioned on landings: Assumed that landings data were more precise than abundance indices. The model is then able to utilize multiple abundance indices by interpreting differences among indices as sampling error. From a statistical view, it is preferable to compute residuals and error using the less precise quantity (i.e., effort and surveys for these models).
2) Representative indices and correlations between indices: Assumed that each survey was representative of the population being evaluated. Negative correlation among any pair of surveys may result in difficulty fitting the model to the available data. However, it was unclear what impact correlation-related errors have on the accuracy of model output, although negative correlations prevent the use of bootstrapping to find confidence intervals.
3) 1991-1994 regional harvest: Assumed to equal to 3.2 times Delaware harvest from 1991-1994. Harvest reporting during this time was not mandatory, but Delaware had relatively reliable landings so we extrapolated Delaware landings to the Delaware Bay region. The ratio of 3.2 was based on landings from 1998 to 2005.

ASPIC options:

1) Weighting: Either equal weightings of surveys or weighted inversely proportional to sampling error. The updated ASPIC run uses equal weighting.
2) Initial guesses (which are subsequently re-estimated within models):
   MSY=1 million, or half of the largest catch
   K=20 million, or 10 times the largest catch
   B_1/K=0.5 (an appropriate default in the absence of other information)

Assumption evaluation:

Sensitivity analyses are presented in Appendix A. There were minimal differences in model output when harvest for 1991 – 1994 was changed from one to 20 times Delaware landings. Sensitivity analyses were conducted for initial estimates of B1/K, MSY, and K; there were minimal differences in levels tested.

The assumptions regarding the appropriateness of applying an age-aggregated model for horseshoe crab assessment are currently not evaluated fully. The underlying concern is the mismatch between model assumptions and horseshoe crab life history. In particular, the substantial recruitment time lag that is exhibited in the horseshoe crab life history is not incorporated in the production model. Prager et al. (1996) conducted a simulation study looking at production models applied to a population with 'pronounced age structure' using swordfish as an example. They found that the production model 'provided qualitatively correct estimates of stock status', which is consistent with our interpretation of results from the updated ASPIC run. However, swordfish life history, with maturity at 5-6 years, does not encompass the horseshoe crab life history, and horseshoe crab survey indices have additional limitations. Horseshoe crabs require 9-10 years to mature, survey indices show strong age-specific catchability, and conversions of survey catches from numbers to biomass across ages have not been developed. Thus, prior to using quantitative estimates from ASPIC for management decisions it would be advisable to conduct a simulation study to evaluate application of surplus production models to horseshoe crab populations (see TOR #4).

The effect of negative correlation among indices is not currently evaluated, but could be evaluated through a simulation study (see TOR #4). The assumption of B_{MSY}=0.5K is currently not evaluated, but we don't have any reason to suggest for HSCs it's anything different.

TOR #3: Evaluate whether or not it is appropriate at this time to use the results of the models, based on the most recent data available, as a basis for management decisions considering the multiple-use fishery management goal specified in the Interstate Fishery Management Plan for Horseshoe Crab (FMP).

There was consensus that it is appropriate to use qualitative results from the updated ASPIC run for management decisions. The results indicate that biomass has declined during the 1990s and that fishing mortality peaked during the late 1990s and has declined to the present (Appendix A). Although biological reference points have not been established for the horseshoe crab stock, fishing mortality rates during the 1990's have reduced adult biomass. Management actions since 1998 have reduced F, but current levels of F still appear to be in excess of Fmsy.

The model provides no information on the multi-use aspect of the fishery. If it can be determined that a production model (ASPIC or an extension) can be used to accurately estimate biomass, then the approach can be part of an assessment framework that includes evaluating egg availability to shorebirds. However, the subcommittee recognized that egg availability for shorebirds also depends on overlap between horseshoe crab and shorebird migrations, density-dependent bioturbation, and wave-mediated vertical transport of eggs to the beach surface.

TOR #4: Provide recommendations for improving the models.

The NJ Ocean Trawl survey should be included in future runs; however the results should be made season-specific and the October results should be moved into the next calendar year to coincide with the spring survey.

Indices and landings should be converted to biomass. However, sex and size specific biomass relationships need to be quantified before the conversion can be done reliably.

The relationship between indices and environmental data should be examined as part of an evaluation of how well indices represent the population.

There should be an effort to construct a longer landings time series. Although there is concern about accuracy of pre-1991 landings estimates and effects on the model, there is substantial value in using data across a wider range of population values, including observations on both sides of MSY.

There should be an effort to include estimates of discards, biomedical harvest, and personal use harvest.

There should be an effort to combine mark-recapture and production models. The subcommittee could conceive of three approaches varying in difficulty and restrictive assumptions. The least difficult and most restrictive would be to use the ratio of abundance estimates from a production model to the mark-recapture abundance estimate and use the ratio to back-calculate throughout the time series. An ad hoc approach to determine confidence limits would be to include both the uncertainty in the production model and in the mark-recapture estimates. An intermediate approach would be to 'plug-in' the mark recapture estimates of abundance into a production model run as "absolute biomass index" and adjust weight and set q=1 for the mark-recapture estimates. The problem with this intermediate approach would be that the uncertainty in the mark-recapture estimates would not be included. The most difficult and least restrictive (most flexible) would be to combine the models so that models are solved and parameters are estimated simultaneously. This is a research topic that might or might not prove fruitful.

The appropriateness of the production (age-aggregated) model for HSC life history should be evaluated. One approach would be to conduct a simulation study by generating index and landings data from an age-structured model and feeding those data into a production model (such as ASPIC) to estimate mortality and biomass. Evaluation of bias would be conditional on population represented by the age-structured model. The inclusion of a shape parameter (m, Pella-Thomlinson model) for the production function (with $m<0.5$ to give low biomass production at low stock size) could be evaluated as a method to account for a long-lived species with a substantial recruitment time lag. Also, as part of this simulation the effect on bias due to negative correlations among indices (as observed in the HSC indices) should be examined.

The decline in relative F from the updated ASPIC model should be compared to the timing changes in management.

2.2 Mark-Recapture Study (Smith et al.)

The Smith et al. paper presents a mark-recapture study to estimate population abundance of adults in the Delaware Bay at the time of peak spawning in 2003. See Appendix B for an update to the Smith et al. paper, which includes estimates for 2004 and further evaluations of assumption violations. Data inputs for population estimates were the number of male horseshoe crabs tagged prior to spawning, the number of male horseshoe crabs with and without tags observed in 1-m^2 quadrats during the spawning survey, and telemetry tracking data used to account for the effect of tagging on spawning behavior. These data were used to estimate the number of spawning adult male horseshoe crabs in the Delaware Bay. Information on the sex ratio of adult crabs during the tagging events allowed estimation of total and sex-specific abundance of crabs spawning in Delaware Bay. Additional information on the commercial harvest (in numbers) from New Jersey, Delaware, Maryland, and Virginia was used to estimate annual harvest rate.

TOR#1: Evaluate adequacy and appropriateness of the models presented in papers I – III and data used in the models for estimating stock biomass and fishing mortality rates or evaluating population dynamics.

Mark-recapture studies are used widely to estimate population abundance for a wide range of species. Mark-recapture studies have a generalized set of underlying assumptions (see TOR #2 in this section). The authors devoted significant effort to meet the assumptions through the study design and with supporting data, and to evaluate assumption validity. Specific details on evaluations of assumptions, such as evaluations of tagging effects on spawning behavior, are in the Smith et al. paper and in Appendix B.

The subcommittee felt that the mark-recapture study was appropriate for abundance estimation and provided useful estimates of harvest rates within the accuracy of the landings data. The estimates from this model alone are not useful for evaluating population dynamics of the target population. In particular, there was no biological reference to compare harvest rate estimates to determine whether contemporary harvest rates are sustainable.

TOR #2: Identify important assumptions of the models and evaluate validity of the assumptions given horseshoe crab life history, characteristics of input data, and design and objectives of the study.

The majority of the assumptions of this study is stated explicitly on page 7 of the Smith et al. paper, and the list of assumptions is consistent with other mark-recapture studies.

Specifically,

1) the population was closed to emigration and mortality during the period between release and recapture;
2) the tagged animals were a representative sample;
3) animals were captured independently of one another;
4) tags were not lost or overlooked; and
5) recapture probability depended only on recapture occasion, was equal among animals of the same sex, and was equal for tagged and untagged animals.

The authors designed the timing, location, and other aspects of the study to maximize the probabilities that assumptions were met. In addition, available information and secondary investigations were used to support these assumptions. Specific information on the supporting data sets and analyses are described in the Smith et al. paper. In general, the authors took a series of steps to ensure that the assumptions of the mark-recapture study were not violated, which adds credence to model validity.

The accuracy of the study results was also affected by several other assumptions that were not explicitly stated. These included that the male to female sex ratio observed during tagging was representative of the spawning population and that the commercial harvest of horseshoe crabs (number of crabs) from the target population was known without error. Violating the first of these assumptions would lead to inaccurate estimates of the number of adult horseshoe crabs in Delaware Bay. The sex ratio used in this study was similar to those found in other studies, and was therefore considered realistic. The subcommittee also suggested looking at data from available trawl surveys within Delaware Bay as additional validation (see TOR #4 in this section). Inaccurate population estimates and/or violating the second assumption (known harvest) would result in inaccurate estimates of harvest rates. There was concern that although states require mandatory reporting of bait harvest, there may have been some under reporting of this sector. In addition, there were other sources of crab mortality, such as biomedical harvest/mortality and discard mortality in other fisheries.

Using estimates of harvest that were smaller than the true harvest would result in underestimates of harvest rate. Another source of error would be the inability to separate harvest by region for a given state (e.g. Chesapeake Bay and Atlantic Ocean from MD and VA). If landings were from sources that did not include Delaware Bay spawning crabs, harvest rates would tend to be overestimated. In order to deal in part with these sources of error, the authors investigated several combinations of harvest in the Smith et al. paper in an attempt to put bounds on harvest rate estimates.

The low recapture rate was a point of discussion and concern. Given the large sample size, in terms of the number tagged and number of animals observed during recapture events, and the extensive evaluations of underlying assumptions, the subcommittee agreed that the most likely explanation for the low recapture rate was high population numbers. The use of profile likelihood to calculate confidence intervals did not assume asymptotic normality and so should be relatively robust.

There was also concern over the sensitivity of the model to overlooked tags during the spawning survey. Overlooking tags during recapture would result in overestimation of abundance and underestimation of harvest rate. However, the authors investigated a range of possible rates of overlooking tags and found that over a wide range of rates, harvest rate estimates remained below 10% in 2003 and 2004 (see Appendix B).

TOR #3: Evaluate whether or not it is appropriate at this time to use the results of the models, based on the most recent data available, as a basis for management decisions considering the multiple-use fishery management goal specified in the Interstate Fishery Management Plan for Horseshoe Crab (FMP).

The mark-recapture study provided several pieces of useful information. These include an independent estimate of population size to ground-truth other survey methods (e.g. benthic trawl survey), estimates of harvest rates, and (indirectly) some indication of horseshoe crab egg production that could become available to migratory shorebirds.

The population estimates are higher than those from other studies (benthic trawl survey), but these differences may be accounted for by gear efficiency in the trawl survey and a portion of the population remaining within Delaware Bay during the fall and possibly overwintering. In addition, the estimates are not directly comparable with other studies, such as the spawning survey because of different survey objectives.

Differences in population estimates between 2003 and 2004 were not statistically significant (see Appendix B). Differences could be attributed to actual abundance changes, sampling variability, or both.

The subcommittee discussed using the mark-recapture based estimates of abundance/biomass as input to the surplus production model (see TOR #4 under evaluation of production models).

TOR #4: Provide recommendations for improving the models.

There should be an effort to improve harvest data to include possible under reporting, discard mortality, and biomedical-harvest mortality.

Future reports should include figures of profile likelihood to show how likelihood changes.

There should be a study to estimate the rate of tag oversight, perhaps with planted tags.

Investigate other sources of sex ratio for the same year and time period as study, such as from the DNREC 30-foot trawl.

There should be an extension of the mark-recapture work with a multi-year analysis and open population models.

Combine mark recapture likelihood with production model (see TOR #4 from production model evaluation).

2.3 Age-Structured Population Model (Sweka et al.)

The Sweka et al. paper was a simulation study with the objective of creating an age-structured population model for female horseshoe crabs in the Delaware Bay region. The model incorporates the best available estimates of age-specific mortality and fecundity. Various combinations of female harvest quotas, harvest timing and density-dependent egg mortality were used to examine the effects on the female horseshoe crab population growth and egg availability to shorebirds. Sensitivity analysis was used to evaluate the relative importance of model parameters.

TOR #1: Evaluate adequacy and appropriateness of the models presented in papers I – III and data used in the models for estimating stock biomass and fishing mortality rates or evaluating population dynamics.

This model is not designed to estimate stock biomass or fishing mortality rates, but is a simulation-based population dynamic model. The purpose of the simulation model was to examine relationships between population parameters and harvest levels as they influence population growth and potential egg availability to shorebirds.

TOR #2: Identify important assumptions of the models and evaluate validity of the assumptions given horseshoe crab life history, characteristics of input data, and design and objectives of the study.

Age-specific natural mortality rates (M) were taken from existing literature. However, some age-specific mortality rates were not obtained from the Delaware Bay population. Age specific survival was allowed to vary randomly each year according to a beta- distribution with CV of 15%. The relative variability was assumed constant over all ages. This variability may likely differ among ages, but information is lacking at this time.

Maximum age was assumed to be 20 years.

Recruitment to the spawning stock was set at zero for ages less than 9; 0.5 for ages 9 and 10; and 1.0 for ages older than 10. There is no information available regarding partial recruitment at age, though the assumption used in the paper seems reasonable until such information becomes available.

Egg mortality was the only density-dependent component of the model. Density-dependent egg mortality curves were developed from a spatial simulation model of spawning females. There were no definitive empirical data for egg mortality curves; although, there was some empirical evidence showing that the model predictions fell within the range observed in a very limited study (Botton et al. 2003). The model has no density-dependence beyond the egg stage, but it seems likely that density dependence operates within other age classes.

There were three egg mortality curves. The authors believe that the curve with the highest egg mortality was implausible because it does not allow for population growth over model starting values of 3 million spawning females. In contrast, medium and low egg mortality curves appeared credible.

Running simulations at high harvest rates suggested something in the model was unrealistic because high harvest did not result in the magnitude of abundance decline, which is thought to have occurred. Egg mortality curves and assumed natural mortality rates warrant further evaluation. However, computation of the mean generation time from the model (8.4 years) is consistent with turnover rate that one would expect given that horseshoe crabs mature at 9 to 10 years old (see Appendix C).

Average fecundity (weighted average across ages and sizes) was assumed to be 90,000 eggs. Based on the limited fecundity information available, the estimate used in the model seems reasonable. However, fecundity at age/size may vary within the female population.

The model assumed that females spawn every year after maturity. Tagging data suggests that a significant portion of the mature female population spawns every year.

The model assumed that only sexually mature animals were harvested. There is some anecdotal evidence that immature animals are harvested; however, their contribution to the Delaware Bay landings is thought to be insignificant.

Harvest was assumed to be proportional to age-specific abundance. However, harvest may not be proportional to age-specific spawner abundance if a behavioral difference among age classes exists.

TOR #3: Evaluate whether or not it is appropriate at this time to use the results of the models, based on the most recent data available, as a basis for management decisions considering the multiple-use fishery management goal specified in the Interstate Fishery Management Plan for Horseshoe Crab (FMP).

Because model parameters are assumed and not estimated with independent data, the model should not be used for management decisions at this time. The model is limited by the lack of validation with any fishery-dependent or fishery-independent data. The model is most useful for identifying life stages that influence population growth. The model indicated that early life history stages are particularly influential. Also, the model is useful for evaluating relative effects of harvest on age structure and relative effects of harvest timing on population growth.

Of the three models reviewed by the subcommittee, the age-structured model provides a framework for linking horseshoe crab harvest rates with egg availability to shorebirds. Though it should not be used as an absolute predictor of stock size or horseshoe crab egg availability, it does serve as a useful tool for evaluating relative impacts of management measures under various scenarios in reference to potential egg production.

TOR #4: Provide recommendations for improving the models.

There should be a continual effort to refine the model by incorporating improved parameter estimates.

The model should incorporate age/size-specific fecundity.

More research is needed on egg exhumation rates. As understanding of this develops the process of exhumation should be incorporated into the model.

Age-specific survival and mortality rates specific to the Delaware Bay should be incorporated into the model as they become available.

3.0 Conclusions and Synthesis of Horseshoe Crab Status in Delaware Bay Region (*TOR #5*)

All three models that the subcommittee reviewed have strengths and weaknesses, and each contributes to evaluating the status and trends of the Delaware Bay horseshoe crab population and furthers our understanding of the dynamics underlying population change. The production model with appropriate index selection provides qualitative estimates of trends in relative fishing mortality and abundance. Mark-recapture studies, given underlying assumptions, provide snapshot estimates of abundance and harvest rate. The age-structured model provides a tool to simulate horseshoe crab population dynamics and gain insight into potential egg availability to migrant shorebirds.

The general picture that emerges from a synthesis of the assessments indicates that

1) relative abundance has declined through the 1990's to present,
2) relative fishing mortality rate has exceeded F_{MSY} since the mid-1990's with the F/F_{MSY} ratio peaking around 1998 and, on average, declining since then, and
3) current harvest rate is below 10%, but appears to be in excess of F_{MSY}.

The mark-recapture and ASPIC results can be viewed as qualitatively consistent given the recent decline in the F/F_{MSY} ratio (shown in the updated ASPIC run) and the recruitment time lag causing a delayed positive response of the population to recent harvest reductions. The recruitment time lag is caused by horseshoe crabs requiring 9 to 10 years to recruit to the fishery, and the inability to incorporate the effects of this temporal lag is a primary shortcoming of the application of the ASPIC model to horseshoe crabs. At this time, we do not have a fishing mortality reference point to compare with the more direct estimates of 2003 and 2004 harvest rates derived from the mark-recapture results. Also, we do not endorse making a quantitative comparison between the mark-recapture estimates of F and the ASPIC model estimates of F/F_{MSY} because of the lack of uncertainty estimates for F/F_{MSY} and the lack of a recruitment time lag in the ASPIC model.

Although biological reference points have not been established for the horseshoe crab stock, we conclude that fishing mortality rates during the 1990's reduced adult biomass. We also conclude that management actions since 1998 have reduced F, but current levels of F still appear to be in excess of F_{MSY}.

The assessments under review along with the previous horseshoe crab stock assessment (ASMFC 2004) represent significant progress. The subcommittee is confident that this movement forward will continue and even escalate as new data and assessment methodologies are applied. While this progress is encouraging, the subcommittee feels it is important to emphasize to the Technical Committee that horseshoe crab assessment must move beyond a traditional fishery framework. Managing for MSY-type reference points might not be equivalent to managing for shorebird energetic needs. The subcommittee suggests that greater interaction between horseshoe crab and shorebird assessment scientists is needed in order to bridge the gap between horseshoe crab stock dynamics and shorebird energetics. This could be achieved through enhanced coordination between the Horseshoe Crab and Shorebird Technical Committees.

4.0 Literature Cited

ASMFC. 2004. Horseshoe crab 2004 stock assessment report. ASMFC, 1444 Eye Street, NW, Sixth Floor, Washington, DC 20005.

Botton, M. L., R. E. Loveland, and A. Tiwari. 2003. Distribution, abundance, and survivorship of young-of-the-year in a commercially exploited population of horseshoe crabs *Limulus polyphemus*. Mar. Ecol. Prog. Ser. 265: 175-184.

Prager, M. H. 1994. A suite of extensions to a non-equilibrium surplus-production model. U.S. National Marine Fisheries Service Fishery Bulletin 92:374-389.

Prager, M. H., C. P. Goodyear, and G. P. Scott. 1996. Application of a surplus production model to a swordfish-like simulated stock with time-changing gear selectivity. Transactions of the American Fisheries Society 125:729-740.

Appendix A: Updated ASPIC Run

ASPIC production model runs conducted by Horseshoe Crab Stock Assessment Subcommittee, January 4-5, 2006.

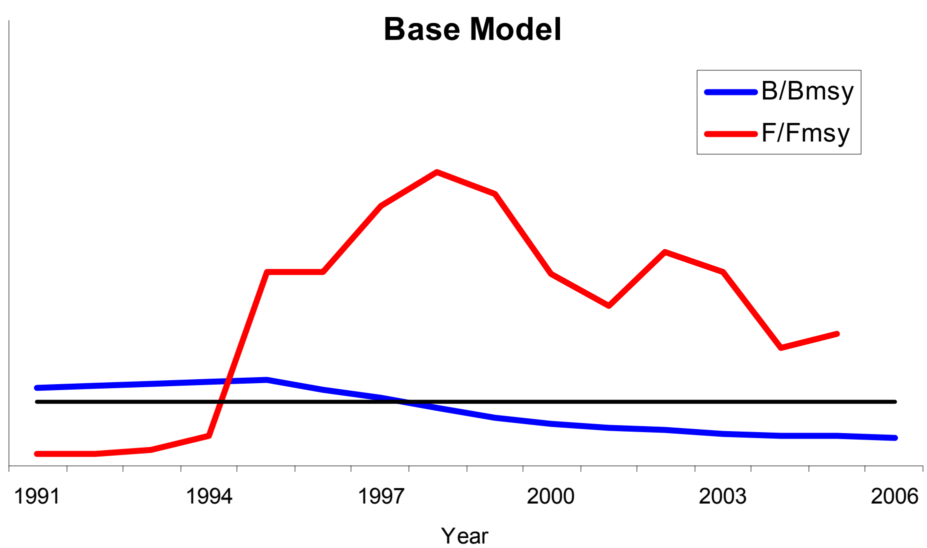
Base Model

Data:

- NMFS Fall trawl, advanced 1 calendar year to coincide with subsequent spring (data from 1991-2004)
- Delaware 30ft trawl (1991-2005)
- Delaware 16ft trawl, crabs >160mm (April-July only, 1992-2005)
- New Jersey Delaware Bay trawl, adults only (1998-2004)
- Delaware Bay Spawning Survey (1999-2004)
- Regional landings in number of horseshoe crabs from 1991-2005, where 1991-1994 landings were assumed to equal 3.2 times Delaware landings

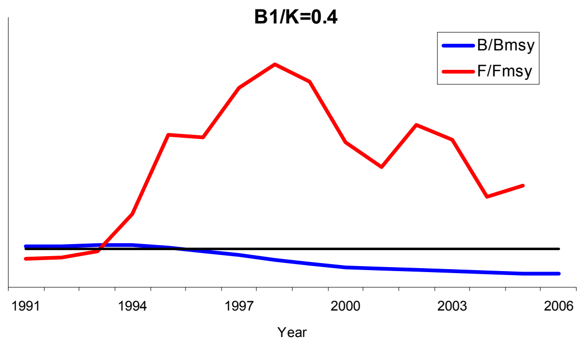
Starting guesses:
B_1/K=0.5 (biomass in 1991 was equal to B_{MSY})
MSY=1,102,000 (half of largest catch)
K=20,232,000 (10 times largest catch)

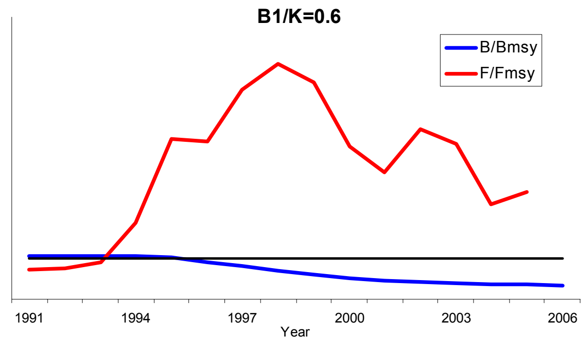
Results: Relative biomass (B/B_{MSY}) has declined since 1995. Relative fishing mortality (F/F_{MSY}) increased through the 1990's, peaked in 1998, and has decreased to the present. Fishing mortality may still be above F_{MSY} (as represented by the horizontal line below).



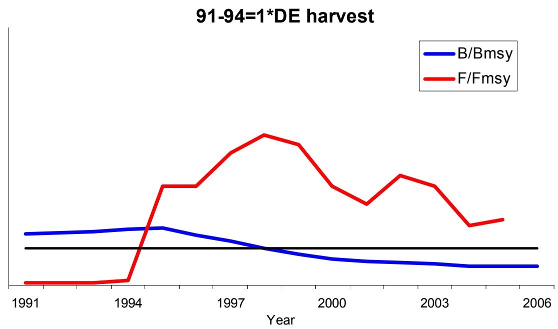
Sensitivity Analyses
Note: Scale is constant among all graphs.

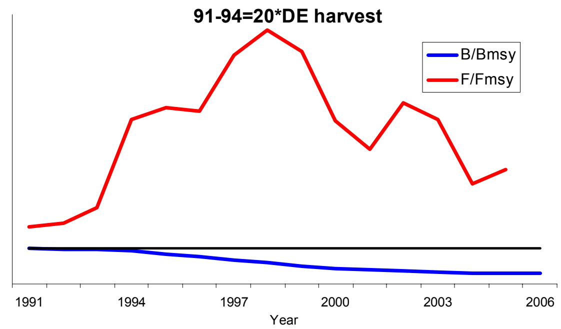
<u>B_1/K initial guess:</u>
Base model: $B_1/K=0.5$
Sensitivity analyses: $B_1/K=0.4$ and $B_1/K=0.6$

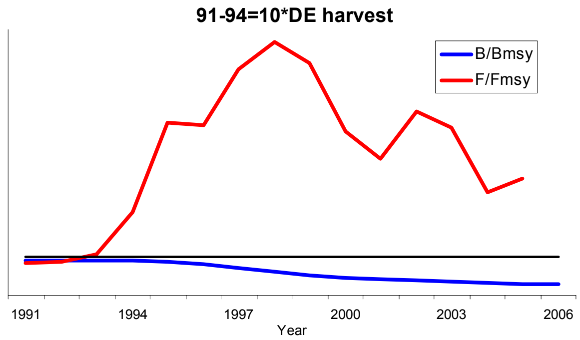




<u>1991-1994 harvest:</u>
Base model: equal to 3.2 times Delaware harvest from 1991-1994
Sensitivity analyses: equal to 1*DE harvest, 10*DE harvest, and 20*DE harvest



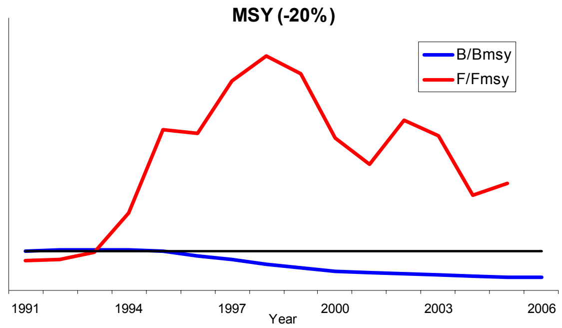


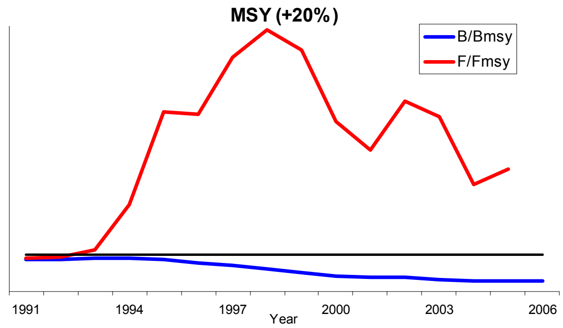


MSY initial guess:

Base model: 1,102,000 horseshoe crabs

Sensitivity analyses: 809,000 (20% fewer) and 1,214,000 (20% more)

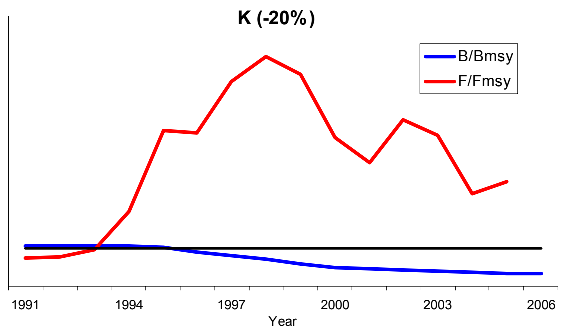


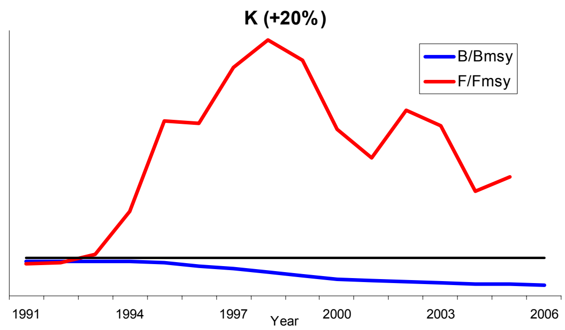


K initial guess:

Base model: 20,232,000 horseshoe crabs

Sensitivity analyses: 16,185,000 (20% fewer) and 24,278,000 (20% more)





Appendix B

Mark-Recapture Estimates of Adult Horseshoe Crab Abundance in Delaware Bay: Updated Estimates for 2003 and 2004 and Assessment of Bias Due to Tags Overlooked During Recapture

David R. Smith, United States Geological Survey Leetown Science Center, 11649 Leetown Road, Kearneysville, WV 25443, 304-724-4467, FAX 304-724-4465, drsmith@usgs.gov

This report provides updated abundance estimates of adult horseshoe crabs in Delaware Bay during spawning season based on mark-recapture methods. Methods of analysis and estimation are described in Smith et al. (*in press*)[1]. Estimates have been updated with data from 2004. Data from 2005 are not yet available.

The validity of these abundance estimates is based on the large number of tag releases and animals checked for tags, the study design that ensured population closure and representative samples, and an evaluation of underlying assumptions. Although underlying assumptions have been outlined and evaluated as best as possible (Smith et al. *in press*), there remains the possibility that some tags were overlooked during the spawning survey. In Smith et al. (*in press*) and here, we restricted the mark-recapture analysis to male horseshoe crabs that were counted and recaptured within 1 m^2 quadrats when surveyors' were on focusing on a small area. Males do not bury and the 4.4 cm white button tag is highly visible in daylight or when illuminated by flashlight. Nevertheless, tags on males could be obscured when horseshoe crabs pile up during high spawning density. Thus, here we examine the effect of tags being overlooked on abundance and harvest rate estimates.

Estimates for 2004

Prior to spawning season in 2004, 7,276 adult male horseshoe crabs were released throughout Delaware Bay. Peak spawning occurred over the second spring tide in May 2004. Spawning survey dates during that spring tide were 17, 19, and 21 May 2004. Spawning counts within quadrats on those dates were 11,004, 15,396, and 15,344, and recaptures of tagged males were 11, 11, and 8, respectively. Abundance estimates are shown in Table 1.

Landings for Delaware Bay region (NJ, DE, MD, and VA) was 398,300 horseshoe crabs according to preliminary reported landings by state as of 4/12/05. Finite harvest rate was estimated as a ratio of landings to abundance estimates. Harvest rate estimates are shown in Table 2.

[1] Smith, D. R., M. J. Millard, and S. Eyler. (*in press*) Abundance of adult horseshoe crabs in Delaware Bay estimated from a bay-wide mark-recapture study. Fishery Bulletin

Table 1. Maximum likelihood estimates of abundance for adult horseshoe crabs (*Limulus polyphemus*) in Delaware Bay during the end of May 2003 and 2004. Estimates of females and total are based on mark-recapture estimates of males and sex ratios among the animals caught and released for this study. Adjusted estimates take into account possible effect of capture on spawning by reducing releases of males by 0.88, which is an observed relocation rate of telemetry tagged males.

	Maximum likelihood estimates adjusted estimates based on relocation rates from telemetry tagged males			
	2003		2004	
	Abundance	90% CI	Abundance	90% CI
Males	13,730,000	8,780,000 – 19,400,000	9,142,000	6,690,000 – 12,250,000
Females	6,250,000	4,000,000 – 8,840,000	4,166,000	3,048,000 – 5,582,000
Total	19,980,000	12,7800,000 – 28,240,000	13,308,000	9,738,000 – 17,832,000

Table 2. Harvest rates calculated from 2003 and 2004 landings and abundance estimates of adult horseshoe crabs (*Limulus polyphemus*) in Delaware Bay. Estimates were adjusted based on observed relocation rate (0.88) of telemetry tagged male animals (see Table 1).

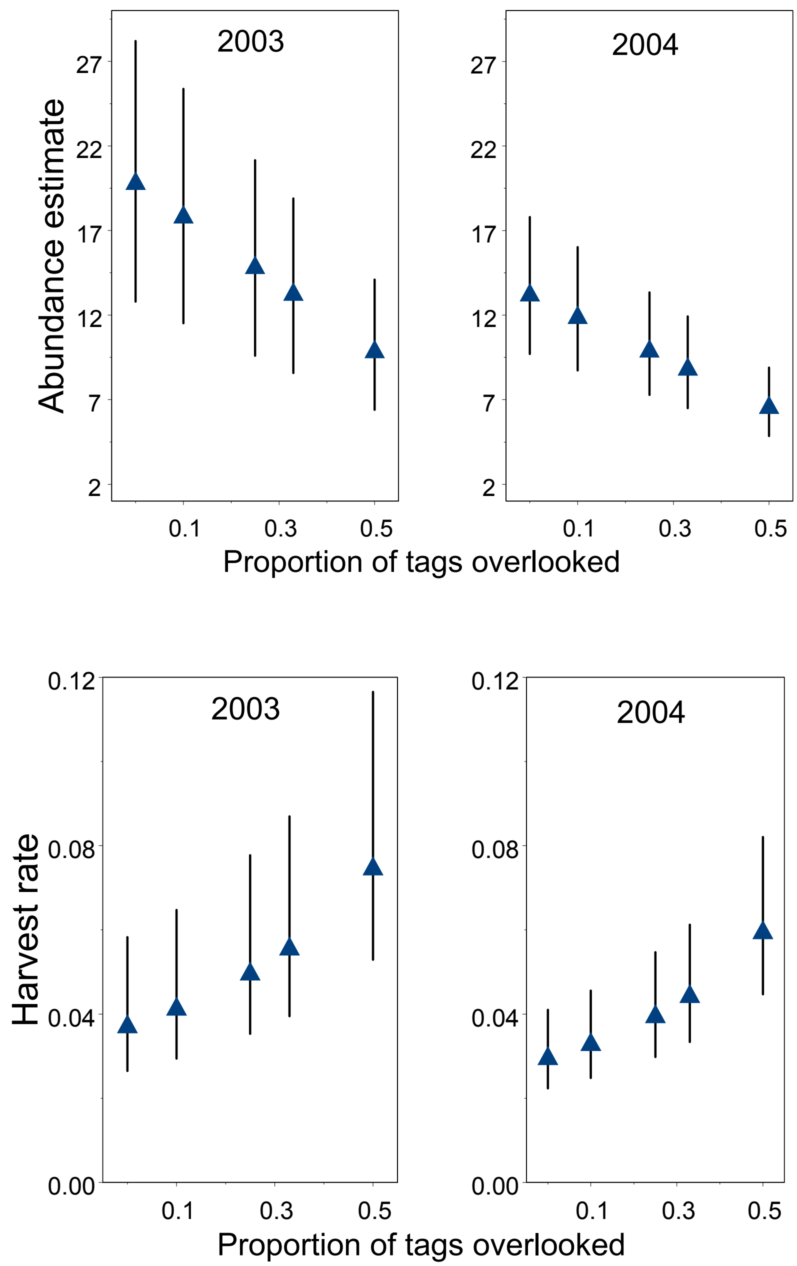
	2003	2004
Landings from NJ, DE, VA, MD[2]	745,800	398,300
Abundance	19,980,000	13,308,000
	12.8 to 28 mil	9.7 to 18 mil
Harvest rate	0.04	0.03
	0.03 to 0.06	0.02 to 0.04

Evaluation of tags overlooked

We examined bias in abundance and harvest estimates due to 10, 25, 33, and 50% of tags being overlooked during the spawning survey. These percentages are equivalent to rates of 1-in-10, 1-in-4, 1-in-3, and 1-in-2 tags being overlooked. The 50% or 1-in-2 case seems unlikely and represents a highly conservative boundary. The effect of tags being overlooked on recapture was to decrease abundance estimates and increase harvest rate (Figure 1). However, accounting for this potential source of bias did not change the general conclusion that harvest rate in 2003 and 2004 was below 10%.

[2] ASMFC (Atlantic States Marine Fisheries Commission). 2004. 2003 Review of the fishery management plan for horseshoe crab (*Limulus polyphemus*). ASMFC, 1444 Eye Street, NW, Sixth Floor, Washington, D.C. 20005

Figure 1. Abundance and harvest rate estimates with 90% CI as a function of tags being overlooked during recapture.



Appendix C

Effect of the initial spawning female HSC population size on the intrinsic rate of population increase, *r*, and the population size by year 30. Simulations were conducted with harvest occurring before spawning, and a quota of 100,000 females per year. The pattern of declining *r* with increasing N1 is due to the effect of density-dependent egg mortality. The high egg mortality curve did not allow the population to grow (r < 0) even under no harvest; thus, it was not included in this comparison.

Egg mortality	N_1 (millions)	Mean *r*	90^{th} percentile range		N_{30} (millions)	90^{th} percentile range
Medium	1.00	0.0376	(0.0137 - 0.0648)		2.06	(0.88 - 3.51)
	3.00	0.0189	(0.0021 - 0.0358)		4.68	(2.88 - 6.68)
	6.00	0.0057	(-0.0090 - 0.0204)		6.74	(4.45 - 9.37)
	9.00	-0.0032	(-0.0184 - 0.0110)		7.99	(5.28 - 10.60)
Low	1.00	0.0500	(0.0234 - 0.0279)		3.00	(1.88 - 2.06)
	3.00	0.0353	(0.0171 - 0.0173)		7.55	(3.06 - 3.53)
	6.00	0.0256	(0.0157 - 0.0153)		12.12	(4.41 - 5.25)
	9.00	0.0187	(0.0159 - 0.0154)		15.05	(5.53 - 5.91)

Computation of mean generation time using the age-structured model developed by Sweka et al.

Mean Generation Time (G): The genration time is an estimate of the amount of time it takes one cohort to grow up and replace another...It can be calculated from from survivorship and fecundity schedules as:

$G = \Sigma x l_x b_x / \Sigma l_x b_x$
where: x = age, l_x = survival at age x, b_x = fecundity of age x

From: *Gotelli, N. J. 1998. A Primer of Ecology, Second Edition. Sinauer Associates, Inc., Sunderland MA.*

Age (x)	l_x	b_x	$l_x b_x$	$x l_x b_x$
0	0.00003	0	0	0
1	0.973848	0	0	0
2	0.973848	0	0	0
3	0.973848	0	0	0
4	0.973848	0	0	0
5	0.973848	0	0	0
6	0.973848	0	0	0
7	0.973848	0	0	0
8	0.973848	0	0	0
9	0.799395	45,000	35,973	258,808
10	0.799395	45,000	35,973	287,565
11	0.625002	90,000	56,250	386,722
12	0.625002	90,000	56,250	421,878
13	0.625002	90,000	56,250	457,035
14	0.625002	90,000	56,250	492,191
15	0.625002	90,000	56,250	527,348
16	0.625002	90,000	56,250	562,504
17	0.625002	90,000	56,250	597,661
18	0.080002	90,000	7,200	10,369
19	0.080002	90,000	7,200	10,945
20	0	90,000	0	0
		Sums =	**480,097**	**4,013,023**
		G =	**8.4**	

*b_9 and b_{10} equalled 45,000 because of partial recruitment to the spawning stock = 50%.

ATTACHMENT II

<u>Horseshoe Crab Stock Assessment Research/Work Plan</u>

Short Term

Catch Survey Analysis
Update on identifying stages
Decide whether to pursue stage id of evaluate alternative methods of assessment
    If decide to pursue state ID, then:
        Need to develop a protocol
        Need to implement the protocol
Clarify differences in peer-review panel's recommendations on proposed model

Surplus Production Model
Work up NJ Ocean trawl for spm
Examine spatial and temporal overlap of indices and environmental data
Examine converting to biomass in spm
Examine including estimates of discards, biomedical harvest, personal use harvest
Explore combining mark recapture estimates and spm
Simulation study to examine bias in spm
Examine the timing of the decline in relative F from the spm with management

Mark Recapture Study
Future reports should include figure of profile likelihood to show how likelihood changes
Examine ways to evaluate tag bias due to over looked tags on recapture
Look at sex ratio in DE Trawl

Age structured Model
Incorporate age/size-specific fecundity
Use model to look at M relation to ecological expectations

Other
Contact R. Carmichael on info on natural mortality for age-based model

Reconvene the tagging subcommittee to examine tagging programs (long term abundance estimates)
    Request tagging data from B. Swan

Work out agreement on getting Virginia Tech trawl data

Explore targets for reopening or expanding the horseshoe crab fishery based on an energetic needs assessment from the Shorebird Technical Committee

Long term

Conduct stock assessment using CSA or alternative that is identified

From 2004 Stock Assessment Report
Continued expansion of the offshore trawl survey
Increased tagging coastwide, particularly in previously untagged areas such as NY & CT
Development and approval of an effective and easily replicated method to id stages HSC
Continued implementation of the redesigned DE Bay spawning survey

Combine Horseshoe Crab and Shorebird population assessment efforts
    Possibly combine assessment models
Refine reference points in terms of shorebird energetic needs