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rpt. D

OFFICE OF THE
DIRECTOR



STATE OF DELAWARE
DEPARTMENT OF NATURAL RESOURCES
& ENVIRONMENTAL CONTROL
DIVISION OF FISH & WILDLIFE
89 Kings Highway
Dover, Delaware 19901

17 August 2001

Dr. Deirdre M. Kimball
U.S. Department of Commerce
NOAA
National Marine Fisheries Service
One Blackburn Drive
Gloucester, MA 01930-2298

Dear Dr. Kimball:

This letter is in response to your questions regarding Delaware's Completion Report for Atlantic Coastal Act Project 3-ACA-072, (NA96FG0319). The investigators have attempted to address your questions in the document text, but I also wish to address them explicitly in this letter.

In the future, I will endeavor to number all pages of our reports in a consistent manner as suggested. I appreciate the difficulty you and your staff face when reviewing these reports.

In reference to **Project 1 - Research to support Management of Blue Crabs and Weakfish in the Delaware Bay Estuary (including Terrapin Bycatch Reduction)**, I offer the following responses to your questions/comments (abbreviated in *italics*).

Objectives 1 and 2 -

We are concerned that the rank orders of the large (equivalent to fully recruited?) crab abundance index and SSB index are substantially different, due to the calculations made to convert the survey data from an index of the large to an index of SSB.

Dr. Helser's Response: The index of SSB was (technically) not derived from the "large" blue crab abundance index. The SSB index is a sub-set of the data used to generate the large crab index consisting of specifically sooks (females) in April-May. It also uses size frequency data of these females which is then converted to weight (kg) using the frequency-weighted mean carapace size. This procedure can produce significantly different rank order relative to the "large" crab index.

The inconsistency between these two adult crab indices, and justification as to why it might be reasonable, needs to be addressed.

Dr. Helser's Response: See above explanation.

The tabulated and plotted DeLury input indices of recruits and fully recruited crabs are inconsistent with indices of recruits and large crabs (>120mm) presented in Figure 9.

Dr. Helser's Response: They were computed slightly different. Those in Figure 9 were generated from Kahn et al (1998). The other was generated from modeling purposes. The intent here was to capture all possible sizes of recruits (0-120mm) which might have slightly faster or slower growth depending on the particular year and environmental conditions during that year. This modeling index of recruits also only spanned August-September which is for the most part after the fishery to measure the impact of exploitation on that group of animals. That is

Delaware's good nature depends on you!

why the indices are then lagged to measure survivors for the following year. Nevertheless, the indices used in the DeLury model are reasonably comparable as those in Figure 9 both in trend and peaks.

Objective 3 -

The report does not address the "Establishment of a bi-state blue crab research and monitoring committee..."

Researchers from the NJ DEP were contacted and did provide data to support the stock assessment. However, prior to Dr. Helser's departure, no formal committee was established.

Objective 4 -

Terrapin bycatch reduction was completed satisfactorily.

Objective 5 -

Proposed maturity-at-age, egg size, and fecundity estimates of annual fecundity were not presented in the report. Their absence must be explained.

Estimates of spawning frequency and batch fecundity have not been completed, but all of the histological slides have been prepared for these procedures. Thus, annual fecundity, which is calculated with batch fecundity and spawning frequency, has not been completed. Egg size will be done at the same as batch fecundity analysis. Complete age data is not yet available to analyze age at maturity, but all these parameters will be completed by the next grant cycle.

Note: Other questions/comments addressed in the report text.

In reference to your questions/comments (abbreviated in italics) regarding **Project 2. Enforcement of Atlantic States Marine Fishery Commission Fishery Management Plans Compliance Criteria**, the following responses were offered.

More detail should be provided concerning law enforcement activities supported under this award.
The report has been revised to include more detail.

The report should devote one brief paragraph to "Special Operations".

Fisheries Management Plan funding is used by the enforcement section to supplement existing patrols in the form of dedicated uniform patrols and special operations (i.e. boat blocks, covert patrols, surveillance and investigations) of species covered by management plans.

An explanation as to why nearly 45% of the budget remained unobligated is requested.

The Enforcement Section was informed that they had been allocated \$32,000 for overtime. The \$15,000 for fringe benefits was not included in the correspondence to them.

In reference to your questions/comments (abbreviated in italics) regarding **Project 3. Horseshoe Crab Fishery Management Plan I** offer the following responses.

In reference to your general comments, let me clarify that the Delaware Bay horseshoe crab spawning survey is only conducted on the Delaware Bay beaches. The state of Maryland has an entirely separate spawning survey in its Chesapeake and Coastal Bays that was not directed at monitoring long-term changes in the population. There are no plans to combine or incorporate these two separate surveys (the Delaware Bay and the Maryland survey) into a single survey or spawning estimate. It should be noted, however, that Maryland provided staff and volunteers at one Delaware Bay beach in 1999 and 2000. The Horseshoe Crab Technical Committee agreed that Maryland's participation in the Delaware Bay survey and its continued work identifying spawning beaches and examining sampling periodicity would fulfill its compliance requirement as specified in the horseshoe crab FMP.

Discuss in greater detail the state's participation with the ASMFC Horseshoe Crab Technical Committee.

Delaware has a representative on the Plan Development/Review Team, the Horseshoe Crab Technical Committee, the Horseshoe Crab Stock Assessment Committee, the Horseshoe Crab Peer Review, the Shorebird Technical Subcommittee and the Horseshoe Crab Management Board. The state has sent representatives to

Horseshoe Crab meetings and workshops, with the exception of one Technical Committee meeting due to inclement weather conditions in Delaware.

Participation in these meetings has led to the development of the FMP, Addendums I and II, a preliminary stock assessment and peer review, the implementation of several monitoring programs required in the FMP, and a framework for a future quantitative stock assessment.

The revised report reflects pertinent information on specific meetings important to this award.

Premature to look for a document and/or model which integrates the horseshoe crab data from all three states for resource management purposes? If so, provide a realistic timeline.

You are correct in wondering if it is not premature to look for a model that integrates the horseshoe crab data and analyses from all three states for resource management purposes. Rather, it is the stock assessment committee's hope that the Delaware Bay horseshoe crab spawning survey will provide a long-term index of relative abundance that will allow us to examine trends in the population until a complete quantitative stock assessment becomes possible. A framework for conducting such an assessment has been established by the Horseshoe Crab Stock Assessment Subcommittee. It is hoped that the Delaware Bay spawning survey, coupled with a number of other important initiatives started this year (a pilot coastwide benthic horseshoe crab survey, microsatellite DNA analysis of spawning populations coastwide, an aerial videography survey, a study to identify new recruits into the spawning population), will facilitate a future quantitative stock assessment (minimally 5 -10 years down the road). This is clarified in the revised report.

This plan-development and implementation exercise is clearly an important, coordinated, interjurisdictional undertaking.

It is very true that the Delaware Bay horseshoe crab spawning survey is an important, coordinated, interjurisdictional undertaking. I am amazed when I think of all the various participants - ASMFC, DE DNREC, NJ DEP, MD DNR, USFWS, USGS, Limuli Labs, Inc., University of Delaware, Delaware State University, several conservation groups and a large number of volunteers - each doing its part. The involvement of so many different parties does make timely data analysis very difficult. After each survey is completed, the forms are sent to the state coordinators (volunteers often delay sending them and must be contacted), the coordinators make copies and forward the data sheets to NJ DEP staff, NJ DEP enters the data which is sometimes illegible (there again volunteers must be contacted), after entry the data is proofed and sent to Dr. David Smith from USGS for analysis. Since the surveys are not completed until the end of June, and all parties involved are busy with other field projects, the final index number is usually not available until late winter. This makes meeting reporting requirements impossible. It is for this reason that I only presented spawning estimates for the two beaches Delaware was responsible for covering in 2000. I realize the limited utility of such data, but my intent was to present some evidence that Delaware fulfilled its grant obligation. It was not the intent of this project to provide a completed summary of all the data collected in the spawning surveys. This portion of the grant was only intended to cover staff time and some supplies necessary for participating in the spawner and egg surveys.

Did the MD DNR and NJ DFG&W actually participate in the 1999 monitoring of DE beaches?

The MD DNR provided staff and volunteers to man one beach in Delaware. MD DNR also conducted a separate survey in the Chesapeake and Coastal Bays directed more toward identifying important habitat. NJ DFG&W staffed NJ beaches (along with federal resource agencies and numerous volunteers) and was, in part, responsible for data entry and analysis of both states data. This is clarified in the revised report.

Were the spawning surveys suspended?

The spawning survey was not suspended. The spawning survey seems to be doing an adequate job of monitoring the relative abundance of Delaware Bay spawning horseshoe crabs (power = 0.75 for $\alpha = 0.20$ sampling 12 beaches; CV=0.12). Additionally, the spawning survey is the only fishery-independent survey in place (coastwide) that is specifically designed to monitor horseshoe crab relative abundance. This is clarified in the revised report.

What was the nature of the relationship(s) between egg and spawner surveys?

Unfortunately, the results of egg sampling in 1999 raised concerns that the egg sampling design was inadequate. Research conducted in 1999 failed to observe a predictive relationship between spawning horseshoe crabs and deposited eggs. One significant relationship occurred in New Jersey between deeply buried eggs (0-

20cm) and spawning density in May. It was possible that there were other relationships; however, several sources of sampling error could have concealed that relationship (variation in the proportion of the population sampled, spatial or temporal mismatch of data collection and sampling variation). Other factors that may contribute to the lack of a strong relationship include disturbance of eggs by wave action, variable fecundity and nesting behavior, or inadequate sampling design due to variable beach slope. Because the cost (in terms of money and manpower) of egg sampling was high, additional egg sampling was suspended in 2000 until the role of beach slope could be investigated further. We focused on testing beach slope in 2000 because of the relative ease in testing this variable and the potential implications it could have on survey design. Although this portion of the project in Delaware involved less than one day of assisting USGS personnel measure beach slopes, it was not necessary to reallocate funds from the egg survey to other elements of the project. This is clarified in the revised report.

Rational for changing the spawning survey protocol from random to mixed design?

The sampling design was changed from a stratified random design to a fixed design to accommodate researchers that were conducting the survey prior to ASMFC involvement (1990 -98). Some of the participants continue to compare the present survey to numbers collected in the previous effort. Although it was explained (emphatically) that changes in sampling design and missed spawning peaks between 1990 and 1998 render annual comparisons invalid, the consensus of the researchers and volunteers present at the planning meeting was that the present survey would not be compromised by fixing a random subset of six beaches. This is the unfortunate consequence of designing a survey by consensus. This is clarified in the revised report.

Why did the number of beaches sampled increase?

The number of beaches sampled changed from eight beaches sampled very intensively (essentially every other night during May and June) to ten beaches sampled two days before, the day of, and two days after the lunar event. This design was based on the sustained availability of volunteers and the results of a power analysis conducted by Dr. David Smith (USGS-BRD) which include estimates of the man-power necessary under a variety of sampling strategies. The USFWS contracted the volunteer coordinator to sample ten beaches (per state) to accommodate instances where volunteers fail to man a beach they sign up for, but the target number of beaches agreed to was actually 12. This is clarified in the revised report.

Why was sampling focused on Woodland Beach?

It is true that the Division's sampling focused on Woodland Beach, an area of typically low abundance. This was at the request of the volunteer coordinator. Low horseshoe crab abundance at Woodland Beach makes it difficult to get volunteers enthusiastic about sampling at this location. Division personnel are also used to sample at other beaches where the need arises. In 2000, we were asked to staff Big Stone Beach during one sampling period and all sampling events at Woodland Beach. Once again, it should be pointed out that the data presented in the report was not intended to be the overall Delaware Bay spawning estimate, but an indication of the work completed by Division personnel. This is clarified in the revised report.

No data analyses were provided under results.

A brief analysis was provided. Commercial horseshoe crab landings are sampled as time permits. Unlike finfish landings, horseshoe crab landings in Delaware are not sold to in-state dealers. Horseshoe crabs in Delaware are generally used by the harvester or sold to out of state dealers. This complicates sampling since the catch must be measured at the point of landing. Only one public area is open to harvest in Delaware (about a mile long strip of extensively rip-rapped beach) and only on Tuesdays and Thursdays. Further, hand harvesting is only conducted around the hours of high tide, as the crabs come ashore to spawn. These factors combine with the demands of other sampling programs to yield few intercepts.

Sampling of the dredge fishery is difficult because harvesters often fish for other species and only harvest horseshoe crabs when they receive orders for them or when the price of other species makes horseshoe crab harvesting lucrative. Several attempts were made to intercept dredge vessels landing crabs, but either the dredger failed to fish or the crabs had already been off-loaded.

Further elaboration on commercial landings is provided in the revised report.

I sincerely appreciate your interest and support and hope that this letter adequately addresses your questions. Please do not hesitate to contact me if you have additional concerns or if I can be of assistance.

Respectfully,

A handwritten signature in black ink, appearing to read "Stewart Michels", written in a cursive style.

Stewart Michels

3-ACA-072
NA96FG0319

(Revised)
Project Completion Report



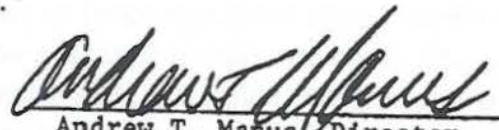
Project: NOAA, NA96FG0319, Coastal Fisheries Management Assistance to the State of Delaware.

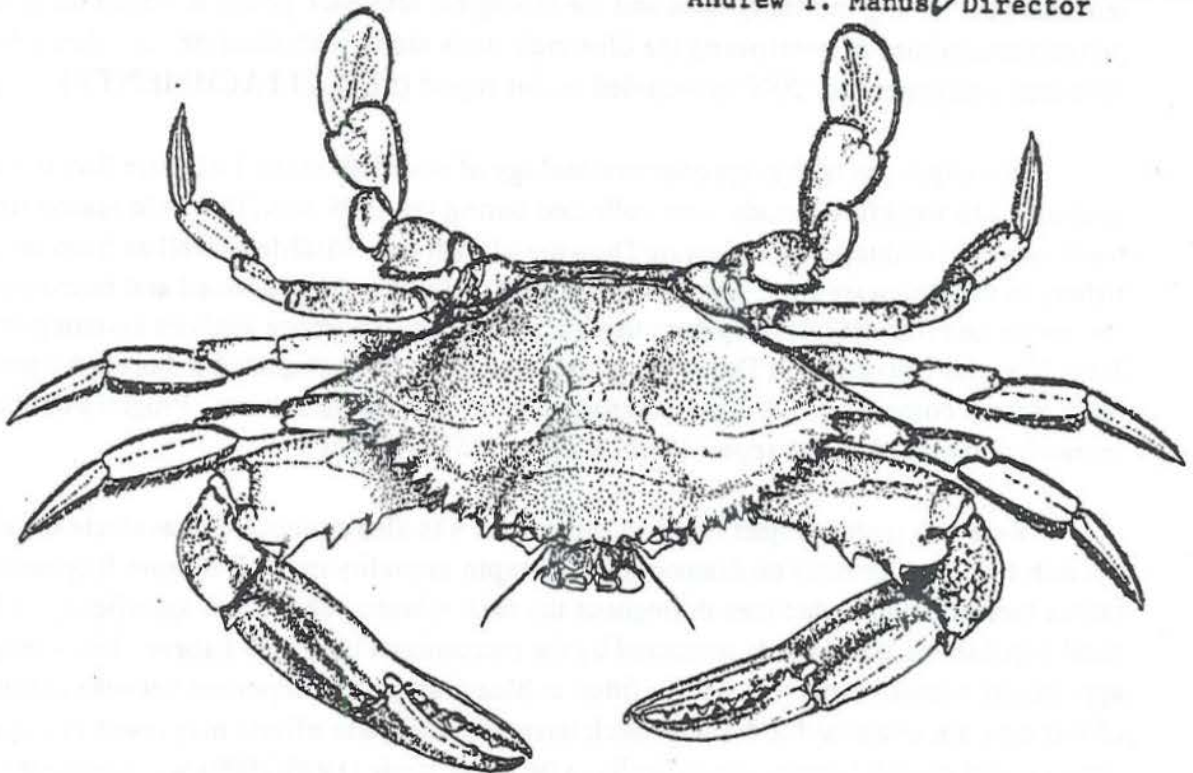
Project Type: Fisheries Research and/or Statistical Analysis

Overall Principal Investigator: Thomas E. Helser, Ph.D., September 1, 1999 - May 1, 2000
Stewart F. Michels, May 1, 2000 - August 31, 2000

Other Investigators: Stewart F. Michels, James Graybeal.

Period Covered: September 1, 1999 - August 31, 2000.


Andrew T. Manus, Director



Project No. 1: RESEARCH TO SUPPORT MANAGEMENT OF BLUE CRABS AND WEAKFISH IN THE DELAWARE BAY ESTUARY.

Principal Investigators: Thomas E. Helser, Ph.D., and Randall V. Cole.

The overall objective of project No. 1 of this award is to continue model development for the stock assessment of the Delaware Bay blue crab. The first comprehensive stock assessment (Helser and Kahn, 1999) was completed last year and served as the basis for development of the Delaware Bay Blue Crab Fishery Management Plan. This year blue crab catch and research survey data have been updated through 1999 and additional analytical procedures have been developed. Specifically, a stochastic decision-based framework has been developed to incorporate uncertainty associated with variable model input parameters, and to formally evaluate the probability of overfishing the blue crab stock. These data updates and procedures used in the uncertainty analysis have been included into the revisited blue crab assessment for 2000 (Helser 2000). In summary, the assessment procedures used in the 2000 assessment include: 1) A catch-survey model (Modified DeLury model) to estimate blue crab stock sizes and fishing mortality rates in the Delaware Bay from 1979-1999; 2) biological reference point estimation based on yield per recruit and spawning stock biomass per recruit models, coupled with estimates of spawning stock biomass and recruitment to derive fishing targets and overfishing thresholds; and 3) an uncertainty analysis to characterize the error associated with the terminal year fishing mortality rates and the biological reference points to which they are compared giving probabilities of overfishing the blue crab stock along with decision confidence levels. The full blue crab assessment for 2000 is included in this report (SEE ATTACHMENT #1).

Investigations of the reproductive biology of weakfish in the Delaware Bay is well underway. A total of 1,248 weakfish gonads were collected during the 1999 and 2000 field season from research trawl surveys conducted by Delaware Division of Fish and Wildlife as well as from the commercial fishery in the Delaware Bay. Samples have been histologically processed and microscopically staged for oocyte and maturity development using a state-of-the-art image analysis system purchased last year. Janet Nye, the University of Delaware graduate student, has completed a thorough literature search and has written a comprehensive research prospectus for her masters thesis. Progress on the weakfish research is included in this report (SEE ATTACHMENT #2).

Research under project No. 1 of this award was also conducted to evaluate the effect of bycatch reduction devices on diamondback terrapin mortality in the Delaware Bay estuary. Terrapin turtles face population declines throughout the mid-Atlantic region, and specifically in Delaware Bay, local populations are severely impacted by the recreational blue crab fishery. Knowledge of the appropriate bycatch reduction device fitted in blue crab pots is important because conservation efforts of this type are essential for diamondback terrapins, and these efforts may result in impacts on the recreation blue crab fishery. Specifically, a two year study (1999-2000) was completed on the effectiveness of four bycatch reduction devices used in blue crab traps to reduce diamondback terrapin bycatch mortality and their effect on blue crab harvest. This two year study complemented earlier

efforts (1997-1998) to evaluate one bycatch reduction device by expanding the suite of devices experimentally tested. Results of these research efforts under project No. 1 are included in this report (SEE ATTACHMENT #3).

As of result of the research and modeling efforts of project No. 1 of this award several abstracts were presented at national and international fishery meetings. In addition, a number of manuscripts have been submitted for publication in peer review scientific journals. Abstracts, reports and manuscripts are listed below.

Abstracts:

Helser, T.E., and D.M. Kahn. 1999. Application of a Size-Structured Population Dynamics Model to Estimate Abundance and Mortality of Delaware Bay Blue Crab (*Callinectes sapidus*). Presented at the Blue Crab Mortality Symposium of the Annual Crustacean Society Meeting, University of Southwestern Louisiana, May 1999.

D.M., Kahn, and T.E. Helser. 1999. Replacement Fishing Mortality Rate for the Delaware Bay Blue Crab (*Callinectes sapidus*) Stock. Presented at the Blue Crab Mortality Symposium of the Annual Crustacean Society Meeting, University of Southwestern Louisiana, May 1999.

Helser, T.E., and D.M. Kahn. 1999. A Stochastic Decision-based Approach to Assessing the Delaware Bay Blue Crab (*Callinectes sapidus*) Stock. Presented at the Workshop on Incorporating Uncertainty into Fishery Models sponsored by Atlantic States Marine Fisheries Commission, Jekyll Island, GA, June 28-29, 1999.

Helser, T.E., and D.M. Kahn. 2000. Population Dynamics of Delaware Bay Blue Crab (*Callinectes sapidus*). 29th Annual Benthic Ecology Meeting, Blue Crab Symposium, University of North Carolina-Wilmington, 8-9 March, 2000.

Helser, T.E., and D.M. Kahn. 2000. Incorporating Uncertainty in the Assessment of Delaware Bay Blue Crab (*Callinectes sapidus*) Stock. 29th Annual Benthic Ecology Meeting, Blue Crab Symposium, University of North Carolina-Wilmington, 8-9 March, 2000.

D.M., Kahn, and T.E. Helser. 2000. Replacement Fishing Mortality Rates for the Delaware Bay Blue Crab Stock (*Callinectes sapidus*). 29th Annual Benthic Ecology Meeting, Blue Crab Symposium, University of North Carolina-Wilmington, 8-9 March, 2000.

Helser, T.E., and R.V. Cole. 2000. The Use of Bycatch Reduction Devices for the Conservation Biology of the Diamondback Terrapin in the Delaware River Estuary. 2nd Workshop on the Ecology, Status, and Conservation of Diamondback Terrapins, Zoological Society of America. Wetlands Institute, Stone Harbor, N.J., October 6-8.

Helser, T.E., and D.M. Kahn. 2000. A Stochastic Decision-based Approach for Assessing the Status of the Delaware Bay Blue Crab (*Callinectes sapidus*) Stock. 3rd William R. and Lenore Mote International Symposium in fisheries Ecology, Targets, Thresholds, and the Burden of Proof in Fisheries Management, 31 October-2 November, Mote Marine Laboratory, Sarasota, FL., 2000.

Reports/Publications:

Helser, T. E., and D. M. Kahn. In Press. Application of a size-structured population dynamics model to estimate abundance and mortality of the Delaware Bay blue crab (*Callinectes Sapidus*) stock. *Proceedings of the Blue Crab Mortality Symposium*, Gulf States Marine Fisheries Commission.

Kahn, D.M., and T. E. Helser. In Press. Replacement fishing mortality rate and other biological reference points for the Delaware Bay blue crab (*Callinectes Sapidus*) stock. *Proceedings of the Blue Crab Mortality Symposium*, Gulf States Marine Fisheries Commission.

Helser, T. E., and D. M. Kahn. In Press. Dynamics, exploitation and biological reference points of the Delaware Bay blue crab (*Callinectes Sapidus*) stock. *Fishery Bulletin*.

Helser, T. E., A. Sharov, and D. M. Kahn. In Press-Book Chapter. A stochastic decision-based approach to assessing the Delaware Bay blue crab (*Callinectes Sapidus*) stock. In *Incorporating Uncertainty into Fishery Models* (Eds. J. Berkson and L. Kline), *American Fisheries Society Publication*.

Helser, T. E., A. Sharov. In Press. Incorporating uncertainty in the assessment of the Delaware Bay blue crab (*Callinectes Sapidus*) stock. *Bulletin of Marine Science*.

Helser, T. E., R.V. Cole. In Review. Effect of three bycatch reduction devices on Diamondback Terrapin (*Malaclemys terrapin*) capture and blue crab (*Callinectes sapidus*) harvest in Delaware Bay. *Ecological Applications*.

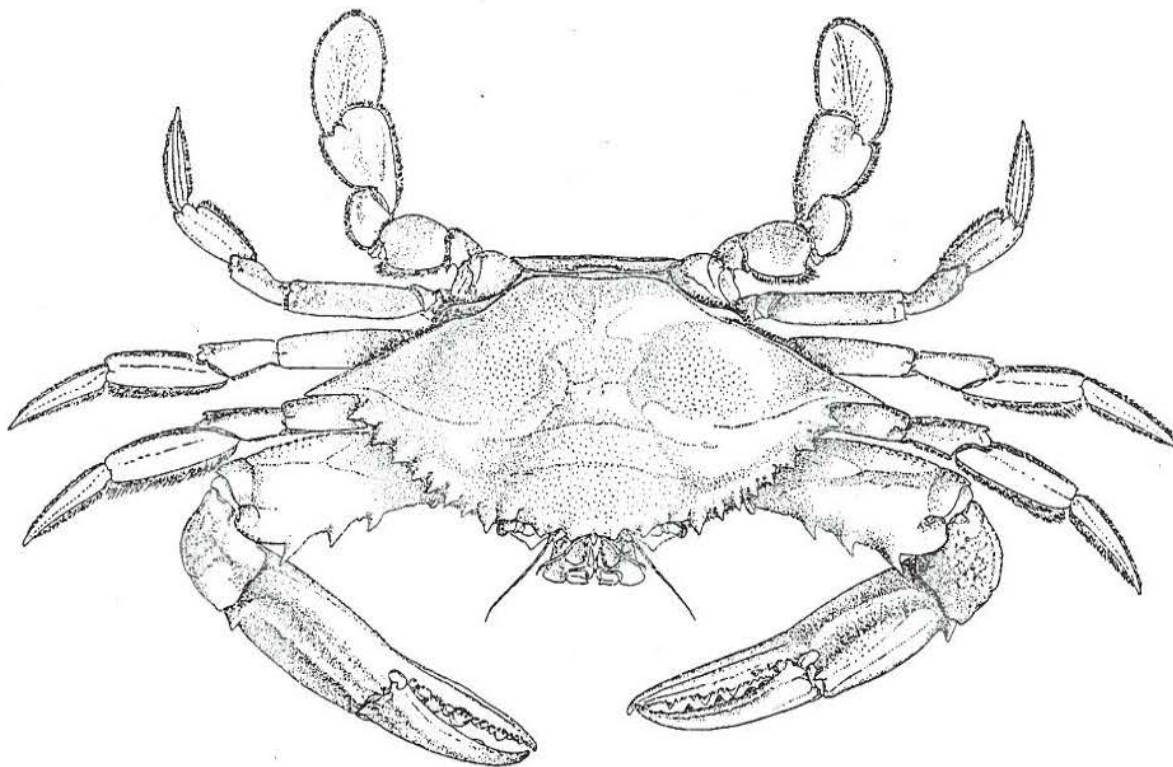
Helser, T.E, and D.M. Kahn. 1999. Stock assessment of Delaware Bay Blue crab (*Callinectes sapidus*) for 1999. Delaware Department of Natural Resources and Environmental Control, Division of Fish and Wildlife, 89 Kings Highway, Dover, DE. 100 p.

Helser, T.E. 2000. Stock assessment of Delaware Bay Blue crab (*Callinectes sapidus*) for 2000. Delaware Department of Natural Resources and Environmental Control, Division of Fish and Wildlife, 89 Kings Highway, Dover, DE. 100 p.

ATTACHMENT #1

**Project No. 1: STOCK ASSESSMENT OF DELAWARE BAY BLUE
CRAB FOR 2000.**

**STOCK ASSESSMENT OF DELAWARE BAY
BLUE CRAB (*Callinectes sapidus*) FOR 2000**



**Thomas E. Helser, Ph.D.
Fisheries Biometrician**

**State of Delaware
Department of Natural Resources & Environmental Control
Delaware Division of Fish and Wildlife
89 Kings Highway
Dover, DE 19901**

April 4, 2000

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EXECUTIVE SUMMARY

This report provides results of the second comprehensive stock assessment of the Delaware Bay blue crab stock. What's new for 2000? Blue crab catch and research survey data have been updated through 1999 and additional analytical procedures have been developed. Specifically, a stochastic decision-based framework has been developed to incorporate uncertainty associated with variable model input parameters, and to formally evaluate the probability of overfishing the blue crab stock. In summary, the assessment procedures included: 1) A catch-survey model (modified DeLury model) to estimate Delaware Bay blue crab stock sizes and fishing mortality rates annually from 1979-1999; 2) estimation of biological reference points (BRP) from yield and SSB-per-recruit analyses, coupled with spawning stock biomass and recruitment plots, to derive fishing targets and overfishing thresholds; and 3) an uncertainty analysis to characterize the error associated with the terminal year fishing mortality rates and the biological reference points to which they are compared, yielding a confidence decision level with the stated probability of overfishing the blue crab stock.

The modified DeLury model fit the Delaware Bay blue crab data fairly well; parameter estimates of recruit and fully-recruited stock sizes were relatively precise (CV's generally ranged from 25-40%). Recruit stock sizes over the last 5 years have been at or above the 1979-1999 average of 76 million. Fully-recruited blue crab stock sizes ranged from 6 to 65 million with an average of 25 million crabs over the 1979-1999 period. Over the last 5 years, fully-recruited stock sizes were estimated to be greater than the 1979-1999 average of 25 million. Exploited blue crab stock biomass ranged from 3.1 million to 26 million pounds, with an average biomass of 10 million pounds over the 1979-1999 period. Blue crab stock biomass has trended upward over time since 1979, but appears to have stabilized at about 14-18 million pounds since 1990. Fishing mortality rates on fully-recruited blue crabs ranged from 0.30 to 1.56, with an average of 0.92 over the 1979-1999 period. Average F in recent years (1997-1999) for fully-recruited blue crabs was 1.1 with 80% confidence intervals ranging from 0.80 to 1.60.

Biological reference points calculated from the Thompson and Bell model were: $F_{0.1} = 0.6$, $F_{MAX} = 1.0$, $F_{20\%} = 1.1$, while F_{REP} calculated from SSB-per-recruit and SSB-Recruitment indices was 1.3. An appropriate overfishing threshold mortality rate is 1.3 (F_{REP}) and fishing mortality rates in excess of this value would increase the likelihood of jeopardizing the resource. The recent average fishing mortality rate is near F_{MAX} and $F_{20\%}$ but is generally below the overfishing threshold mortality rate of 1.3. While the uncertainty analysis revealed significant overlap in the empirical probability density functions of $F_{97.99}$ (80% CI from 0.8 to 1.5) and F_{REP} (80% CI from 0.9 to 1.6), at the 80% confidence decision level the probability that $F_{97.99}$ is equal to or greater than F_{REP} is less than 15%.

Based on yield and SSB-per-recruit considerations, we recommend a fishing target somewhere between of $F_{0.1} = 0.6$ and $F_{MAX} = 1.0$. Given the shape of the yield-per-recruit response to fishing mortality, there would be little yield to gain by fishing above F_{MAX} (=1.0), while the potential consequences of a fishing target above that level could result in depleting spawning biomass ($F_{REP} = 1.3$). An appropriate interim fishing mortality target would be an F of 0.94 (F_N weighted

by N over 1990-1999 period). Fishing mortality rates over this period corresponded to a landings and stock biomass trajectory that was relatively stable, averaging approximately 9-10 million pounds and 14-18 million pounds, respectively.

We believe the Delaware Bay blue crab stock is fully exploited and at moderate levels of stock biomass. Therefore, it is recommended that increases in fishing effort should be avoided. This has already occurred to some extent through limited entry regulations (cap on license sales) put in place in between 1993-1995; latent effort with crabs pot currently not used, however, could increase directed effort. Further, targeting of maturing female crabs in the fishery, particularly when they are concentrated, should be discouraged.

INTRODUCTION

The Blue crab (*Callinectes sapidus*) inhabits nearshore coastal and estuarine habitats throughout the western Atlantic, Caribbean and as far south as Ecuador (Williams 1984). Despite the fact that Delaware Bay is near the northern extremity of its range, blue crab catches currently produce the largest dockside value of any fisheries resources in Delaware. Cole (1998) has estimated that commercial landings of blue crab from 1988-1995 averaged 4.5 million pounds and produced an annual dockside value of \$2.5 million.

With an increasing demand for crab meat, coupled with declines of harvests in the Chesapeake Bay stock, effort on the Delaware Bay stock has increased markedly since the mid-1980's (Cole 1998). Very recent declines in landings and catch-per-unit-effort has raised concerns that these declines may foreshadow future stock depletion. This concern has mandated a development of a bi-state fishery management plan to be submitted to the Delaware State legislature. The Division of Fish and Wildlife was tasked with providing an analysis of available blue crab data, an assessment of the stock, and estimates biological reference points and fishery management benchmarks.

The report presented herein provides results of the second annual blue crab stock assessment for the Delaware Bay. The blue crab stock assessment for 1999 (Helser and Khan, 1999) represented the first successful attempt at analytically deriving estimates of stock sizes and fishing mortality rates, and at estimating biological reference points from which a fishing target and overfishing threshold can be derived for the Delaware Bay blue crab stock. This assessment served as the basis for the development of the Delaware Bay Blue Crab Fishery Management Plan which was submitted to both Delaware and New Jersey. As before, there was currently no method of aging mature blue crabs, therefore an age-structured assessment could not be conducted. Instead, we employed the catch-survey model (Collie and Sissenwine 1983) or the modified Delury model (Conser and Idoine 1992) which models the population using only two size groups. Auxiliary information of relative abundance of the size groups from research surveys and annual catches are integrated into a single model framework to estimate stock sizes, stock biomass and fishing mortality rates. Overfishing definitions based on biological reference points were developed

from other methods such as yield and SSB-per-recruit analyses and standard spawning stock-recruitment plots. Finally, a mixed Monte Carlo-Bootstrap procedure was developed to incorporate uncertainty in the terminal year fishing mortality rates and the biological reference points to which they are compared (Helser et al. In Press). A probabilistic framework was then used to evaluate decisions regarding the overfishing status of the Delaware Bay blue crab resource.

BLUE CRAB LIFE HISTORY

Distribution and Stock Structure

The bi-state Delaware Bay fishery is prosecuted on a single stock inhabiting the Bay. Because the larval stage is transported to the coastal shelf before re-entering the Bay to settle, mixing with other stocks in the region may occur at this stage. Kahn et al. (1998) discussed the hypothesis that the Delaware Bay stock should be considered part of a metapopulation because of larval mixing (Epifanio 1995). Considering the significant stock-recruitment relationship, ocean circulation patterns and the dominant size of the stock compared to other nearby estuaries, they concluded that the stock was probably the primary source of its own recruits. The mouth of Chesapeake Bay is 160 km to the south, so they did not consider it a likely dominant influence on Delaware Bay recruitment.

Age and Growth

Terms in the following discussion: age 0 implies the size from the first appearance of recruit size blue crabs in August or September until the following September. We do not use the January 1 birthday convention. The small size stage is defined as 0 – 59 mm CW, the medium stage is from 60 – 119 mm CW and the large stage is 120 mm and greater.

Since blue crabs continually molt as they grow, aging specimens by the typical convention of hard parts is impossible. A representative set of monthly length-frequency samples from the Delaware Division of Fish and Wildlife's juvenile crab and finfish survey as shown in Figure 1.

New recruit blue crabs first appeared (e.g., 1979 year class) in August of 1979. During this month, the 1+ crabs (the previous year's recruits) ranged from 65 mm CW to 175 mm. In September, recruits generally extended to 80-90 mm CW and also appeared to overlap to some extent with the age 1+ crabs. By October, the new recruits appeared to have grown up to 100 mm CW. By May of 1980, faster growing new recruits had merged with 1+ crabs near 100 mm CW or higher. By July 1980, the mode for age 0 was about 60 mm, but some have probably passed 120 mm. In August 1980, when the new year class appears, the new age 1 crabs had merged with any older crabs at a mode of 135 – 150 mm CW, and by September, age 1+ crabs grown to a size greater than 100 mm. By October 1980, new recruits had virtually merged with the distribution of older crabs. In June 1981, there was virtually a unimodal distribution with a mode of 80 mm and by July 1981 crabs had grown larger to a mode of about 115 CW. By August 1981, the large majority of 1+ crabs were 120 mm or greater, as new recruits again appeared in the survey.

To summarize the growth pattern of this stock, new recruits appear in August or September samples. By October, some have grown into the medium stage (60 – 119 mm CW). By the following June, some age 0 crabs have become large crabs. This is substantiated by timing of peeler landings. In many years, the largest peeler landings are made in June. This indicates many females are molting into maturity and usually the large size category. By July, hard crab landings usually increase as more age 0 animals recruit into the legal size (127 mm in DE, 120 in NJ). The large majority of new recruits are large crabs by the end of October, although a minority commonly overwinter as mediums. This proportion varies among years. Kahn et al. (1998) substantiated this description of blue crab growth using life-stage-specific indices of abundance to predict later life stages.

As with growth, blue crab maximum size and lifespan is also not fully known, although more is known about terminal molting. Females have, for all intents and purposes, a terminal molt into maturity. An occasional sook (mature female) is found in a peeler condition, but when held they have always died in the molt, according to several watermen. Overwintering mature crabs are reported to have less vitality than younger crabs by watermen. We believe most crabs die naturally by the end of their third year. The tag returns of older females from the Chesapeake

show there are exceptions to this, but our observations and those of the literature (Churchill 1919, Van Engel 1958 and others) indicate the general pattern to be two to three year lifespan. We point out that all those tag recaptures in the Chesapeake were of sooks which had not molted in the several years they were at large. If they had molted, they would have lost their tags. Males, in contrast can continue to molt. We have collected 98,579 crabs from 1978-1998 in our juvenile trawl program. The largest crab was 205 mm CW; this represented 0.00001 of the total sample.

We employed MULTIFAN to conduct width frequency analysis of research survey width frequency samples (Fournier et al. 1991). Our goal was to obtain Von Bertalanffy growth parameters and number of significant ages present in the trawl samples. These goals have been only partly realized at present, and we consider this a work in progress. The procedure analyzes multiple length frequency samples simultaneously, employing maximum likelihood methods to enable formal hypothesis tests. The maximum number of samples we were able to analyze at once was 21. Some parameter estimates which had the highest G statistic, indicating the best fit, were actually unrealistic, having L_{∞} infinity values of several thousand mm. CW. The trawl data was broken into several subsets, three of which were analyzed. The result was a suite of von Bertalanffy parameter estimates, rather than the one set of estimates. We currently have a range of estimates of K and L_{∞} from MULTIFAN (Fournier et al. 1991) which were judged to be reasonable and good fits to the data. Models employed included variable standard deviation of lengths at age and seasonal growth effects. We were able to detect three significant age-classes in the data at a maximum. An L_{∞} of 300 mm or more and a K of less than 0.2 was considered unrealistic. We recovered the three most realistic sets of von Bertalanffy growth parameters estimated from the MULTIFAN runs that also generally gave the highest values of the G-statistic. The predicted growth trajectories of crab carapace width as a function of age for the three sets of parameters are shown in Figure 2. For the purposes of subsequent analyses that use size at age such as yield and SSB per recruit models, the expected size at age is defined as in the growth trajectories, except that for crabs less than one year age is set 0.5.

Reproduction and Maturity

Our understanding of blue crab reproduction for this stock is that females mate immediately after

their molt into sexual maturity, usually late in their first year. Females then store the sperm overwinter and produce eggs in the following summer during their second year (age 1). Prager et al. (1990) estimated fecundity per batch as over 3×10^6 eggs. The literature states that females may spawn twice in their first year of spawning (Churchill 1921, Van Engle 1958). Some authors believe it is possible for females to spawn in their fourth summer as age 3. One method to determine survival of previous spawners is based on a nemertean egg parasite. This worm changes states if it has fed on eggs, indicating the host crab has previously spawned. Cole and Beck (1975) found 4.5% of overwintering females in Delaware Bay held parasites indicating previous spawning. This may be a lower bound of the proportion of previous spawners that overwintered. We cannot assume that all these females would survive the winter and spawn the following summer. Winter appears to be a time of highest mortality for mature crabs in Delaware Bay, according to anecdotal reports from watermen.

The literature indicates females may only mate when they molt into maturity. How long sperm can remain viable from this mating, normally at the end of their first year of life, is unknown. Taken as a whole, the literature and parasite evidence suggests that a small minority of females survive to a second spawning season. Some of these may spawn. There is no indication from the literature that females spawn after a possible second season. Larvae hatch in the summer. The peak month of larval abundance in Delaware Bay is July. They exit the Bay and the current hypothesis is that they travel southward in a current until southwesterly winds push them further offshore and back north toward the mouth of the Bay (Epifanio 1995). Major re-entry into the Bay as megalopae is hypothesized to occur during northeasters in the late summer and autumn.

Maturation by carapace width (maturity ogive) of Delaware Bay blue crabs was estimated from a sample of 1,335 female crabs collected from the commercial catch between 1995-1997. Female blue crabs were categorized as either mature or immature, based on the shape of the crab's apron, and modeled as a binary response using the statistical logistic regression model (Agresti 1990):

$$\text{logit}(P) = \log(P/(1-P)) = \alpha + \beta * CW + \epsilon$$

where: $P = \Pr(Y=1|X)$ is the response probability, CW = carapace width (mm) and α, β are

parameter estimates. Results of logistic regression were highly significant as measured by the concordance metric, a goodness of fit measure between the predicted and observed response, which was 97%. The predicted and observed maturity response by size are shown in Figure 3. Our results were similar to those of Rothchild and Ault (1992) who found very few mature crabs with carapace widths of less than 100 mm, and nearly all crabs were fully mature by 140 mm.

THE FISHERY

Commercial Fishery

Regulations differ slightly between states. Minimum size for male hard crabs in Delaware is 5" (127 mm) CW, while in New Jersey the commercial limit for males is 4 ¾" (120 mm) CW and recreational is 4 ½". Mature females of any size can be harvested. Sponge crabs are protected from harvest. Commercial crabbers in New Jersey are limited to 600 pots; in Delaware crabbers can obtain license for 50 to 200 pots in increments of 50. A Delaware crab vessel with three licenses assigned to it can fish 500 pots. Both states have established limited entry for the fishery. Delaware has attempted to cap the number of licenses, and the number of pot licenses peaked in 1996 and declined slightly to 214 in 1997 (Table 1). New Jersey pot licenses peaked in 1994 at 506 and were at 408 in 1997 (Table 2). Dredge licenses have climbed in New Jersey to 378 in 1997. Only a portion of total New Jersey licensees, however, fish Delaware Bay. Several coastal embayments and Raritan Bay in the north also have active blue crab fisheries. Delaware dredge licenses have dropped slightly to 40 in 1997.

Two primary components comprise the Delaware Bay blue crab fishery; a spring to fall pot fishery and a winter dredge fishery. The dredge fishery primarily lands mature females (sooks) which have congregated in overwintering aggregations in the higher salinity of the lower Bay. Bushels of males comprised 6.6% of the total bushels landed from 1985 through 1995, on average. This fishery is limited to December 15 – March 30.

In recent years crab pots have been modified with 1" mesh to target peelers (immature crabs about to molt). Previously, 1 ½" mesh was standard. Landed peelers are almost exclusively

females, which are targeted by baiting the pots with a mature male (jimmy). Females seeking a male to protect them and mate immediately after molt are attracted into the pot. Peelers are high value landings used by the soft crab rearing operations and for fishing bait. Peeler landings have peaked for both states in recent years (Table 3).

Certain characteristics of Delaware Bay result in significant differences between the pot fishery here and that of Chesapeake Bay. Delaware Bay has stronger tidal currents and about 8 feet of tidal amplitude. Chesapeake Bay tides are not as strong and are lower in amplitude, reportedly a few feet. The implications for the fishery are that pots must be weighted much more heavily in Delaware Bay to remain stationary. Stronger tides mean crabbers must work down a line of pots and then motor back to the beginning of the next line. They report that in at least some areas of the Chesapeake, crabbers can work up one line and back down the next. Delaware Bay crabbers also report that their waters are deeper than large areas of the Chesapeake, requiring longer buoy lines and longer pick-up times with heavier pots. The total effect of these differences indicates lower effective effort in Delaware Bay.

The typical yearly pattern for the pot fishery is to start in April or May with a "sook run", where mature overwintering females are targeted; they tend to feed more strongly early in the season. As sooks produce eggs and become sponge crabs, they are protected from harvest and crabbers move up-bay and away from higher salinity areas inhabited by spawning females. By June, or some years in May, significant peeler landings occur, centered primarily around the new and full moons. By July, landings of mature males or jimmies pick up and usually peak in August or September as the new year-class recruits into the pot fishery. Landings decline through October. One trend in the last few years is an increased targeting-of sooks in September and October as they migrate down bay (Cole 1998; Table 4). Increasing market demand for sooks, including some Oriental export and western U.S. demand, drives this trend.

Landings are affected by severe winters in this region. In these years, the winter dredge fishery catches significant proportions of dead adults. In 1996, the Delaware DFW conducted at-sea samples of dredge catches and found over 30% mortality. Landings in the subsequent year declined by 40%. Jamieson (1986) reported large interannual variation in landings from the Mid-

Atlantic north of Chesapeake Bay (primarily Delaware and New Jersey) between 1965 and 1984; CV of 96% compared to 37% in the Chesapeake and 19% in the South Atlantic. High variability in abundance due to intermittent severe winters may be the cause of high variation in landings.

Bi-state landings showed a sharp drop in 1977 to about 800,000 pounds, approximately 16% of 1976 landings (Figure 4). The winter of 1977 was the most severe in recent decades, which was followed by another severe winter in 1978. Following these two unusually cold winters, landings remained relatively low during the early 1980's averaging about 1.5 million pounds, but then rose sharply from that point to 13 million pounds in 1990. Since 1990, Delaware Bay blue crab landings have fluctuated around 10 million pounds, but peaked to a time-series high of 14.5 million pounds in 1995 (Figure 4). Landings for 1998 and 1999 (1999 landings are provisional) were near 10 million pounds. Based on historical landings data back to 1941, recent landings are the highest yields ever documented. Two other periods had relatively high yields. From 1952 through 1961, landings averaged 2.4 million pounds and from 1970 through 1976 landings averaged 1.9 million pounds. Landings in both Delaware and New Jersey have followed a very similar patterns (Tables 5 and 6).

Delaware nominal effort (number of licensed pots) has increased in general since 1970, although a dip occurred following the 1977 winter kill (Figure 5). However, effort has declined slightly from 1997 to 1999. Catch per unit effort (CPUE) dropped in 1977, then slowly climbed until it jumped upward in 1985. It fluctuated without trend until 1994, then has slowly declined through 1997 with a slight increase in 1998 and 1999. New Jersey's effort and CPUE trajectory has been similar (Figure 6). Nominal effort in New Jersey has been at all-time highs between 1994-1997, but has declined substantially in recent years. Nominal effort measures in Delaware and New Jersey may not adequately gauge or index the actual effort expenditure in the Delaware Bay blue crab fishery. This is because nominal effort measures the number of crab pots watermen are licensed to fish and not the actual number of pots fished during the season. Mandatory logbook data and fishery intercept survey data collected in Delaware since 1985 indicate that directed effort has also increased confirming the increases in nominal effort (Figure 7). Two measures of directed effort were calculated from these surveys, number of boat days and crab pot days, which are measures of the actual number of boats and crab pots fished. Directed effort in terms of crab

pot days in 1995 and 1997 were the highest recorded since 1985.

Recreational Fishery

Cole (1996), utilizing a bus route design on land and a riverine boat sampling program, surveyed the Delaware recreational blue crab fishery in the Delaware estuary. In 1996, estimated harvest by recreational crabbers was only 1,022 bushels. This was 1% of the commercial pot fishery for that year. No estimates are available for the New Jersey recreational fishery.

FISHERY-INDEPENDENT SURVEY

Delaware Division of Fish and Wildlife has operated a blue crab and juvenile finfish survey since 1978 in Delaware Bay. Kahn et al. (1998) details the distribution and other aspects of the survey. Basically, the survey employs a 16 ft. trawl with a 0.5 inch cod end liner, and 1.5 inch mesh throughout. The sampling design is a fixed site grid on the western inshore areas of the Bay up into the Delaware River. Data employed here is from the lower 26 stations that have been sampled since 1978 (Figure 8). Sites are sampled monthly from April through October with ten minute tows against the tide. Blue crabs are measured to 5 mm. increments, sexed and counted. No individual weights have been taken.

Several stage-specific indices of abundance have been developed from this data. A YOY index is developed from geometric mean CPT of small crabs (< 60 mm CW) in September and October. A second index was developed as a measure of recruitment. This index also uses the GM CPT of medium crabs (60 mm CW – 199 mm CW) in the following April – August tows. The index of recruitment was validated against peeler landings (Kahn et al. 1998). The index of recruits shows an increase over the time series, with saw-toothed fluctuations (Figure 9).

Two indices of large crabs were also developed (≥ 120 mm). One is the annual index, which was validated against landings (Kahn et al. 1998). This index shows a gradual increasing trend over the time series (Figure 9), although it has flattened out in recent years with two particularly large peaks in 1990 and 1992. The second index was developed to follow year-classes, and is

termed the year-class index of large crabs. Kahn et al. (1998) showed these indices are coherent in that the YOY index predicts the lagged index of recruits and the lagged year class index of large crabs with a curvilinear regression. The index of recruits predicts the year-class index of large crabs for the same year with a linear regression. The curvilinear regressions may suggest density-dependent mortality occurs in the small crab stage. A biomass index was developed from the survey width frequencies. Since the index was intended to measure biomass of fully-recruited blue crabs, widths less than 120 mm were excluded from the calculations. Widths were converted to weight for each tow using a width-weight equation for sexes combined reported by Rothschild et al. (1992). Then for each tow the average weight (weighted by number in each size-weight category) in that sample was calculated and log-transformed after adding a value of unity. The annual biomass index was calculated by estimating the log(weight) per tow and then retransformation to the geometric mean weight per tow (kg/tow). The fully-recruited biomass index (Figure 10), while showing a similar general trend as the large crab index, indicates a more steady increase in biomass between 1982 and 1990, which is followed by a decline until 1996.

Kahn et al. (1998) developed a measure of spawning stock biomass (female spawning biomass) from the trawl survey. Any large females captured in spring tows were considered to be the spawners for that year. Originally the arithmetic mean CPT of large crabs in spring tows (April and May) was an index of spawning stock. This was then elaborated to account for variation in female mean size among years, since Prager et al. (1990) found fecundity was a function of biomass. Following Uphoff (1995) we converted numbers of females per tow to biomass by converting the average carapace width per year for large spring females to weight using the width-weight model from Rothschild et al. (1992). We then multiplied this estimate of mean biomass per crab per year by the AM CPT of large females in the April-May tows. This number was converted to kilograms per tow.

Index-Based Stock-Recruitment Model

The index of recruitment (see above) was plotted as a function of the index of spawning stock biomass, lagged one year, since the recruits are defined as the medium crabs from April-August of the year following birth. Two stock recruitment models were fit to the data. One model was a

null model with no density-dependent mortality (Fogarty et al. 1992). This is a simple regression of recruitment on spawners with a linear term, a quadratic term and no intercept. If the quadratic term in the regression model is significant then curvature is present in the relationship between recruitment and spawning stock and the null model of no compensation should be rejected. If rejected, we then fit the standard Ricker model with an additive normal error structure using the Marquardt algorithm in SAS (1985). We rejected the null model of no compensation based on the linear regression of recruitment on spawning stock. The quadratic term in the regression analysis was highly significant ($p < 0.01$) and substantially improved the model fit ($r^2 = 0.62$; $p = 0.0002$) over a model based on just the linear term ($r^2 = 0.38$; $p < 0.002$). Based on the alternative hypothesis of compensatory mortality for blue crab, we then fit the Ricker model. The nonlinear least squares S-R analysis produced significant Ricker parameter estimates ($r^2 = 0.42$, $\alpha = 250.7$, $\beta = -39.82$, $p < 0.05$). Figure 11 shows the fit of the Ricker model to observed indices of recruitment and spawning biomass revealing both high resilience from the initial slope of the Ricker function and strong compensation. In particular, the analysis revealed a relatively strong compensatory response; recruitment peaked and then declined with increasing levels of spawning stock biomass. Other investigators suggested compensatory processes are important in blue crab population dynamics, and have thus fit the Ricker-type model to data (Tang 1985; Lipcius and van Engel 1990; Rugolo et al. 1997). We tested for serial autocorrelation between the index of recruits and the future index of spawning stock biomass. The former was lagged one year. The Durbin-Watson D statistic was 1.796 (first-order correlation was 0.048 $n = 20$, $P = 0.116$), indicating no serial correlation.

We then derived a recruitment overfishing threshold based on the work of Mace (1994), from the Ricker parameter estimates. This reference point, labeled as SSB_{50} , defines the threshold level of spawning stock biomass that will, on average, produce $\frac{1}{2}$ the maximum theoretical level of recruitment. In theory, when spawning stock biomass is reduced below the threshold recruitment becomes severely diminished resulting in stock depletion. Since the value of the recruitment threshold estimated from the Ricker parameters is deterministic and the S-R model was based on relatively few data points, we used the bootstrap to evaluate the Ricker parameter estimates and to estimate a variance for the reference point. The Ricker parameter estimates were significantly different from zero in the bootstrap results. The median of the alpha parameter estimates from

1000 bootstrap runs was 375.9, with the 95% CL from 192.0 to 632.2. The beta parameter mean was -51.1, with the 95% CI from -72.8 to -30.8. The alpha parameter is interpreted as 375 recruits produced per kilogram of spawning stock biomass. On average, there are 6.6 mature females per kilogram (Kahn et al. 1998), so the alpha parameter indicates that at low densities, each female spawner can produce about 57 recruits. This is a very high alpha level and indicates the stock should be very resilient to fishing. Based on the bootstrap, the index value corresponding to SSB_{50} was 0.006 kg SSB/ tow. We used the median value since the empirical distribution was non-normal. The 95% confidence limits were 0.003 to 0.008 from 1000 bootstrap replicates. Median recruitment below this reference point was markedly reduced (Figure 11).

ESTIMATION OF MORTALITY AND ABUNDANCE

Estimates of Natural Mortality

No previously published estimates of natural mortality were available for Delaware Bay blue crabs. Rugolo et al. (1998) suggested an M of 0.375 for Chesapeake Bay blue crab based on the $M=(3/\text{maximum age})$ convention (Vetter 1985) and an assumed maximum age of 8 years. We believe that while it may be possible for crabs to reach that reported longevity in the Chesapeake Bay, blue crabs in Delaware bay most likely do not live that long. Delaware Bay is in the northern most extent of the species distribution and, unlike blue crabs that have been reported to live as long as 5 years in North Carolina (Fletcher 1965), probably live no more than 3-4 years (See Life History). Thus, using the ICES convention, natural mortality for Delaware Bay blue crab may more realistically be $M=0.75$ to 1.0. This value is considerably larger than that reported for the Chesapeake Bay by Rugolo et al. (1998). However, recent studies using lipofuscin accumulation rates of blue crabs (Ju et al. 1999; Ju et al. 2000) under natural conditions as an alternative to aging using hard parts suggests that blue crabs grow faster than previously assumed by Rugolo et al.(1998). Thus, higher growth rates observed in natural conditions may indicate that longevity may be lower and therefore natural mortality higher for blue crabs in the Mid-Atlantic region.

Estimates of Fishing Mortality and Abundance

The modified DeLury model (Collie and Sissenwine 1983; Conser and Idoine 1992) was applied to Delaware Bay Blue crabs to estimate abundance and fishing mortality rates. Information for Delaware Bay Blue crabs was available to meet minimum data requirements for the modified DeLury model, which include: 1) annual indices of population size (numbers) for each life history stage (i.e., recruit and fully-recruited size) estimated by research surveys, 2) total annual fishery catch in numbers, 3) information on the partial recruitment of recruit size animals to the commercial fishery (fully-recruited life stage), and 4) an estimate of instantaneous natural mortality. Other auxiliary data not endogenously required by the model are needed such as mean weights for each life stage and the relative selectivity to the survey gear. The DeLury model is based on the first order difference equation

$$N_{0,y+1} = (N_{0,y} + R_{0,y} - C_y) e^{-M} \quad (1)$$

which relates the fully-recruited stock size at the beginning of the year ($N_{0,y+1}$), to the fully-recruited stock size at the beginning of the previous year ($N_{0,y}$), plus recruitment in the previous year ($R_{0,y}$), minus the catch (C_y), all discounted for natural mortality, M .

The above equation assumes that a recruit is any animal smaller than the minimum size vulnerable to the fishery at the beginning of the survey year whose size will be greater than or equal to the fully-recruited size by the end of the survey year. In other words, recruits must grow from a size not vulnerable to fully-vulnerable size within one year. For this analysis, we defined the "survey year" to run from August-September of each year to the next. New year-classes appear in the research survey during this time, whereas large crabs from the previous years cohorts are still available to the survey gear/area before they migrate down bay during the fall. In addition, we defined recruit and fully-recruited blue crabs to be less than and greater than or equal to 120 mm, respectively. There are three reasons why this would be a somewhat natural construct for the DeLury model: 1) current conservation measures specify a 120 mm and 127 mm minimum carapace width for hard crabs in New Jersey and Delaware, respectively; 2) width frequencies indicate that the large majority of recruits, which appear in the research surveys

during August-September, have grown to the fully-recruited size (120 mm) by the following survey (Figure 1); and 3) Kahn et al. (1998) demonstrated a significant positive correlation between large blue crab indices (defined as > 120 mm) in a given year and recruit size crab (< 60 mm) indices during the previous year. The DeLury model is predicated on the basis that a “signal” exists between recruit and fully-recruited sizes. Since approximately 70% of the blue crab catches are taken prior to the mid-point of the August-September research survey (Figure 12), indices of recruit and fully-recruited relative abundance were lagged to index population abundance at the beginning of the next calendar year. In addition, catches of blue crab are taken at a point 60% into the calendar year. Therefore, the above difference equation can be formulated

$$N_{0,y+1} = [(N_{0,y} + R_{0,y})e^{-0.60M} - C_y] e^{-0.40M} \quad (2)$$

so that recruited blue crab ($N_{0,y} + R_{0,y}$) experience 60% of the natural mortality ($e^{-0.60M}$), catch is removed, then the survivors $[(N_{0,y} + R_{0,y})e^{-0.60M} - C_y]$ experience the remaining 40% of natural mortality. For the DeLury analysis, natural mortality was assumed to be 0.8. Survey indices of abundance are related to absolute stock sizes estimated by the DeLury model by catchability coefficients

$$n'_y = q_n N_{0,y} e^{\eta'} \quad (3)$$

and

$$r'_y = q_r R_{0,y} e^{\delta'} \quad (4)$$

where r'_y and n'_y are the observed research indices of recruit and fully-recruited blue crab, q is the catchability coefficient of the research survey gear, and $e^{\eta'}$ and $e^{\delta'}$ are lognormally distributed random variables, which represent survey measurement errors for the recruits and fully-recruited indices, respectively. In essence, these errors represent the difference between the observed survey indices of recruits and fully-recruited animals and the expected indices predicted within the nonlinear least squares (NLLS) framework by the DeLury difference equation. Another

source of error, called process error, arises from the DeLury equation itself, which is the difference between calculated indices of fully-recruited animals and the expected value of the fully-recruited indices again predicted within the NLLS framework from the DeLury model. Substituting the above equations into the DeLury difference equation and including the lognormally distributed process error (e^{ϵ_t}):

$$n_y = [(n_{y-1} + r_{y-1}/s_r)e^{0.60M} - q_n C_{y-1}]e^{-0.40M} e^{\epsilon_t} \quad (5)$$

where

$$s_r = q_r / q_n \quad (6)$$

is the relative selectivity of recruits to the fully-recruited blue crab. For the analysis of Delaware Bay blue crabs the relative selectivity was set equal to unity. The research survey uses a 1.5 inch mesh with a 0.5 inch codend liner (shrimp trawl) and it is unlikely that small blue crabs of recruit size observed in the survey would escape at a rate different from that of fully-recruited crabs. If anything, it may be possible that larger blue crabs could differentially avoid capture by swimming out of the way of the on coming net.

Thus, the above equation is a statistically estimable function with $2Y$ parameters to be estimated; n_y for all years, Y , r_y for all years except the last year, and q_n . Estimates of these parameters (θ) are obtained by minimizing the least squares objective function (S):

$$S(\hat{\theta}) = \lambda_{\epsilon} \sum_{y=2}^Y \epsilon_y^2 + \sum_{y=1}^Y \eta_y^2 + \lambda_{\delta} \sum_{y=1}^{Y-1} \delta_y^2 \quad (7)$$

where λ_{ϵ} and λ_{δ} are relative weights for the process error and recruit measurement error, respectively (relative to the measurement error for indices of the fully-recruited size). Conser (1995) describes an approach to weighting process and measurement errors within the least squares objective framework which is implemented in this analysis to evaluate model sensitivity.

Given estimates of n_y , r_y , and q_n from the nonlinear least squares minimization, and the value of relative selectivity, s_r , population sizes for the recruit and fully-recruited blue crabs are:

$$N_{0y} = \frac{\hat{n}_y}{\hat{q}_n} \quad R_{0y} = \frac{\hat{r}_y}{s_{ry}\hat{q}_n} \quad (8)$$

Then instantaneous rates of total and fishing mortality for all crabs of recruit size and larger can be calculated as:

$$Z_{R+N_y} = \log_e \left[\frac{N_{0y} + R_{0y}}{N_{0,y+1}} \right] \quad (9)$$

$$F_{R+N_y} = Z_{R+N_y} - M \quad (10)$$

Fishing mortality can then be partitioned to recruit and fully-recruited sizes according to the average partial recruitment (p) of recruits over the survey year (typically a function of growth toward the size at which they become fully-recruited):

$$F_{N_y} = \frac{F_{R+N_y}(R_{0y} + N_{0y})}{p_{Ry}R_{0y} + N_{0y}} \quad (11)$$

and

$$F_{Ry} = p_{Ry}F_{N_y} \quad (12)$$

For Delaware Bay blue crabs, the average partial recruitment was derived from empirical average monthly percent change in mean size relative to the fully-recruited size (120 mm) over the survey year (Figure 13). These data suggest that between October and March very little, if any, growth of blue crab occurs in Delaware Bay, while recruits grow rapidly toward the fully-recruited size from May through August (Figure 13).

DeLury results are summarized in Table 7 with more detailed model output showing nonlinear least squares and bootstrap results provided in Appendix A and Appendix B, respectively. This model formulation (Base Run) assumed $M=0.80$, $S_r=1.0$ with equal error weights among process and measurement errors. Evaluation of the model's performance is discussed below by examining the reciprocal of the signal-to-noise ratio, or the coefficient of variation (CV), and standardized residual patterns. Coefficients of variation provide a measure of parameter precision while standardized residuals indicate the fit of the data to the model. CV's greater than 0.50 represent practical problems since, under normality assumptions, 95% confidence intervals will include negative values which have no meaningful interpretation for any of the DeLury model parameters. For the application of the DeLury model to Delaware Bay blue crab, parameter estimates were reasonably precise. With the exception of fully-recruited stock size in 1979 and recruitment stock size in 1991, most CV's were generally less than 40% (CV's for 39 of the 40 parameters estimated were in the 20%-30% range). Coefficients of variation for fully-recruited stock sizes ranged from 25% to 40%. Estimates of recruitment were generally less precise with CV's ranging from 29% to 40%. The CV on the catchability coefficient was among the parameters most precisely estimated (CV=22%). The bootstrap estimates of coefficients of variation, which are the preferred variance measures of the model's parameter estimates, were generally smaller than those from the nonlinear least squares (NLLS) routine. Bootstrap CVs for fully-recruited stock sizes ranged from 18% to 29%, CV's for recruit stock sizes ranged from 11% to 26%, and CV for the catchability coefficient was 14%.

Standardized residuals suggest that the data fit the DeLury model reasonable well. Here standardized residuals revealed no significant annual patterns with values generally ranging between -1.0 and 1.0 (Figure 14). The residual associated with the fully-recruited stock size in 1991 was an exception with a value of -1.7. Standardized residuals outside the range (-2,2) are usually considered outliers under normality theory (Draper and Smith 1981). One pattern that emerged is that relatively large positive residuals, associated with larger recruit indices (1986, 1990, 1995), seem to be related to relatively large negative residuals associated with fully-recruited indices one year latter (1987, 1991, 1996). The implication here is that the DeLury model under-predicted recruit indices when they were high, and over-predicted fully-recruited indices of blue crabs resulting from these large recruit indices. This pattern in the predicted

indices is mirrored by the calculated fully-recruited indices, which are simply calculated from the observed recruit and fully-recruited indices using the DeLury equation. These are generally greater than the indices predicted by the model for those year-classes where recruit size indices are large. Measurement error on the fully-recruited size group (38.6%) was roughly equal to that of measurement error of the recruits (33.4%). The remaining error as associated with process error (28%). One possible interpretation of this from a biological perspective is that natural mortality may vary over time and may be related to environmental and/or density-dependent effects. Evidence for density-dependent mortality in Delaware Bay Blue crab has been suggested by Kahn et al. (1998). Despite the slight disparity (where large year-classes occur), the fully-recruited indices predicted by the DeLury model track the calculated fully-recruited indices fairly well with no significant problematic residual errors.

Further insight into the DeLury model performance is gained by examining the error with respect to the underlying catchability relationships (Figure 15). Figure 15 shows the measurement error of the recruit and fully-recruited blue crab indices viewed as variability about the linear catchability model assumption used in the analysis given in Equation 3-4. In general, scatter plots of recruit and fully-recruited indices on estimated stock sizes appear to be fairly randomly distributed about the solid line depicting the linear catchability function. There is, however, somewhat of a tendency for relatively large recruit indices to lay above the catchability line, particularly for the estimated large 1998 and 1995 recruit stock sizes. Although this may indicate the possibility that catchability increases with increasing recruit stock sizes, lack of a time trend in the pattern of the standardized residuals with the present data suggests that the constant catchability assumption is valid.

DeLury estimates of blue crab recruit stock sizes ranged from 13 to 189 million, with an average of 76 million over the 1979-1999 period (Table 7; Figure 16). The 1998 value of recruitment (185.5 million crabs) was not estimated by the NLLS routine, but rather is calculated using the estimated catchability coefficient. While considerable year-to-year variability exists, recruit stock sizes appear to have, in general, increased over time. During the most recent years (last 5 years), recruitment has generally been at or above the 1979-1999 average of 76 million crabs. Estimates of fully-recruited blue crab stock sizes ranged from 6 to 65 million with an average of

25 million (Figure 16). Fully-recruited blue crab stock sizes also appear to have generally increased over time. Estimates of the most recent 5 years were all above the 1979-1999 average of 25 million crabs. Total exploited blue crab stock biomass (biomass potentially available for exploitation by the fishery given the average partial recruitment pattern) ranged from 4 million to 27 million pounds, with an average biomass of 10.6 million pounds over the 1979-1999 period (Figure 17). Overall, blue crab stock biomass has appeared to trend upward between 1979 and 1991, but has stabilized at about 14-16 million pounds in recent years. In 2000, exploited blue crab biomass was estimated to be 14.1 million pounds with 80% confidence intervals ranging from 10.8 to 22.1 million pounds. Blue crab catches (in weight) have also increased concurrently with increasing total biomass.

Annual estimates of instantaneous fishing mortality for blue crabs of recruit size and greater (F_{R+N}) ranged from a low of 0.18 in 1984 to a high of 0.81 in 1995, with an average F of 0.52 over the 1979-1999 period (Table 7; Figure 18). Fishing mortality rates on fully-recruited blue crabs ranged from a low of 0.30 to a high of 1.56, and averaged 0.92 over the 1979-1999 period. The high fishing mortality rates during the 1993-1995 fishing seasons coincide with reported relatively high levels of fishing effort (total boat days) in recent years (Cole et al. 1998). Estimates of mortality in the first and last years are the least reliable in the DeLury analysis because they are linked to one adjacent year rather than two which precede and proceed the one being estimated. Average terminal fishing mortality rates (F_{97-99}) were estimated to be 0.45 and 1.08 for the blue crabs of recruit size and greater and for fully-recruited blue crabs, respectively. These estimates are estimated to be slightly greater than the 1979-1999 averages.

Coefficients of variation associated with fishing mortality rates were estimated from two hundred bootstrap replicates, which were derived from randomly resampling model (base run) residual errors. Coefficients of variation associated with annual fishing mortality estimates were highly variable in some years. In particular, CVs on F 's in 1983 and 1984 exceeded 75%, and therefore 80% confidence intervals encompass zero (Table 7; Figure 18). Excluding these years and the first year in the analysis, most CVs on estimated fishing mortality rates were less than 40%. Despite the uncertainty associated with estimated fishing mortality rates for a number of years, CVs on the average terminal year F s (F_{97-99}) were only 21%, indicating that these were relatively

precisely estimated. Uncertainty in terminal fishing mortality rate was characterized using the bootstrap and its probability density function represented in figure 19. The terminal year fully-recruited F ($F_{97.99}$) ranged from 0.6 to 1.8, and confidence intervals (80%) about the expected value of fishing mortality ranged from 0.77 to 1.30. Thus, there is a 90% probability that ($F_{97.99}$) is greater than 0.90 and a 25% probability of being greater than 1.30 (Figure 19).

Sensitivity Analysis

Alternative formulations of the DeLury analysis were conducted to evaluate sensitivity of the results (Base Run; $M=0.80$, $S_r=1.0$, equal weights) to different assumptions including varying natural mortality rates (M), relative selectivity of the recruits (S_r), and statistical weighting (Table 8; Figure 20). The DeLury model was re-run on different assumptions of M (1.0, 0.6), S_r (0.60, 0.80) and process error weighting (2x, 0.50x) and results evaluated in terms of estimated mortality (Z) and stock sizes and model diagnostics which include mean square residual error (MSR), percent sums of squares (%SS) and CV's on parameter estimates.

The level of natural mortality (M) for Delaware Bay blue crabs is uncertain. Re-running the DeLury model using values of natural mortality of $M=0.60$ and $M=1.0$ (bounding our estimates of M) suggested that the magnitude and overall temporal pattern of instantaneous total mortality (Z) is generally insensitive to varying levels of M in the 0.6 to 1.0 range (Table 8; Figure 20). Different values of M do, however, affect the estimates of the catchability coefficient, q , and consequently the magnitude of the estimated recruit and fully-recruited stock sizes. As M was increased from 0.6 to 1.0, catchability decreased and estimated stock sizes increased. Also, as M was increased, coefficients of variation associated with q increased, whereas CV's on fully-recruited stock sizes decreased.

The relative selectivity of recruits (S_r) represent the vulnerability of recruit size blue crab to the research survey gear, relative to the fully-recruited blue crabs. By using a value of $S_r=1.0$, as was used in the base run of this analysis, it is assumed that both size groups are equally available or vulnerable to the survey gear. Because there is no exogenous information available to estimate relative selectivity, sensitivity analysis of the base run was conducted with $S_r=0.60$ and 0.80.

Generally, absolute values of the total mortality rates were moderately affected by varying the value of relative selectivity equal to 0.8, while the time trend in Z s were similar to other sensitivity runs. Setting $S_r = 0.60$ had a more profound affect on estimated Z s; producing mortality rates generally higher than the base run. Estimates of average Z over the 1979-1999 period were approximately 10% and 20% greater for $S_r = 0.8$ and $S_r = 0.6$, respectively, than compared to the base run. Most striking was the percentage of the total sums of squares attributable to the measurement and process errors; as S_r decreased the process error increased considerably. Overall, the fit of the data to the model as measured by total variance (MSE) was substantially poorer than compared to the base run ($S_r=1.0$).

Terminal estimates of recruit and fully-recruited stock sizes from DeLury analysis are typically sensitive to the statistical weighting of process and measurement errors (NEFSC 1995). The purpose of *a priori* weighting the process error is to “force” the estimated stock sizes to adhere to the DeLury difference equation because it is generally recognized that large variability exists in abundance indices from research surveys. In essence, increasing the process error weights (e.g., 2x) relative to the measurement errors results in a “smoothing effect” of estimated fishing mortality rates over time, although care must be taken not to over-smooth. The percent sums of squares (%SS) attributable to the DeLury process was already relatively low at 28% in the base run with equal weighting (unity) of the measurement and process errors. This indicated that the DeLury model depicted the population dynamics of Delaware Bay blue crabs fairly well given the inherent variability in the recruit and fully-recruited abundance indices. Different statistical weights were assigned to the process error (2x and 0.5x relative to measurement error) in an attempt to explore the sensitivity of the model to different weights. As expected, increasing the process error weight twice the measurement error (2x) resulted in %SS that were roughly half the base run, while decreasing the process error weight (0.50x) almost doubled %SS (Table 8). Time trends in total mortality and stock sizes were relatively insensitive to different process error weights. The magnitude of Z (average Z 's nearly equal) and stock sizes were, however, moderately affected. This would be expected since decreasing weight on the process error results in less smoothing of estimated mortality rates over the time series.

Retrospective Analysis

A retrospective analysis of the modified DeLury model was performed in order to evaluate whether the model propagates a systematic inconsistency of terminal years estimates of mortality and/or stock size. Error propagation of this sort has been observed in other analytical fishery models which use nonlinear process equations such as ADAPT (Mohn 1993). The retrospective analysis was performed by sequentially re-running the DeLury model on catch and abundance data that was truncated by deleting one year from the time series; fitting the model to 1978-1999, 1978-1998, 1978-1997, etc. To evaluate the retrospective pattern, we truncated the time series up to 6 years and examine the estimates of total mortality (Z). Terminal mortality estimates were quite stable and consistent in most years, particularly further back in time (Figure 21). In some years (1991-1993), mortality estimates were slightly underestimated for each retrospective run compared to the base year (1999). However, estimates of mortality were not consistently underestimated and for those years in which it was (e.g. 1991-1993) Z never differed by more than around 5-7%.

In summary, the reported level and temporal pattern of mortality and stock size estimates are robust to the assumptions evaluated in the sensitivity analysis. The base run ($M=0.80$, $S_r=1.0$, equal weights) was therefore chosen as the most probable to represent the population dynamics of Delaware Bay blue crabs. Down-weighting the process errors would not be appropriate because it is not likely that the process errors are greater than the survey measurement errors. Further, there is no exogenous or *a priori* reason for a relative selectivity value other than 1.0 as recruits and fully-recruited crabs are likely to be equally vulnerable to the survey gear. Retrospective analysis of the DeLury model applied to Delaware Bay blue crab also suggests that terminal year estimates are robust with regard to systematic biases.

BIOLOGICAL REFERENCE POINTS

Yield and SSB-Per-Recruit Analyses

Yield and spawning stock biomass per recruit were performed using the methods of Thompson

and Bell (1934) and the results super-imposed on blue crab recruitment patterns to generate biological reference points for the maintenance of spawning stock biomass (Gabriel et al. 1989). The structure of yield and SSB per recruit simulations included: 1) ages 0 through 3 with age 3 the terminal year (not plus group), 2) range of fishing mortality rates ranging from 0 to 2.0 by increments of 0.1, 3) three different sets of growth parameters (derived from MULTIFAN) to evaluate sensitivity to blue crab growth, and 4) a Mixed Monte Carlo-Bootstrap simulation to evaluate sensitivity and variances of reference points to uncertainty in M. Model input for yield and SSB analysis consisted of a fishery partial recruitment pattern, mean weights at age in the fishery and stock, proportions of crabs mature at age, and an estimate of natural mortality (M).

Age-specific partial recruitment of blue crabs to the fishery was estimated based on length frequency data from at-sea sampling of the pot fishery, minimum size regulations, and the relative contributions of each harvest category to total landings in number. The dredge fishery has not been sampled and was therefore not included in the analysis. For this analysis, we assumed that the Delaware at sea length frequency samples were representative of the fishery as a whole. Length frequency samples of male hard crab, female hard crab and peelers were collected from the Delaware commercial catch from 1994-1997; these represent the three different market categories in the commercial harvest. Since these samples represent the uncultured portion of the catch, length frequency distributions by percent were calculated on the basis of samples greater than 120 mm which corresponds to the minimum crab size in New Jersey. While Delaware's minimum crab size is 127 mm, we suspect the results will be virtually unaffected by the minor difference in legal sizes. Percentages by length for each category were then multiplied by the total number of crabs harvested in each market category over the same period of the L-F samples (1994-1997) and then divided by the grand total (in number) taken in the commercial pot fishery. Percentages were then summed by length and across each market category and the cumulative frequency generated over the entire length sample (Figure 22). Here we assume that cumulative percent of the total catch for each length category is proportional to the relative amount of fishing mortality on each size. Based on the expected growth for each age (Figure 2) the partial recruitment was taken as the value corresponding to the greatest carapace width attained for each age. The PR was 0.42 and 0.90 for ages 0 and 1, respectively, and 1.0 for ages 2 and greater.

Development of female blue crab maturity schedules were calculated using a similar approach as blue crab in the Chesapeake Bay (Rugolo et al. 1998) based on maturity at size ogive weighted by the percentage of research survey catches by size within an assumed age class. The predicted maturity ogive and the research survey size composition, given earlier in this document (Figure 3), was used for this procedure. Based on weighting these percentages mature for each 5 mm increment by percentages of research survey catches for the same years, and the expected growth from the von Bertalanffy growth equations (Figure 2), we found the proportion mature at age 0 (0-130 mm) to be low at 10%. Applying the same procedure to ages 1 and greater, we calculated the proportion mature at age 1 to be 90% and 100% for ages 2 and above. Unlike the “dome-shaped” maturity schedule developed for the Chesapeake Bay, we assumed that for Delaware Bay blue crab that live to only three years the maturity schedule increases with age, but does not decline.

Mean weights at age in the catch and the stock were calculated using predicted lengths from the von Bertalanffy growth parameters derived from MULTIFAN and the sex-specific weight-at-carapace width equations of Rothschild and Ault (1992). Individual weights have not been collected from the commercial catch or research surveys in Delaware Bay. Since the commercial harvest consists of both sexes, we used the weight-at-width parameters for the sexes combined to generated yield per recruit as a function of fishing mortality rates:

$$W_g = 0.00081636 * CW^{2.430}$$

However, since SSB per recruit, percent maximum spawning potential (%MSP), and the index of blue crab spawning stock (used in the S-R plots) are based on female weights, we applied the female-specific weight-at-width parameters to calculate stock weights:

$$W_g = 0.003486 * CW^{2.1165}$$

We did not examine sensitivity of yield and SSB per recruit to different functional relationships between weight and carapace width. However, the calculated weights varied based on the three different scenarios of growth derived from MULTIFAN: 1) $K=0.75$, $L_\infty = 234.7$; 2) $K=0.62$, L_∞

= 200.6; and 3) $K=0.93$, $L_{\infty} = 200.3$. A recent study using lipofuscin accumulation rates as a measure of blue crab age in Chesapeake Bay (Ju et al. 1999) indicates that blue crab growth is close to the $K=0.75$ scenario (Ju et al. 2000).

The estimate of natural mortality (M) is probably the most uncertain parameter used as input for Delaware Bay blue crab yield and SSB per recruit modeling. The effects of varying M on yield and SSB per recruit are somewhat predictable, at least in a directional sense; higher M results in a lower absolute value of Y/R , a Y/R curve which is "flat-topped" and reference points such as F_{MAX} are shifted to higher values of F . The effects of different values of M on the distributional properties of reference points calculated from yield and SSB per recruit analyses are less predictable. Therefore, we chose to incorporate a Monte Carlo simulation into the structure of the model to evaluate the variances of biological reference points. For this, we simply re-ran the yield and SSB per recruit analysis for each realization of a value of M which was generated randomly from a triangular distribution. For each of these distributions, 1000 values of M were generated from a possible range of values approximately from 0.40 to 1.2 with a most likely value of 0.8. This range roughly encompasses the value of M reported for the Chesapeake Bay and the value estimated by regression of total mortality (Z) on fishing effort (Figure 13) in this document.

Results of the yield and SSB per recruit analyses are shown in Figure 23 with detailed model output/input given in Appendix C. Fishing mortality rate-based reference points from yield per recruit results such as F_{MAX} and $F_{0.1}$ varied moderately, but systematically depending on choice of growth parameters (Appendix C). The value of F_{MAX} increased from 1.0 to 1.30 and $F_{0.1}$ ranged from 0.60 to 0.7 as the value of the von Bertalanffy growth parameter K decreased (Figure 23). Yield per recruit at F_{MAX} ranged from 0.021 to 0.030 Kg/recruit. Reference points based on SSB per recruit calculations such as percent maximum spawning potential (%MSP) also varied with differing growth rate scenarios. Fishing mortality rates at 20% MSP (F_{20}) ranged from 1.16 to 1.23. F_s at 10% MSP (F_{10}), a commonly used fishing targets in crustacean fisheries, were all in excess of 1.8-1.9 for our analyses. We believe the F -based reference points calculated from growth scenario 1 of $K=0.75$ and $L_{\infty} = 234.7$ ($F_{MAX} = 1.0$, $F_{0.1} = 0.60$) are the most realistic given recent blue crab lipofuscin accumulation rate studies by Ju et al. (1999). Reference point

calculations from this analysis are somewhat higher than those estimated for Chesapeake Bay blue crab ($F_{MAX}=0.64$, $F_{0.1}=0.36$) by Rugolo et al. (1998). While our yield per recruit formulation differed in terms of the cohort's life span, growth and the value of M , the greatest influences affecting the differences in reference points are probably due to our choice of growth rate and M estimates. These imply that higher fishing mortality rates are needed to achieve maximum yield to offset foregone yields due to natural mortality.

SSB-per-Recruit and Stock-Recruitment Analysis

Results of the SSB per recruit analysis were coupled with research index-based stock and recruitment plots for Delaware Bay blue crab to generate biomass-based reference points needed for stock enhancement or replacement. For this analysis, we used the research survey index-based stock biomass and recruitment data given by Kahn et al. (1998), but updated their analysis through the 1997 year class. This analysis is based on the concept that under a given fishing pattern (F and recruitment pattern to the fishery), the value of SSB/R from yield per recruit analysis can be superimposed as a line on the standard stock-recruitment plot which has a slope equal to the inverse of (SSB/R) and an intercept of zero (Shepherd 1982; Gabriel et al. 1989). A common reference point from this analysis is F_{MED} or F_{REP} (Sissenwine and Shepherd 1987) which, for a certain fishing mortality rate, generates a line that bisects the standard S-R plot (i.e., equal number of recruitment points on each side of the line). The fishing mortality rate F_{REP} defines the fishing pattern for which, on average, adequate recruitment was generated from the stock to replace the stock biomass lost due to mortality; therefore, stock biomass and recruitment theoretically stabilize. Other reference points of this type such as F_{LOW} and F_{HIGH} (Anon. 1984, 1985) can also be calculated from this analysis; these define stock and recruitment plot lines that leave 90% and 10% of the points above the line, respectively. As per the convention used in the Chesapeake Bay blue crab assessment (Rugolo et al. 1998), we define F_{LOW} and F_{HIGH} to represent 75% and 25%, respectively.

Based on growth scenario 1 ($K=0.75$ and $L_{\infty}=234.7$), the median line which bisects the blue crab S-R plot is shown in Figure 24 along with a Ricker model fit to the same data. The replacement value of F (F_{REP}) for the S-R analysis was estimated to be 1.3. The slope of this line

corresponds to the inverse of the value of SSB/R of 0.014 (kg/R) (See Appendix C). Also shown on the S-R plot is $F_{0.1}$ (0.60) which was roughly equal to F_{LOW} (0.50), indicating that 75% of the recruiting year classes were more than sufficient to replace the spawning stock lost due to all sources of mortality. The value of F_{HIGH} (25% of recruitment points above line) for this growth assumption was calculated to be 1.9, which was similar to $F_{10\%}$. It seemed unlikely to us that a value this high would be useful as a maximum fishing rate threshold since at this level the survival ratios are low, increasing the likelihood of poor recruitment. Therefore the reference points F_{HIGH} and $F_{10\%}$ were not considered for further analysis concerning differing growth assumptions. Also, since the values F_{LOW} and $F_{0.1}$ were nearly identical, we only examined the sensitivity of F_{REP} to differing growth scenarios. As with the other reference points generated from yield per recruit, F_{REP} varied with different growth assumptions as well (Figure 23). The value of F_{REP} increased as a function of increase in growth rate, ranging from 1.1 to 1.4.

UNCERTAINTY ANALYSIS

Incorporation of Uncertainty into BRPs

Management of fish stocks at sustained and productive levels requires the development of biological reference points that define limits beyond which stocks can not be exploited or targets about which exploitation is expected to fluctuate. Biological reference points defined as limits and targets can be developed both in terms of fishing mortality rates or biomass levels. For the Delaware Bay blue crab stock, Helser and Kahn (1999) proposed a limiting fishing mortality rate threshold, known as the replacement fishing mortality rate (F_{REP}), to define the recruitment overfishing threshold. The fishing mortality rate F_{REP} defines the fishing pattern for which, on average, adequate recruitment was generated from the stock to replace the stock biomass lost due to mortality; therefore, stock biomass and recruitment theoretically stabilize. This concept was first developed by Sissenwine and Shepherd (1987) who showed that biologically meaningful reference points could be generated from combining spawning per recruit analysis and stock-recruitment data. Sissenwine and Shepherd (1987) proposed estimating F_{REP} from the median survival ratio from stock-recruitment data.

We used this approach to generate the replacement fishing mortality rate for the threshold biological reference point for blue crab (Helser and Khan, 1999). Based on the original stock-recruitment data set, an estimate of F_{REP} can be derived by estimating median survival ratio R/SSB , taking its inverse (SSB/R) and finding a corresponding F value from equilibrium SSB/R curve as a function of fishing mortality. This, however, only provides one realization of F_{REP} based on the original stock-recruitment data. Since we wanted to quantify the uncertainty in the estimate of F_{REP} corresponding to the median survival ratio through the simulation of multiple S-R data sets we employed a blue crab population projection model. The conceptual basis for this approach is that while uncertainty is incorporated into yield and SSB-per-Recruit analyses through variable M , the projection model attempts to capture the uncertainty and inherently stochastic nature of the stock's dynamics through time. The SSB/R and S-R projection model were structurally linked through random values of natural mortality drawn from the triangular distribution and seeded into both analyses simultaneously. The output from the projection model contained 1000 data sets each with 19 pairs of simulated S-R observations, thus allowing estimation of 1000 values of the median survival ratio and corresponding values of SSB/R . Then coupling these S-R realizations with standard SSB-per-Recruit analysis 1000 realizations of F_{REP} could be generated.

Survival Ratios From Simulated S-R Data

Survival ratios (R/S) are estimated from stock-recruitment (S-R) data and when coupled with a spawning stock biomass-per-recruit analysis, are used to derive a reference point known as the fishing replacement level (F_{REP}). This section deals specifically with the S-R data used in this analysis and how uncertainty was incorporated. Rather than simply bootstrapping the residuals from the original S-R values estimated from the Catch-survey model to generate survival ratios we chose to use a stochastic projection model for blue crab. This procedure attempted to capture the inherent stochastic nature of the process which originally generated the S-R data by incorporating uncertainty in the form of variable M (triangular distribution) and two sources of uncertainty associated with the stock-recruitment data. The projection model depended on input sets of Ricker model parameter estimates that were generated from a conditioned nonparametric bootstrap. First, the Ricker model (1957) was fit to the original blue crab S-R data estimated

from the catch-survey model using nonlinear least squares in SAS (1985) with additive normal error structure. For this analysis, the index based stock and recruitment data was scaled to absolute values using the survey catchability coefficient estimated from the catch-survey model. The bootstrap procedure was then applied by randomly resampling model residual errors with equal probability and adding these at random to the predicted values of recruitment from the Ricker S-R model to generate 1000 new psuedo data sets each consisting of 19 new stock and recruitment realizations. Finally, the Ricker model was then re-fit to the 1000 new psuedo-replicated data sets to generate 1000 realizations of the Ricker S-R parameters. The projection model used sets of 1000 random (α^* β^*) pairs of the Ricker model parameter estimates rather than single realizations from univariate distributions to maintain the covariance structure of the parameters.

For the stochastic projection model, the blue crab population abundance can be represented as the vector $N(t)$,

$$N(t) = \begin{bmatrix} N_0(t) \\ N_1(t) \\ N_2(t) \\ N_3(t) \end{bmatrix} \quad (13)$$

where $N_a(t)$ was the number of age- a crabs alive at the beginning of the year. Here we assumed that crabs do not live past their third year and therefore a plus group was not used to accumulate survivors after that age. To describe annual survival through mortality, let M_a denote the constant instantaneous natural mortality rate and let $F_a(t)$ denote the instantaneous fishing mortality rate for age- a crabs in year t of the 19-year time horizon. For the projection analysis, a value of M was drawn randomly from a triangular distribution centered on $M=0.80$ (range 0.60 to 1.0) and used for each of the 1000 19-year time trajectories. The population size at age in year t is given by

$$N_a(t) = N_{a-1}(t-1) \cdot e^{-M_{a-1} - F_{a-1}(t-1)} \text{ for } a=0 \text{ to } 3 \quad (14)$$

Population sizes at age from initial year estimates (1979) of the catch-survey model were seeded into the projection model and served as the starting conditions. Since the catch-survey model provides only recruit (age 0) and fully-recruited (age 1-3) stock size estimates, population sizes for age 1-3 were decomposed into individual ages using the above equation and the estimated F for that year and $M=0.80$. The vector of year-specific F s estimated from the catch-survey model was used for each subsequent year in 19 year projection.

The numbers of new recruits which enter the fishery at age 0 (1 year after hatching) at the beginning of each year, are determined as a function of spawning biomass with some stochastic elements. The spawning stock biomass in year $t-1$ that produced recruits in year t is

$$SSB(t) = \sum_{a=1}^7 W_{s,a} V_a N_a(t) e^{-p[M_a + F_a(t)]} \quad (15)$$

where: $SSB(t)$ is the sum over all age classes of the weight of mature crabs at the midpoint of the spawning season; V_a is the fraction of age- a crabs that are mature; $W_{s,a}$ is the average weight of an age- a crab; and p is the average fraction of total annual mortality that occurs from January 1st to the mid-point of the spawning season.

The Ricker model was used for simulating recruitment, where survival to recruitment age is a function of SSB with a density-dependent or compensatory response, subject to stochastic variation. This stochastic variation incorporates two sources of uncertainty. The first arises from the fact that the functional form of the Ricker model is ill defined because there were only 19 original S-R data points for the blue crab stock with which to estimate the parameters. Therefore, random realizations of pairs of Ricker parameter estimates (α^* β^*) generated from the bootstrap were used to characterize the “family” of possible functional forms of Ricker S-R model:

$$R_0(t) = a^* \cdot SSB(t-1) \cdot e^{-b^* \cdot SSB(t-1)} \quad (16)$$

We then simulated environmental disturbances which added variability about the expected S-R relationship from each particular random set of parameters. This random noise component to the recruitment function was added using:

$$N_0(t) = R_0(t) + N(\mu, \sigma^2) \quad (17)$$

where μ is randomly drawn value from normal distribution with mean equal to 0 and variance equal to the 58% of the mean square error (MSE) from the Ricker fit to the original S-R data. Since the original fit of the Ricker model explained 42% of the variability in R through SSB, we attributed the remaining 58% to environmental variability. We did not explicitly consider serial autocorrelation in fitting the stock-recruitment data or correct for it in projections, although weak evidence for it existed (i.e., Durbin-Watson test statistic = 1.796., $p < 0.10$). Positive autocorrelation in time series data produces nominal variances about parameter estimates that are smaller than they should be (Bence 1995). Its impact on the simulation results would lead to increased variability than expected. Finally, median survival ratios (R/SSB) were estimated for each of the simulated time series of spawning stock biomass and recruitment values and SSB/R estimates obtained from the reciprocal of the survival ratios.

Development of F_{REP} Probability Distribution

Results of the SSB per recruit analysis were then coupled with standard stock and recruitment plots for Delaware Bay blue crab to generate biomass-based reference points needed for stock enhancement or replacement. Under a given fishing pattern (F and recruitment pattern to the fishery), the value of SSB/R from yield per recruit analysis can be superimposed on the standard stock-recruitment plot as a line which has a slope equal to the inverse of (SSB/R) and an intercept of zero (Shepherd 1982; Gabriel et al. 1989). A common reference point from this analysis is F_{REP} or F_{REP} (Sissenwine and Shepherd 1987) which, for a certain fishing mortality rate, generates a line that bisects the standard S-R plot (i.e., equal number of recruitment points on each side of the line). Other reference points of this type such as F_{LOW} and F_{HIGH} (Anon. 1984, 1985) can also be calculated from this analysis; these define stock and recruitment plot lines that leave 90% and 10% of the points above the line, respectively. The output of the projection model contained 1000 data sets, each with

19 pairs of simulated S-R observations, thus allowing estimation of 1000 values of the median survival ratio and corresponding values of F_{REP} . The frequency distribution of F_{REP} was treated as a probability distribution of F_{REP} as a biological reference point, which could be compared with the probability distribution of the terminal fishing mortality estimate.

Stochastic Decision-Based Framework

The stochastic decision-based framework attempts to capture the fact that there is uncertainty in both the estimates of terminal fishing mortality rate (F_t) and replacement fishing mortality rate (F_{REP}) by using the empirical distributions of these quantities generated from the uncertainty analysis. Specifically, we desired to provide a decision as to whether $F_t > F_{\text{REP}}$ in the form of a probability statement, i.e., $\Pr(F_t > F_{\text{REP}})$. Probability statements of this type can be easily estimated using the empirical distribution of F_t and the deterministic (expected) value of F_{REP} which is typically done in many assessments. However, uncertainty in F_{REP} remains uncharacterized. Therefore, we proposed a second tier probability statement which specifies the condition $\Pr(F_t > F_{\text{REP}})$ for a given decision confidence (%) calculated from the empirical distribution of F_{REP} . Figure 2 gives a conceptual illustration for calculating the $\Pr(F_t > F_{\text{REP}})$ for various decision confidence levels (%) from two hypothetical probability density functions of F_t and F_{REP} , as well as the resulting probability profile. The decision confidence level can be thought of as a one-tailed α -probability from standard statistical hypothesis testing. Therefore, at the value of F along the domain of the x-axis (top graph) where the probability level $\alpha = 90\%$ (10% of the area under the F_{REP} PDF), the corresponding area under the F_t PDF gives the $\Pr(F_t > F_{\text{REP}})$. Thus, for each decision confidence level there is a corresponding $\Pr(F_t > F_{\text{REP}})$ which forms a probability profile (lower graph). For instance, a statement such as, there is an 80% confidence level that $\Pr(F_t > F_{\text{REP}}) = 0.80$ provides strong evidence of overfishing.

The empirical probability distribution of median survival ratios (R/S) generated from 1000 simulated S-R scatter plots is shown in Figure 25. This distribution, as well as its inverse function (S/R), is clearly log-normally distributed (Figure 25). For the simulated S-R data, median survival ratios ranged from roughly 20 to 100 recruits/Kg spawners, with a median value of 55. When the inverse is taken, these survival ratios translate into median S/R values ranging from 0.010 to 0.05 Kg S/R,

with a median value of 0.020 (Figure 25). Finally, coupling these realizations of S/R generated from the simulated S-R data with spawning stock biomass-per-recruit analysis, the median fishing mortality rate at replacement (F_{REP}) can be found for each realization. Figure 25 illustrates the full extent of uncertainty captured in this analysis showing the empirical distribution of S/R realizations from the simulated S-R data superimposed on the standard SSB-per-recruit graph. Variability in the estimate of natural mortality was incorporated into both the SSB-per-recruit analysis and in simulating the S-R data. Thus, confidence intervals around yield and SSB-per-recruit curves shown in Figure 25 illustrate the extent that uncertainty in M effect the model output. The point where the expected value of S/R from the S-R realizations intersects the expected value of S/R from the SSB-per-recruit analysis, is an estimate (not necessarily the expected value) of the replacement fishing mortality rate (F_{REP}).

The most cogent aspect of this analysis is not the point estimate but rather the empirical probability distribution of the replacement fishing mortality rate. The probability distribution of the replacement fishing mortality rate (F_{REP}) is provided in figure 26 in concert with the terminal year fishing mortality rate ($F_{97.99}$). Considerably uncertainty exists in the estimation of F_{REP} , with the empirical probability distribution negatively skewed and values ranging from 0.5 to 2.1. In contrast, the probability distribution for the terminal year fishing mortality rate is positively skewed with values ranging from 0.7 to 1.8. If the deterministic approach were used to evaluate status of the stock by comparing say median values, it would be concluded that F_t is substantially below F_{REP} and therefore the stock is not at risk. However, without characterizing the uncertainty in both estimates through development of their probability distributions (which overlap significantly) our level of confidence in that decision would be largely unquantifiable. Thus, the probability profile shown in figure 26 calculates for each level of decision confidence (i.e., 90%, 80%, 70% based on the empirical F_{REP} PDF), the $\Pr(F_t > F_{REP})$. As an illustration, at the 80% decision confidence level, which is the value of F corresponding to the upper 20% of the F_{REP} PDF, the $\Pr(F_{95.97} > F_{REP}) = 0.14$. Thus, with high confidence (80%) it would be concluded that the Delaware Bay blue crab stock is not currently being overfished.

FISHING TARGETS AND OVERFISHING THRESHOLDS

In this section we define and develop fishing targets and overfishing thresholds to manage the Delaware Bay blue crab stock. A distinction should be made between the use of these two definitions in that the former defines a target about which fishing activity is expected to fluctuate while the latter defines a threshold that should generally not be crossed (Rosenberg et al. 1994). For the Delaware Bay stock of blue crab, an overfishing threshold based on recruitment overfishing (e.g. S-R data) may be difficult to estimate due to the limited number of years for which indices of spawning stock biomass and recruitment are available from the Delaware research trawl survey as well as the uncertainty in these data themselves. Stock and recruit data may be strongly affected by environmental conditions which often obscure the functional relationship of the effects of exploitation on stock size and recruitment. The uncertainty in these data are illustrated by the fact that recruitment indices for 1978, 1981, 1983 and 1996 were associated with zero female spawning biomass indices in the previous year. This implies that spawning stock biomass may be imprecisely measured in the survey. From the analysis, F_{rep} was calculated to be 1.3 (reciprocal of $SSB/R=71.4$ R/kg) which we tentatively adopt as a recruitment overfishing threshold. Alternatively, $F_{20\%}=1.1$, could also be used. These reference points should be considered risk averse given the that $F_{10\%}$ (1.9) is a commonly used threshold for crustacean fisheries. These estimates should be considered preliminary pending more definitive estimates of blue crab growth rates and additional years of S-R index data from the research survey.

As stated earlier, a threshold is a measure which should not be exceeded. Doing so increases the likelihood of driving the spawning biomass to dangerously low levels that may result in recruitment failure. In contrast, the fishing target is a level of fishing considerably below the overfishing threshold about which the fishery may fluctuate in an effort to obtain long-term sustainable yields from a stock subject to fluctuating recruitment. Based on yield and SSB-per-recruit considerations, we recommend a fishing target somewhere between $F_{0.1} = 0.6$ and $F_{MAX} = 1.0$. Given the shape of the yield-per-recruit response to fishing mortality (Figure 25), there would be little yield to gain by fishing above $F_{MAX}(=1.0)$, while the potential consequences of a fishing target above that level could result in depleting spawning biomass ($F_{REP}=1.3$). An appropriate interim fishing mortality target would be an F of 0.93 (Average F_N over 1989-1999 period). Fishing mortality rates over this period

corresponded to a landings and stock biomass trajectory that was relatively stable, averaging approximately 8-10 million pounds and 16-18 million pounds, respectively.

DeLury estimates of exploited biomass also appeared to have been relatively stable over the 1990 to 1999 period. Determination of potential stock biomass levels, however, is uncertain. While recent biomass levels are high relative to the 1978-1999 time series over which it was estimated and measured by the survey index, we have a poor historical perspective on the levels of biomass prior to the severe 1977-78 winters.

Based on these analyses, we believe the Delaware Bay blue crab stock is fully exploited and at moderate levels of stock biomass. Therefore, increases in fishing effort should be avoided and fishing activity which differentially targets maturing females discouraged. To some extent, caps on fishing effort has already occurred through limited entry regulations. License sales in New Jersey were capped in 1993. Delaware license sales were limited in 1991, but the cap did not become fully effectively until new legislation 1995. Effort could still increase, however, through latent effort with crabs pot currently not in use by watermen.

RESEARCH RECOMMENDATIONS

1) New Jersey research survey data (in terms of quality and quantity) should be evaluated in an effort to improved the spatial coverage of blue crab in Delaware Bay. The current stock assessment is predicated on the assumption that the Delaware research trawl survey data, which covers only the western portion of the Bay, is representative of the population as a whole. Changes in blue crab distribution patterns may in part be responsible for what is interpreted as changes in abundance. In addition, individual blue crab lengths and weights should also be routinely collected in the research trawl surveys

2) Catch and effort data from the commercial log book collection program, particularly from New Jersey, needs to be evaluated for quantity and quality. Reliability of the log book data should be evaluated relative to an intercept survey. Currently, effort information is unreliable and attempts should be made to gather appropriate information to measure effective effort in the pot fishery. The

levels of recreational harvest of blue crab in the Delaware Bay, particularly in New Jersey, should also be estimated.

3) Blue crab life history information:

A. Sex specific growth rates should be evaluated for blue crabs. Differences in growth between the sexes is one factor that may have contributed to the difficulty of estimating growth from length-frequency samples by obscuring modes in the data. Therefore, MULTIFAN should be applied to width frequencies by sex. More importantly, improved techniques such as tagging experiments with markers that are retained through the molt need to be conducted to derive estimates of molt probability, molt increments, and lifespan for each sex.

B. Sexual maturity information of blue crab in the Delaware Bay need to be augmented. Sexual maturity by length category should be collected in both Delaware and New Jersey research trawl surveys during the early spring and into the summer. Frequency and duration of spawning activity as well as longevity should also be evaluated in the field using tagging experiments.

4) At sea sampling of the commercial fishery should be conducted to acquire information on length frequency distributions and individual weights of the harvest. As a general rule, samples consisting of 100 individual lengths and weights of blue crab should be collected monthly and by market category. At sea sampling should also be aimed at evaluating the extent of discarding and survival in the pot and dredge fishery

5) Analytical models applied to the sexes separately should be investigated since catches can be partitioned by sex and exploitation patterns appear to differ between males and females. Females can be harvested as soon as they mature (~5% maturity at 115 mm CW), but males are managed strictly by minimum legal sizes (120 or 127 mm). Such differences may be substantial enough to alter some of the signals in the survey or catch data. In addition, growth differences may be substantial enough to change reference points.

6) Fishery management control laws based on a quantitative objective function which incorporates risk should be evaluated within the framework of simulation studies. Simulations can be conducted which incorporate size-structured population dynamics, stock-recruitment and growth models to

evaluate the effects of various management strategies on fishery performance in general, and on the effects of management actions that are to be taken if overfishing thresholds are crossed.

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Table 1. Delaware blue crab commercial licenses issued for the crab pot and dredge crab fisherys, 1975-1999. The shellfish license year begins on May first and extends through April of the following year.

SEASON	CRAB POT LICENSES	DREDGE LICENSES	TOTAL LICENSES	PERCENT CHANGE PREVIOUS YR.
1975	91	12	103	-
1976	106	22	128	24.3%
1977	66	26	92	-28.1%
1978	40	0	40	-56.5%
1979	45	0	45	12.5%
1980	67	10	77	71.1%
1981	56	0	56	-27.3%
1982	53	5	58	3.6%
1983	60	5	65	12.1%
1984	70	5	75	15.4%
1985	77	6	83	10.7%
1986	102	12	114	37.3%
1987	111	15	126	10.5%
1988	126	5	131	4.0%
1989	132	22	154	17.6%
1990	172	31	203	31.8%
1991	169	16	185	-8.9%
1992	164	30	194	4.9%
1993	184	23	207	6.7%
1994	219	42	261	26.1%
1995	219	42	261	0.0%
1996	219	40	259	-0.8%
1997	214	40	254	-1.9%
1998	214	17	231	-9.1%
1999	214	37	251	8.7%

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Table 1. Commercial blue crab licenses issued statewide by the New Jersey Division of Fish, Game and Wildlife, 1990-1998. Licenses are issued annually and the season is on a calendar year basis (Jan-Dec).

License Year	Commercial Crab Pot	Commercial Crab Dredge	Total Licenses	Percent Change Previous Yr.
1990	311	166	477	-
1991	312	133	445	-6.7%
1992	365	209	574	29.0%
1993	420	289	709	23.5%
1994	506	222	728	2.7%
1995	458	280	738	1.4%
1996	430	301	731	-0.9%
1997	408	378	786	7.5%
1998	170	19	189	-76.0%
1999	130	2	132	-30.2%

Note: Beginning in 1997 the New Jersey commercial blue crab dredge fishery was licensed by water body. There were 289 licenses issued for the Atlantic coast and 89 for the Delaware Bay.

Table 3. Annual harvest of peeler crab from the Delaware and New Jersey commercial blue crab pot fisherys operating in the Delaware Bay Estuary, 1978-1998.

Season	Delaware Number of Peeler Blue Crab	New Jersey Number of Peeler Blue Crab	Combined Number of Peeler Blue Crab	Delaware Pounds of Peeler Blue Crab	New Jersey Pounds of Peeler Blue Crab	Combined Pounds of Peeler Blue Crab
1978	7,589	90,720	98,309	1,581	18,900	20,481
1979	269,957	112,320	382,277	56,241	23,400	79,641
1980	138,576	71,520	210,096	28,870	14,900	43,770
1981	267,939	214,080	482,019	55,821	44,600	100,421
1982	65,870	38,880	104,750	13,723	8,100	21,823
1983	55,852	73,440	129,292	11,636	15,300	26,936
1984	183,131	135,360	318,491	38,152	28,200	66,352
1985	177,709	479,069	656,778	37,023	99,806	136,829
1986	495,590	428,160	923,750	103,248	89,200	192,448
1987	294,687	353,280	647,967	61,393	73,600	134,993
1988	753,646	1,119,360	1,873,006	157,010	233,200	390,210
1989	556,905	790,858	1,347,763	116,022	164,762	280,784
1990	936,492	1,411,800	2,348,292	195,103	294,125	489,228
1991	112,406	180,710	293,116	23,418	37,648	61,066
1992	2,120,935	1,565,472	3,686,407	441,861	326,140	768,001
1993	909,175	730,925	1,640,100	189,411	152,276	341,687
1994	1,463,229	1,642,651	3,105,880	304,839	342,219	647,058
1995	2,486,463	3,661,752	6,148,215	518,013	762,865	1,280,878
1996	1,056,993	691,522	1,748,515	220,207	144,067	364,274
1997	464,297	977,400	1,441,697	96,729	203,625	300,354
1998	932,927	1,985,172	2,918,099	194,360	4,565,896	4,760,256
1999	453,653	1,142,696	1,596,349	94,520	2,628,829	2,723,349

Table 4. Harvest of female blue crab, in bushels, from the Delaware commercial blue crab dredge and crab pot fisherys operating in the Delaware Bay Estuary, 1984-1998.

Season	Crab Pot Fishery		Dredge Crab Fishery		Combined Harvest Delaware Commercial Female Blue Crab Harvest
	Bushels of Hard Female Blue Crab	Bushels of Female Peeler	Bushels of Hard Female Blue Crab	Bushels of Female Peeler	
1984	6,123	610	2,000		8,733
1985	15,397	592	2,326		18,315
1986	19,156	1,652	9,297		30,105
1987	24,867	982	16,400		42,249
1988	23,623	2,512	17,507		43,642
1989	43,289	1,856	26,211		71,356
1990	34,382	3,122	25,218		62,722
1991	57,480	375	12,845		70,700
1992	26,905	7,070	1,091		35,066
1993	47,919	3,031	33,624		84,574
1994	33,537	4,877	19,325		57,739
1995	41,042	8,288	23,796		73,126
1996	21,599	3,523	25,649		50,771
1997	43,276	1,548	26,603		71,427
1998	29,597	3,110	8,201		40,908
1999	27,947	1,436	21,691		51,074

Table 5. Delaware hard crab landings, in pounds of edible meat, from the commercial crab pot and dredge fisherys, 1975-1997.

Season	Crab Pot Fishery Harvest	Dredge Crab Fishery Harvest	Combined Harvest	Percent Change Previous Yr.
1975	2,655,000	304,000	2,959,000	-
1976	2,361,560	609,320	2,970,880	0.4%
1977	379,000	387,400	766,400	-74.2%
1978	277,920	-	277,920	-63.7%
1979	427,040	-	427,040	53.7%
1980	583,333	188,800	772,133	80.8%
1981	730,560	-	730,560	-5.4%
1982	679,480	87,800	767,280	5.0%
1983	971,360	8,000	979,360	27.6%
1984	840,760	87,600	928,360	-5.2%
1985	2,677,488	102,960	2,780,448	199.5%
1986	2,170,840	418,320	2,589,160	-6.9%
1987	2,682,480	685,960	3,368,440	30.1%
1988	2,515,760	767,160	3,282,920	-2.5%
1989	3,693,760	1,089,760	4,783,520	45.7%
1990	5,220,080	1,099,920	6,320,000	32.1%
1991	4,464,600	541,720	5,006,320	-20.8%
1992	3,761,960	46,080	3,808,040	-23.9%
1993	4,549,320	1,464,520	6,013,840	57.9%
1994	4,121,240	813,025	4,934,265	-18.0%
1995	5,286,280	969,400	6,255,680	26.8%
1996	2,697,852	1,083,131	3,780,983	-39.6%
1997	3,664,684	1,187,833	4,852,518	28.3%

Note: One bushel of blue crabs yields 40 pounds of edible crab meat.

Table 6. New Jersey hard crab landings from the Delaware Bay Estuary, in pounds of edible meat, from the commercial blue crab pot and dredge fisheries, '1978-1999

Season	Crab Pot Fishery Harvest	Dredge Crab Fishery Harvest	Combined Harvest	Percent Change Previous Yr.
1978	808,200	0	808,200	-
1979	617,100	0	617,100	-23.6%
1980	1,062,900	14,700	1,077,600	74.6%
1981	1,003,400	0	1,003,400	-6.9%
1982	507,200	0	507,200	-49.5%
1983	815,900	0	815,900	60.9%
1984	1,223,600	4,000	1,227,600	50.5%
1985	1,848,200	68,700	1,916,900	56.2%
1986	1,748,900	230,100	1,979,000	3.2%
1987	1,625,400	540,500	2,165,900	9.4%
1988	2,218,300	491,100	2,709,400	25.1%
1989	2,355,594	486,800	2,842,394	4.9%
1990	2,482,860	288,580	2,771,440	-2.5%
1991	2,571,280	189,780	2,761,060	-0.4%
1992	3,314,080	126,200	3,440,280	24.6%
1993	3,636,360	734,350	4,370,710	27.0%
1994	2,746,555	221,330	2,967,885	-32.1%
1995	4,160,300	412,350	4,572,650	54.1%
1996	1,590,300	367,742	1,958,042	-57.2%
1997	2,157,912	143,850	2,301,762	17.6%
1998	3,452,912	83,520	3,536,432	53.6%
1999	3,210,040	*		

Note: One bushel of blue crabs yields 40 pounds of edible crab meat.

* Unavailable

Table 7. Results from modified DeLury model applied to Delaware Bay blue crab stock.

Inputs				Results $q=0.0507$ (CV=0.22 IRQ=20%)						
Fishing Season	Recruits (#/tow)	Fully-Recruited (#/tow)	Catch (Millions)	Recruits (Millions)	Fully-Recruited (Millions)	Exploited Biomass (mt)	Instantaneous Fishing Mortality Rates			F(N) CV
							F(R)	F(N)	F(N+R)	
1979	2.0453	0.3215	4.96	38.06	6.28	1417	0.21	0.51	0.25	0.39
1980	1.2429	0.7984	7.40	22.04	15.44	2629	0.32	0.77	0.51	0.32
1981	5.6438	0.4686	7.37	86.87	10.15	1956	0.33	0.78	0.37	0.28
1982	2.0182	1.4805	4.43	31.74	30.01	5316	0.30	0.73	0.51	0.29
1983	0.5445	0.4689	6.73	12.48	16.64	3043	0.14	0.33	0.25	0.85
1984	0.8334	0.5469	8.40	24.04	10.20	1851	0.13	0.30	0.18	1.10
1985	3.3573	0.9648	17.01	51.10	12.87	2809	0.58	1.40	0.75	0.26
1986	7.7959	0.6088	18.57	100.84	13.63	3153	0.56	1.35	0.66	0.18
1987	1.5283	0.8476	20.77	35.00	26.67	4341	0.42	1.00	0.67	0.34
1988	3.0433	0.7794	24.96	75.47	14.23	2620	0.37	0.88	0.45	0.35
1989	3.9328	1.5408	28.85	74.32	25.77	3669	0.48	1.16	0.66	0.28
1990	10.4935	1.16	34.54	188.82	23.31	5820	0.33	0.79	0.38	0.36
1991	0.7382	2.0649	26.84	16.05	65.12	11903	0.25	0.61	0.54	0.39
1992	4.7499	1.3115	32.01	113.66	21.34	4445	0.28	0.67	0.34	0.42
1993	3.7585	2.4699	38.98	76.77	43.11	7620	0.48	1.15	0.72	0.31
1994	8.1238	1.4642	32.49	117.58	26.25	4232	0.55	1.33	0.69	0.23
1995	11.2166	1.3925	48.53	153.06	32.28	6334	0.65	1.56	0.81	0.21
1996	2.6204	1.4587	20.37	51.57	37.15	5547	0.29	0.70	0.47	0.35
1997	4.0091	1.2629	25.95	79.86	25.02	4216	0.38	0.90	0.50	0.36
1998	12.1192	1.5719	32.83	157.79	28.51	5727	0.56	1.35	0.69	0.22
1999	5.3159	1.5903	31.94	93.17	42.18	6787	0.41	0.98	0.59	0.30
2000	9.4112	1.5452		185.53*	33.86	6377				
1979-1999 Averages =				76.20	25.05	4545	0.38	0.92	0.52	0.37
1997-1999 Averages =				-	-	-	0.45	1.08	0.59	0.21

* Not estimated from NLLS routine, but rather calculated from catchability coefficient, q_n .

Table 8. Summary of results from sensitivity DeLury analyses of Delaware Bay blue crab.

Sensitivity	Base Run*						
M	0.60	0.80	1.00	0.80	0.80	0.80	0.80
Sr	1.00	1.00	1.00	1.00	1.00	0.60	0.80
Weighting	1.00	1.00	1.00	2.00	0.50	1.00	1.00

Estimates

Mean Z	1.31	1.32	1.34	1.32	1.33	1.66	1.46
Min. Z	0.99	0.98	0.96	1.05	0.96	1.28	1.13
Max. Z	1.63	1.61	1.61	1.57	1.63	2.00	1.77
q	0.0736	0.0511	0.0312	0.0536	0.0498	0.1065	0.0715
Min. N	4.3	6.3	10.6	5.9	6.4	2.9	4.5
Max. N	49.1	65.1	99.8	65.5	67.3	44.4	53.4
Min. R	8.5	12.5	21.1	11.8	11.7	10.8	19.8
Max. R	129.7	188.9	317.9	183.7	197.9	149.9	166.9

Diagnostics

TSS	0.0586	0.0510	0.0441	0.0445	0.0463	0.0788	0.0618
MSE	0.0029	0.0025	0.0022	0.0022	0.0023	0.0039	0.0031
%SSn	37.60	38.60	39.50	44.40	43.50	36.50	37.60
%SSr	37.60	33.40	28.80	39.50	21.20	42.90	37.70
%SSp	24.70	28.00	31.70	16.10	35.20	20.50	24.70
CV(q)	0.17	0.22	0.35	0.21	0.22	0.18	0.20
Min. CV(N)	0.24	0.29	0.26	0.25	0.26	0.28	0.26
Max. CV(N)	0.42	0.40	0.38	0.43	0.44	0.50	0.45
Min. CV(R)	0.28	0.29	0.29	0.28	0.26	0.28	0.29
Max. CV(R)	0.43	0.40	0.35	0.40	0.31	0.45	0.41

* Accepted as best DeLury run

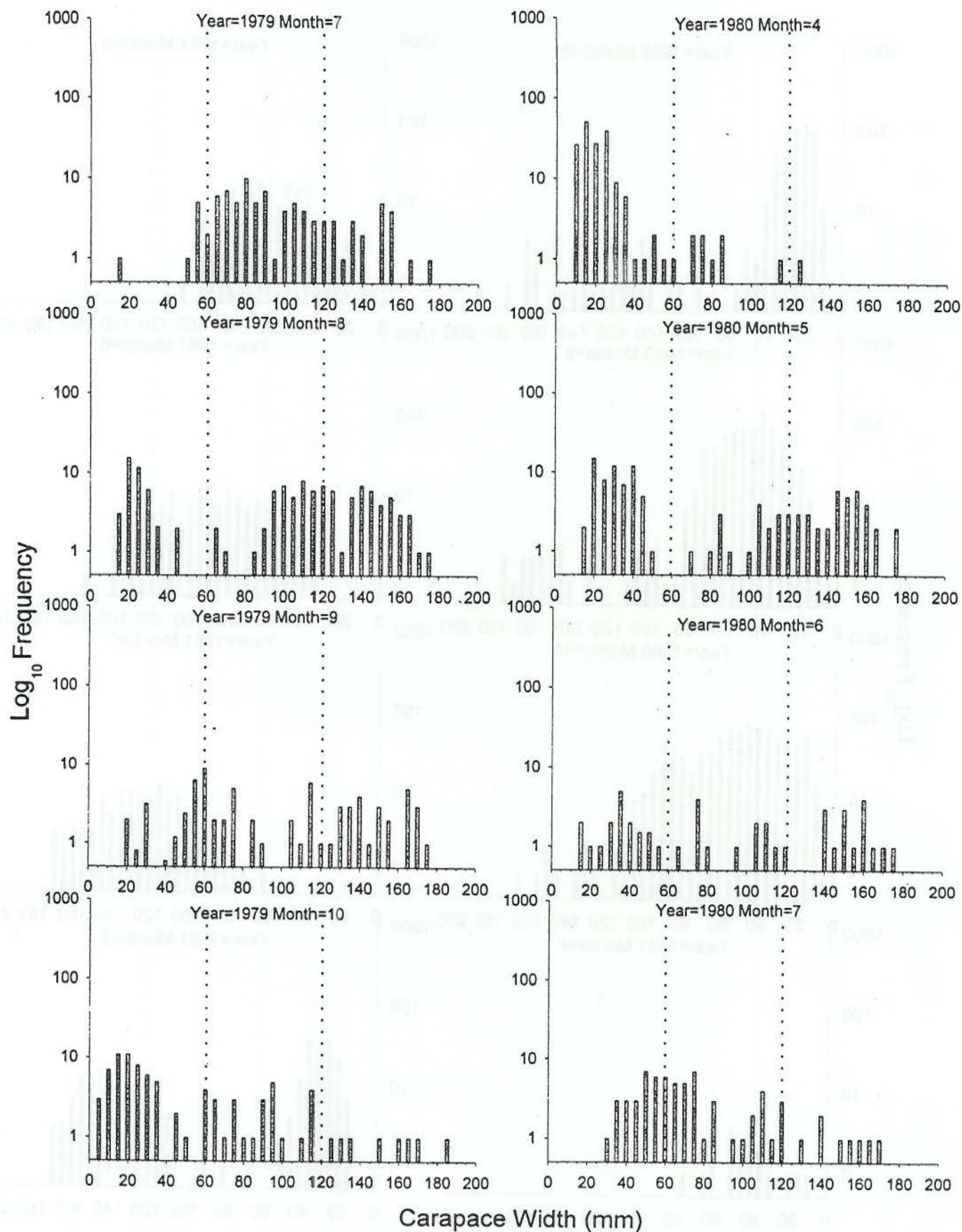
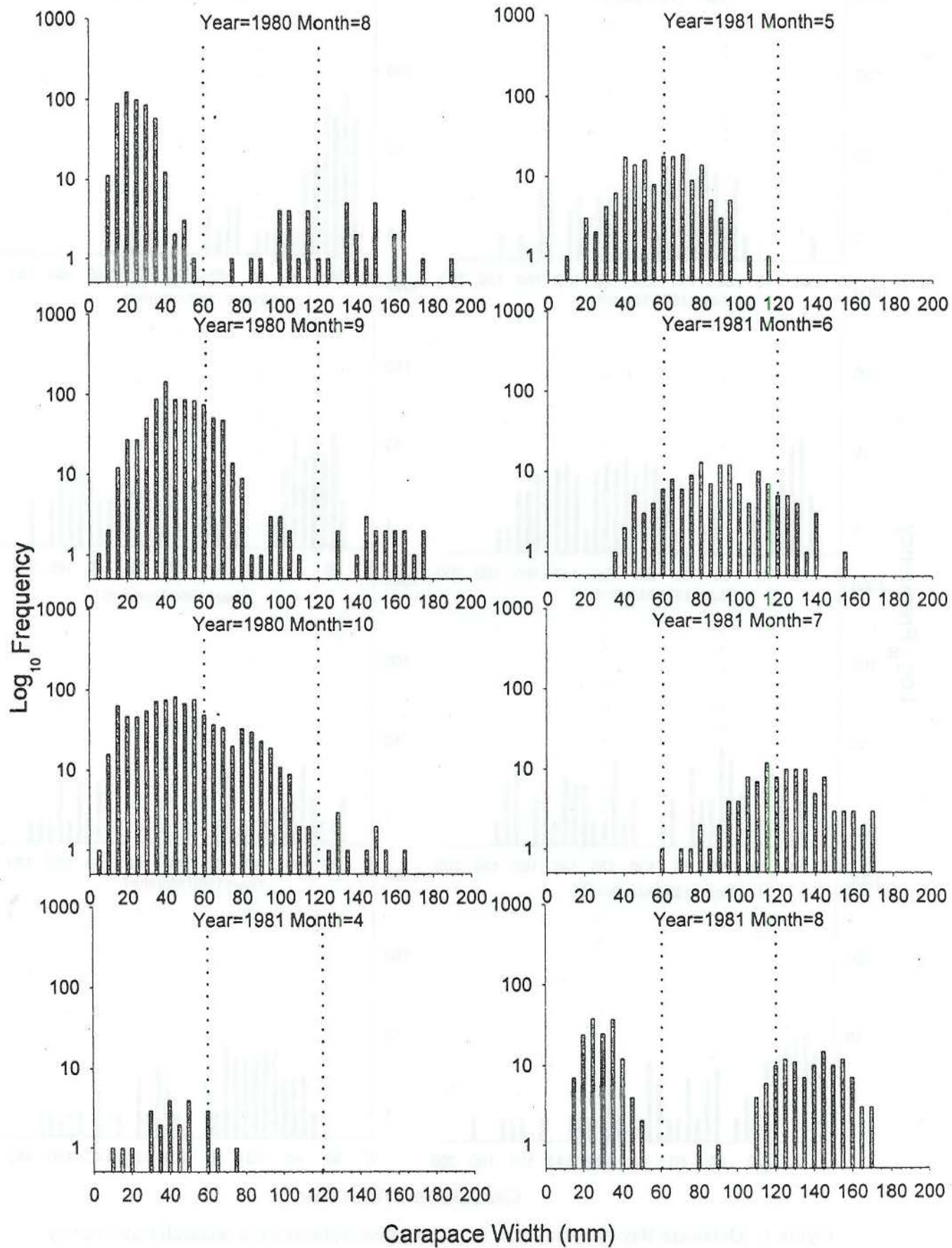


Figure 1. Delaware Bay blue crab size frequency distributions from research trawl survey.



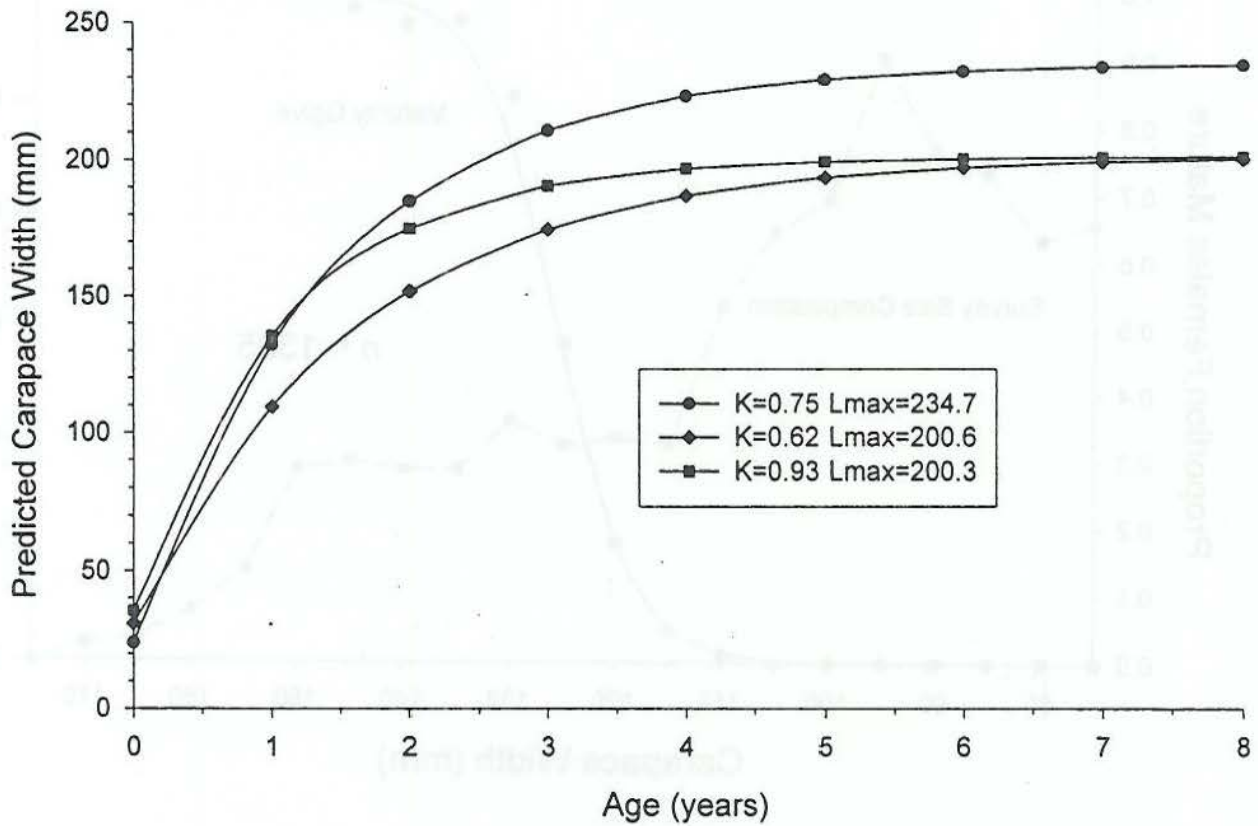


Figure 2. Predicted growth trajectories derived from von Bertalanffy growth parameters estimated by MULTIFAN applied to Delaware research trawl survey size frequency distributions.

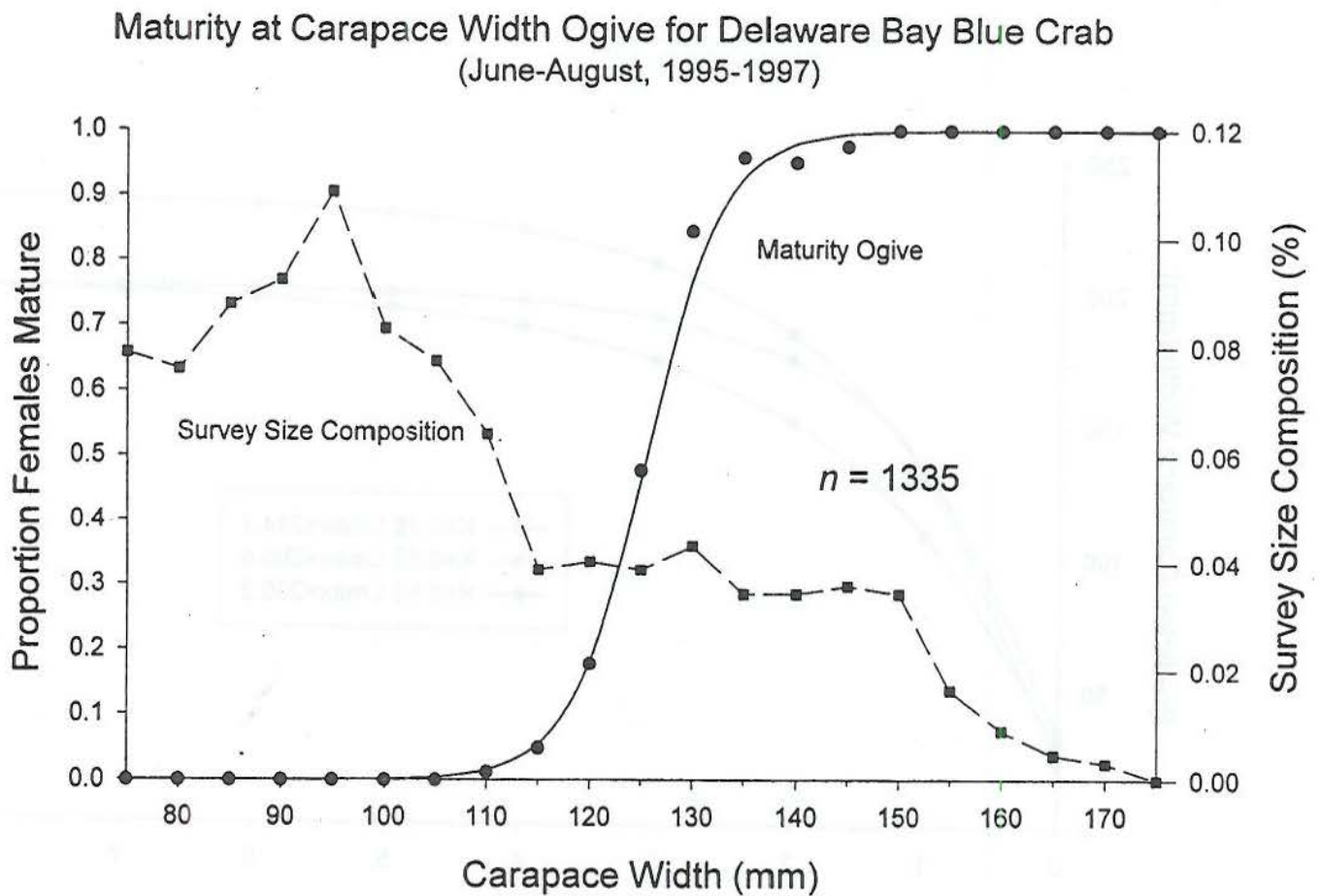
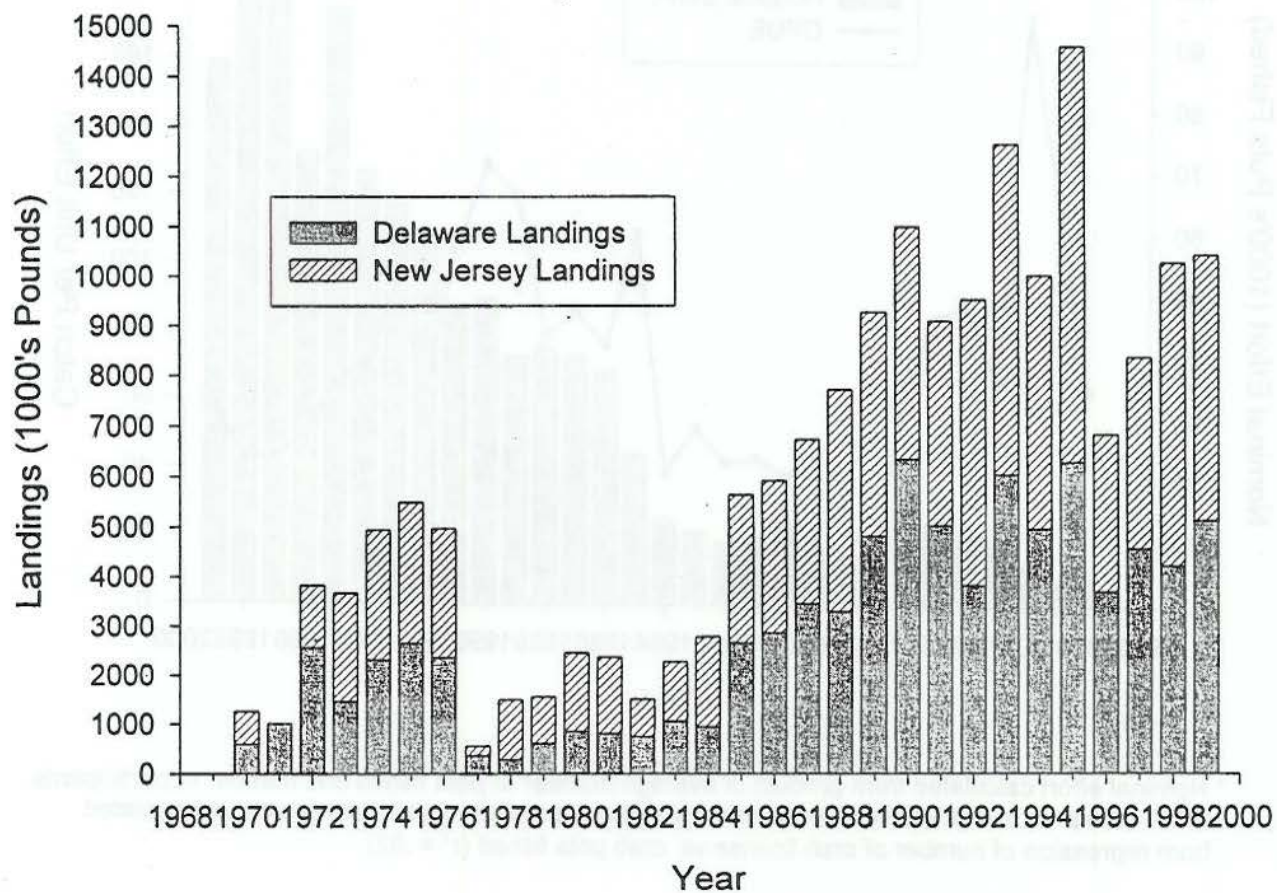


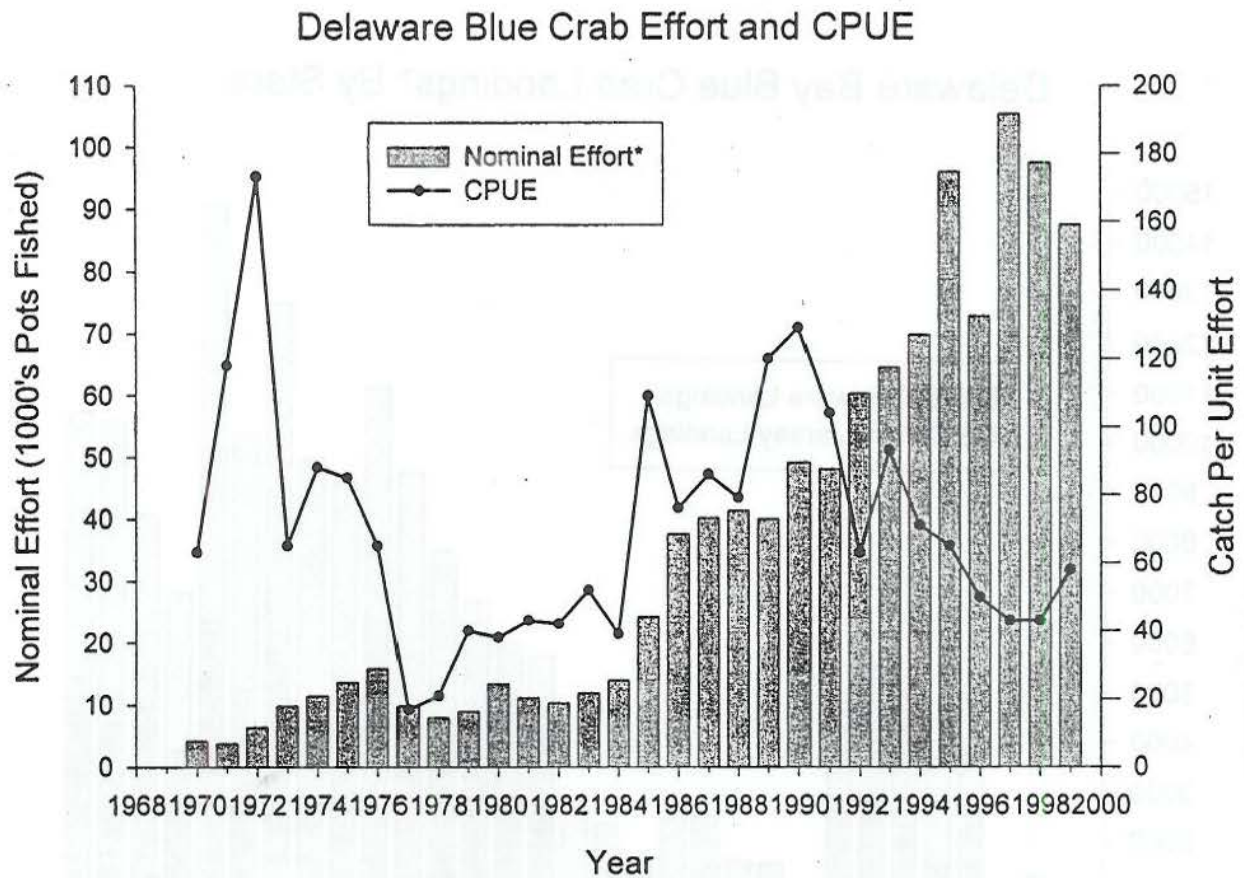
Figure 3. Observed and predicted proportion of Delaware Bay blue crabs (females) mature by carapace width. Predicted maturity was estimated using logistic regression applied to females crabs collected from the commercial crab pot fishery, 1995-1997. Also shown is research survey size composition of blue crabs for calculation of maturity ogive by age group.

Delaware Bay Blue Crab Landings* By State



* Landings based on conversion of 40 lbs / bushel. 1999 landings preliminary.

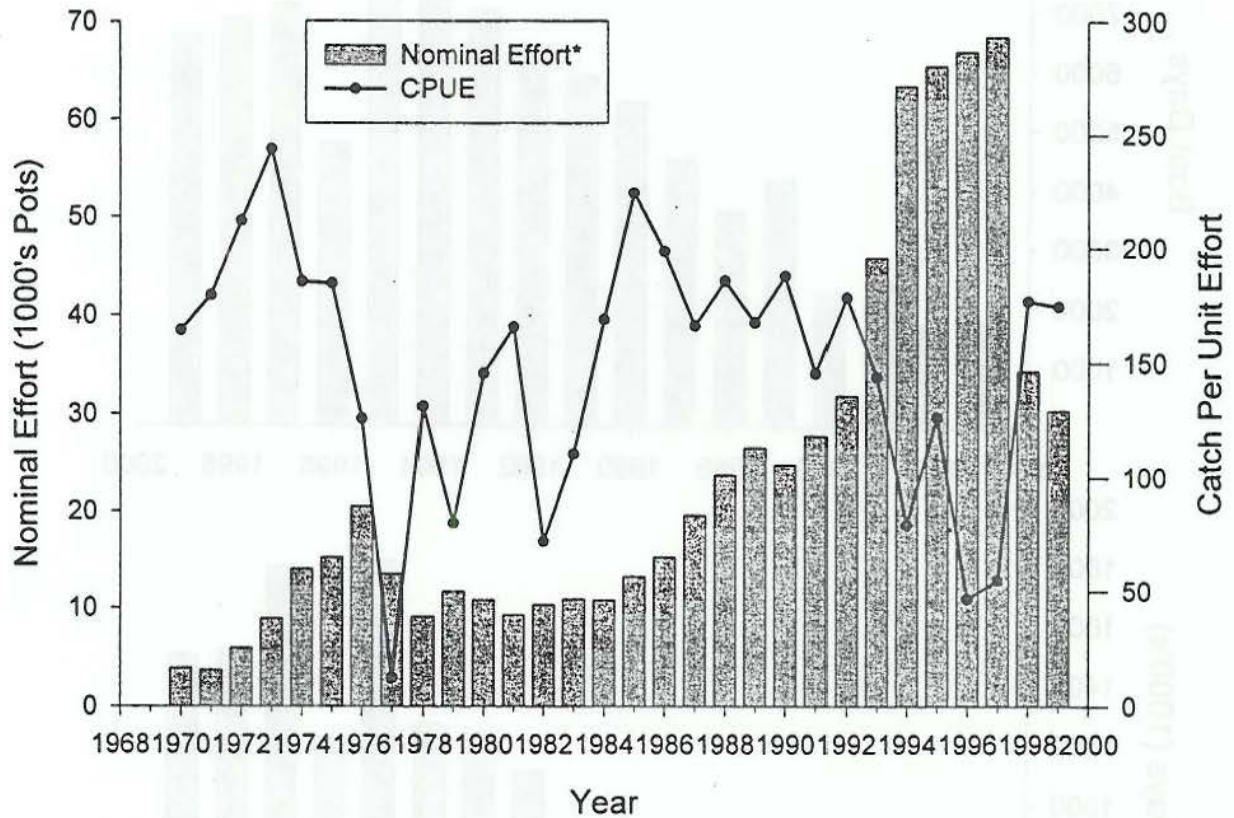
Figure 4. Delaware Bay blue crab landings (000's pounds) by state from 1970-1997.



* Nominal effort calculated from product of average number of pots fished and number of participants. Effort data prior to 1985 (when the mandatory logbook program was initiated) were extrapolated from regression of number of crab license vs. crab pots fished ($r^2 = .92$).

Figure 5. Nominal fishing effort (# crab pots) and catch per unit effort (CPUE) of Delaware Bay blue crab caught in Delaware.

New Jersey Blue Crab Effort and CPUE



* Nominal effort calculated from product of number of licenses and average number of pots.

Figure 6 Nominal fishing effort (# crab pots) and catch per unit effort (CPUE) of Delaware Bay blue crab caught in New Jersey.

Directed Effort Measures in the Delaware Bay Blue Crab Fishery

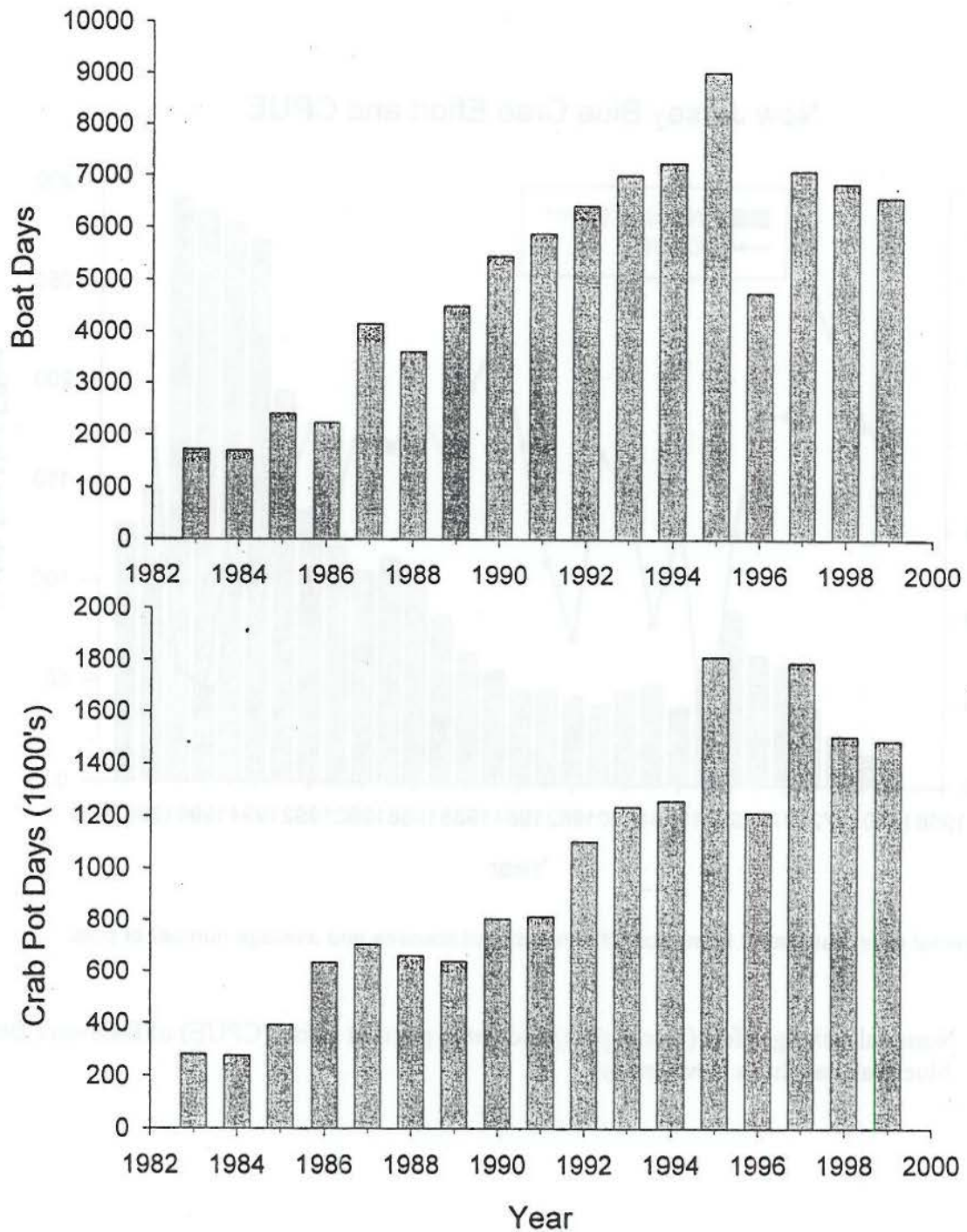


Figure 7 Directed measures of Delaware fishing effort (Boat Days and Crab Pot Days) from Delaware's Intercept Survey Collection Program, 1985-1999.

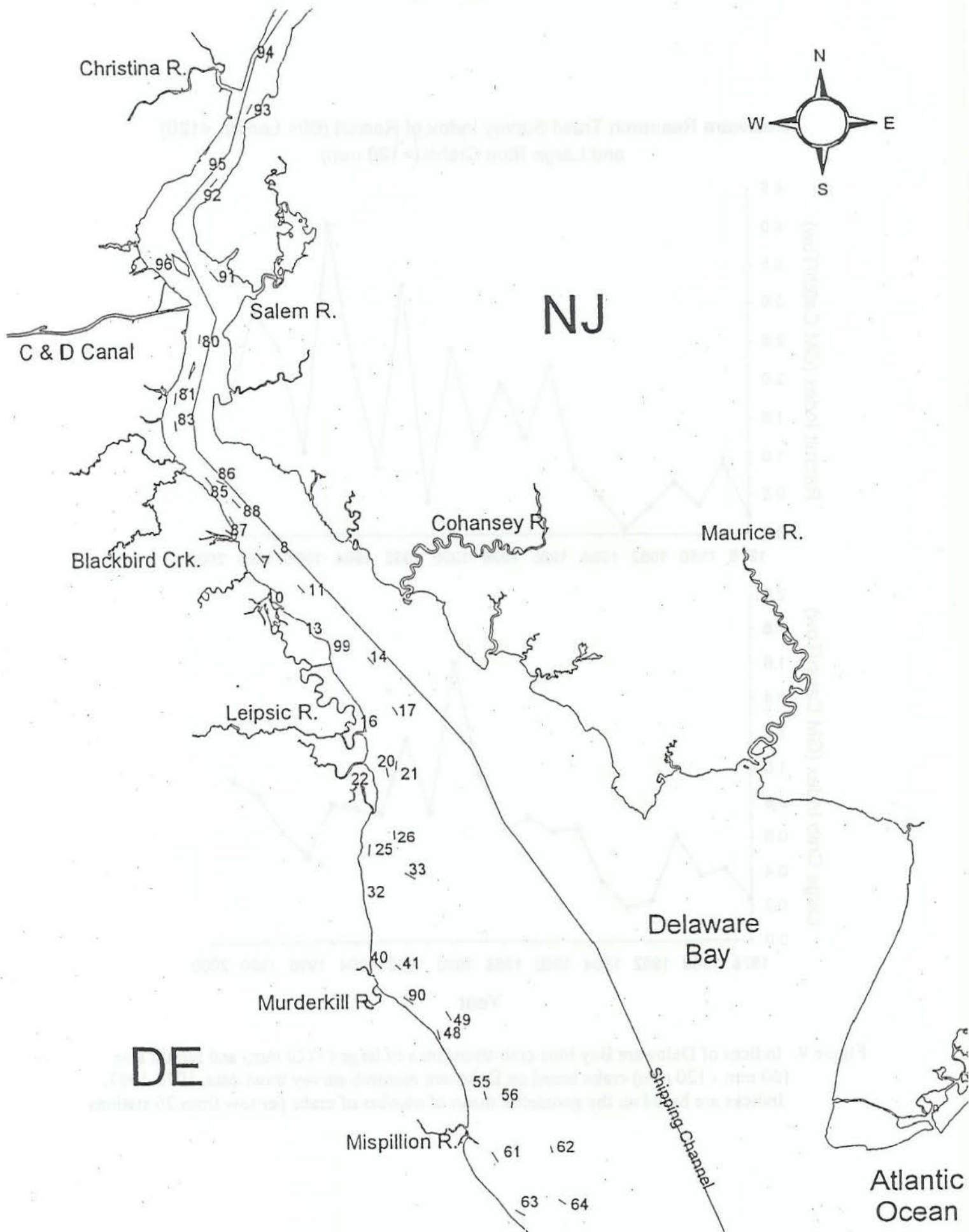


Figure 8. Stations sampled with a 16-foot otter trawl in the Delaware Bay and River during 1997. Numbers indicate station numbers.

Delaware Research Trawl Survey Index of Recruit (60 < Length < 120)
and Large Blue Crabs (>120 mm)

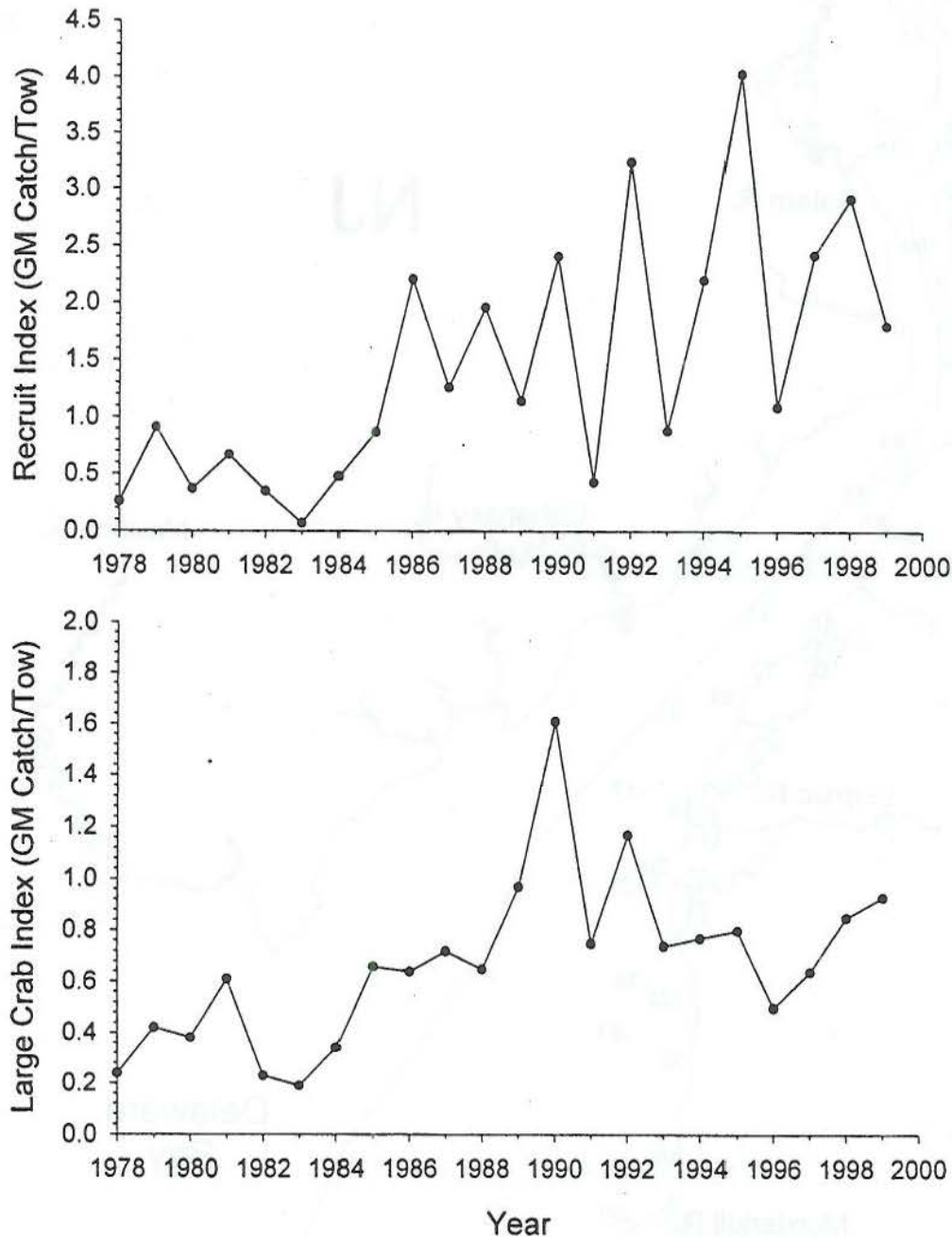


Figure 9. Indices of Delaware Bay blue crab abundance of large (>120 mm) and recruit size (60 mm - 120 mm) crabs based on Delaware research survey trawl data, 1978-1997. Indices are based on the geometric mean of number of crabs per tow from 26 stations.

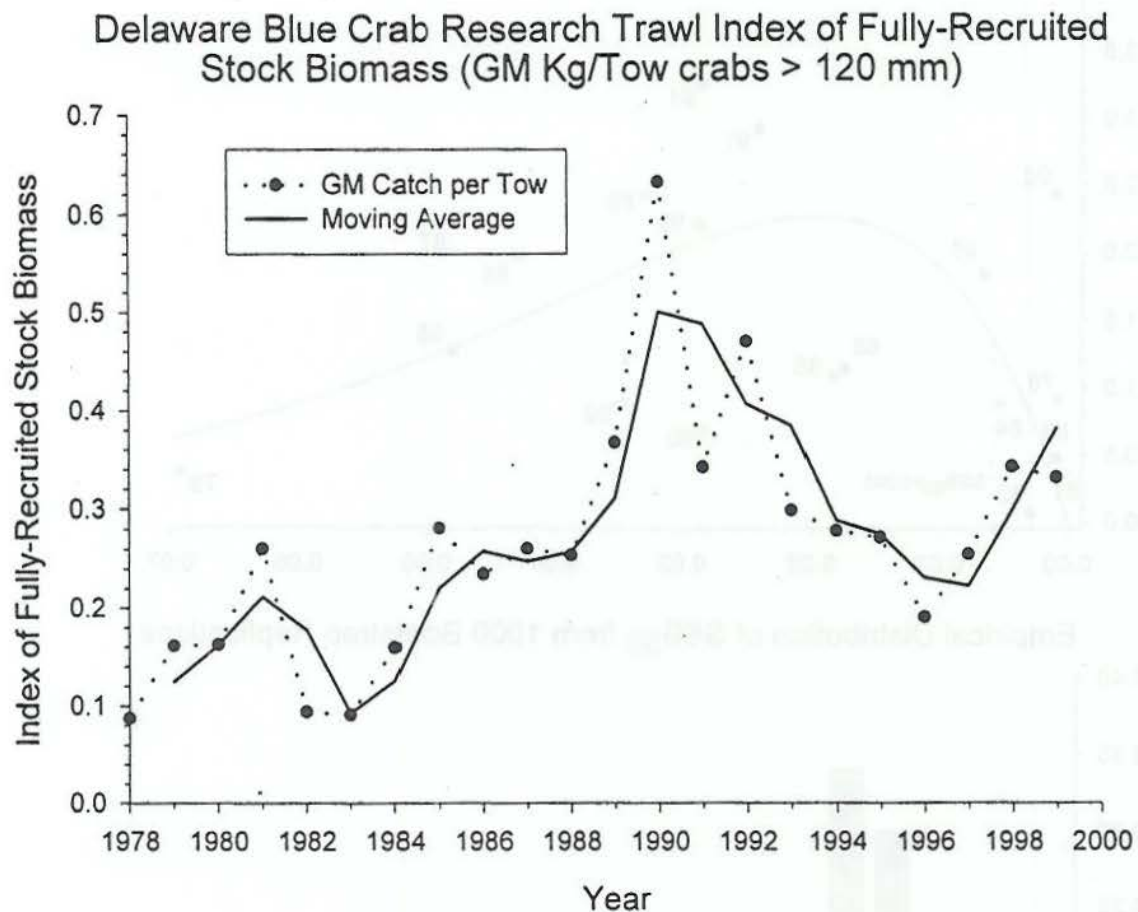


Figure 10. Index of fully-recruited (> 120 mm) crab stock biomass (kg/tow) from Delaware research survey trawl data, 1978-1999. Indices are based on geometric mean of weight per tow in survey where carapace widths are converted to weight ($W=0.0008164 \cdot CW^{2.430}$) and weighted by number of crabs in each size category.

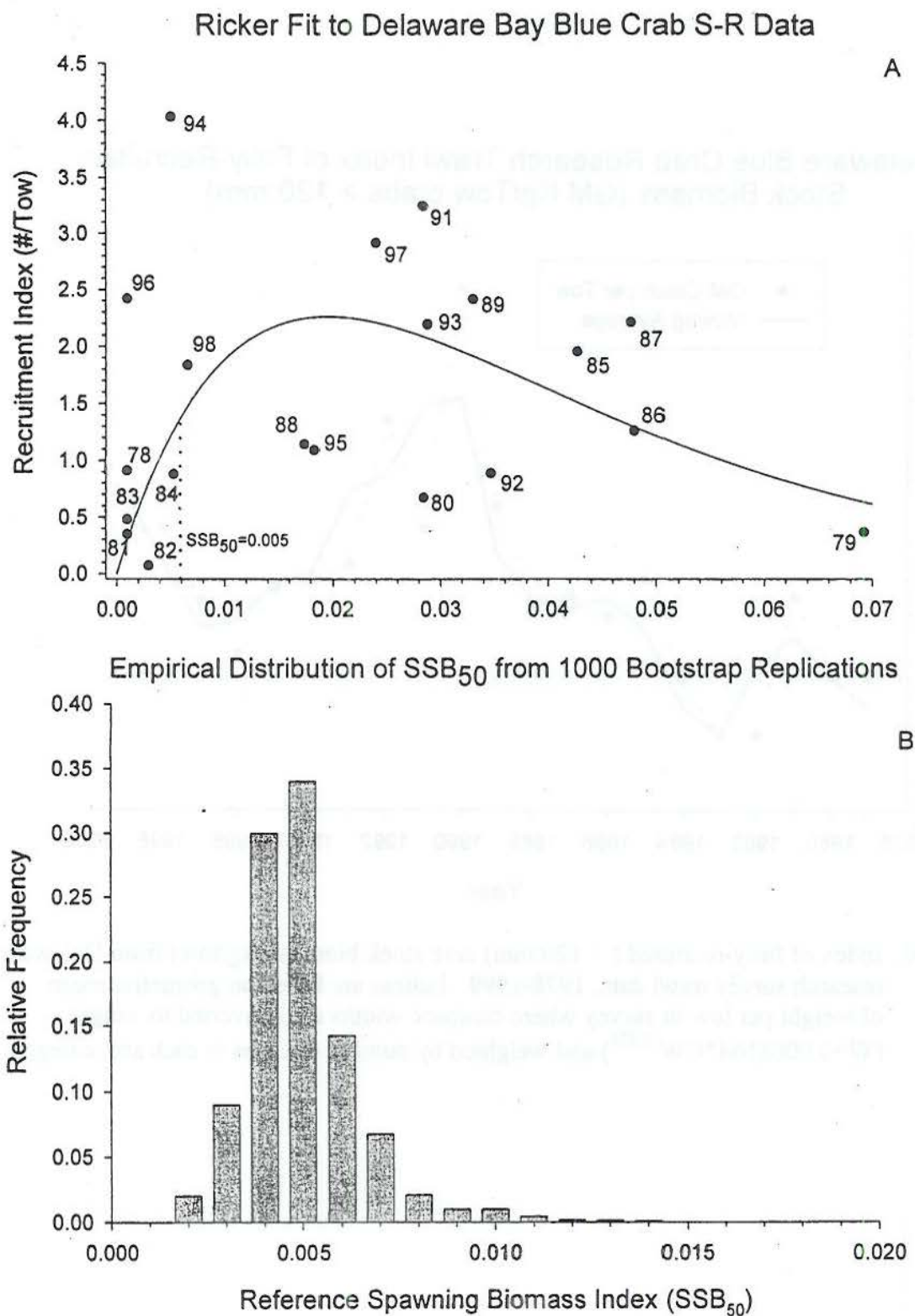


Figure 11. A) Index-based spawning stock biomass and recruitment relationship for Delaware Bay blue crab. Solid line shows fit of the Ricker S-R model to observed indices derived from Delaware research trawl survey. B) Empirical distribution of the calculated reference point (SSB_{50}) from Ricker parameters based on 1000 bootstrap replications.

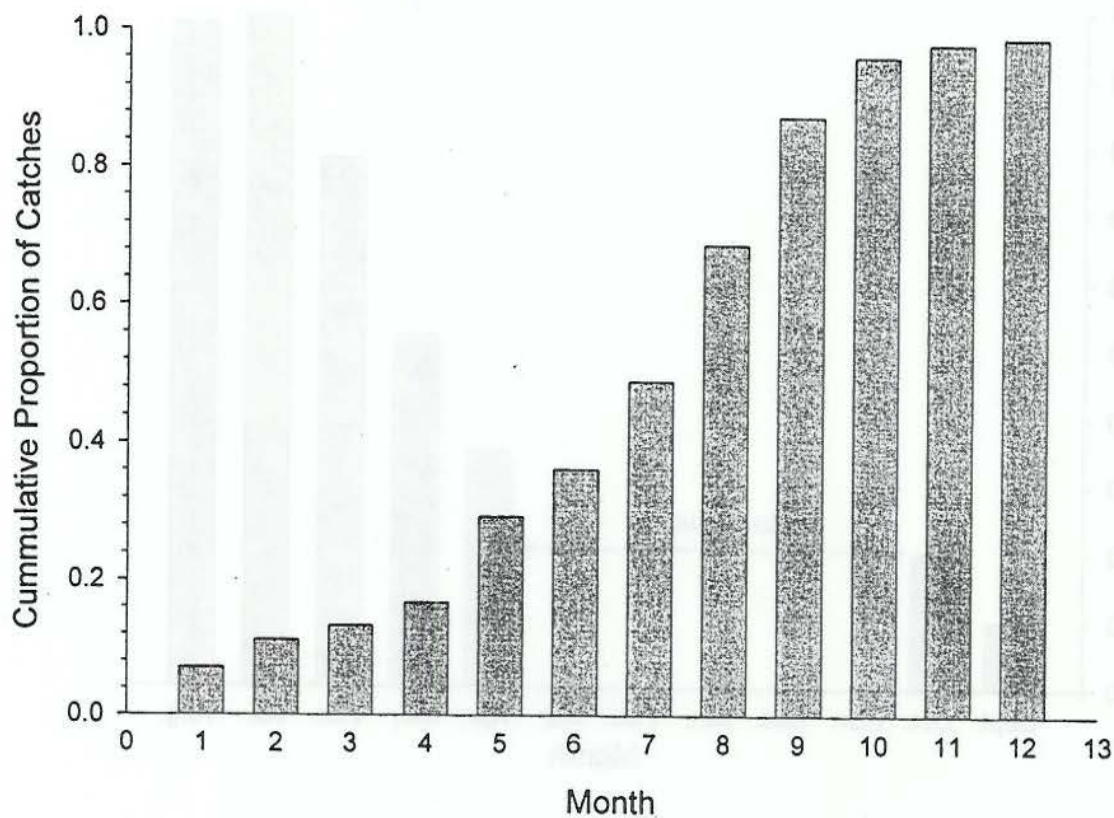


Figure 12. Distribution of monthly landings of Delaware Bay blue crab as expressed by the average cumulative proportions, 1991-1999.

Estimated Partial Recruitment Pattern of Recruit Size Blue Crabs
Based on Delaware Research Trawl Survey

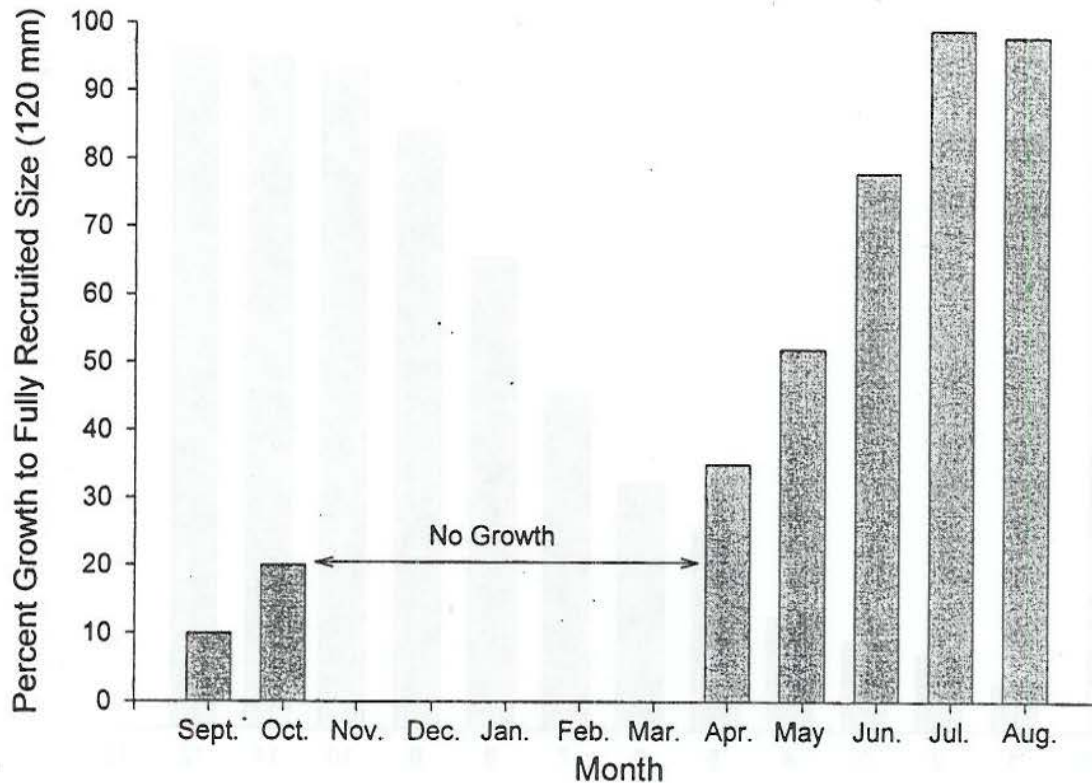


Figure 13. Percent growth of recruit size (< 120 mm) blue crabs by month toward the fully-recruited size (> 120 mm). Data based on Delaware research trawl size frequencies and was used to define the partial recruitment pattern used in the Modified DeLury model.

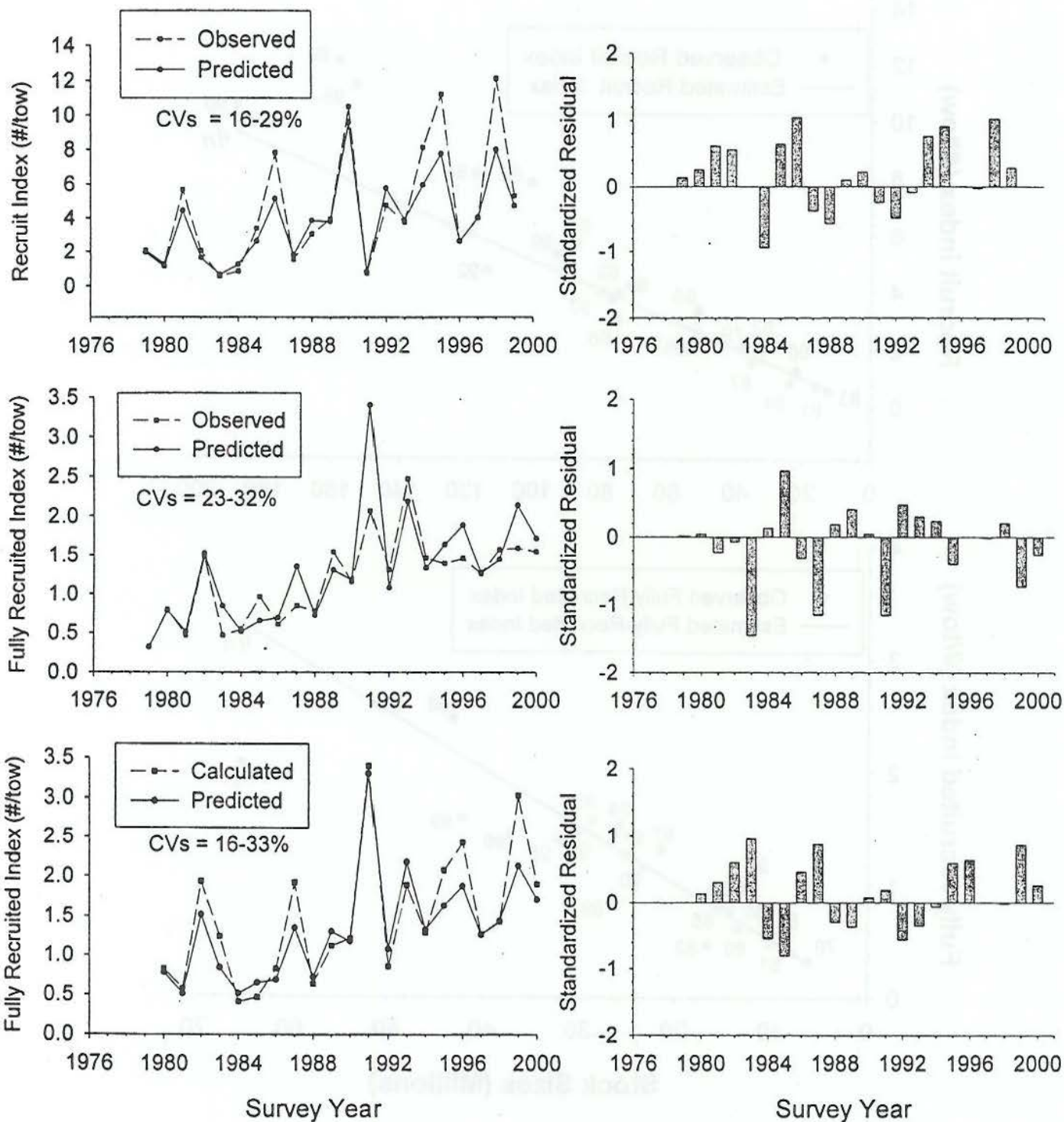


Figure 14. Summary of results from modified Delury model applied to Delaware Bay blue crab. Results shown are from base run ($M=0.80$, $Sr=1.0$, equal statistical weights).

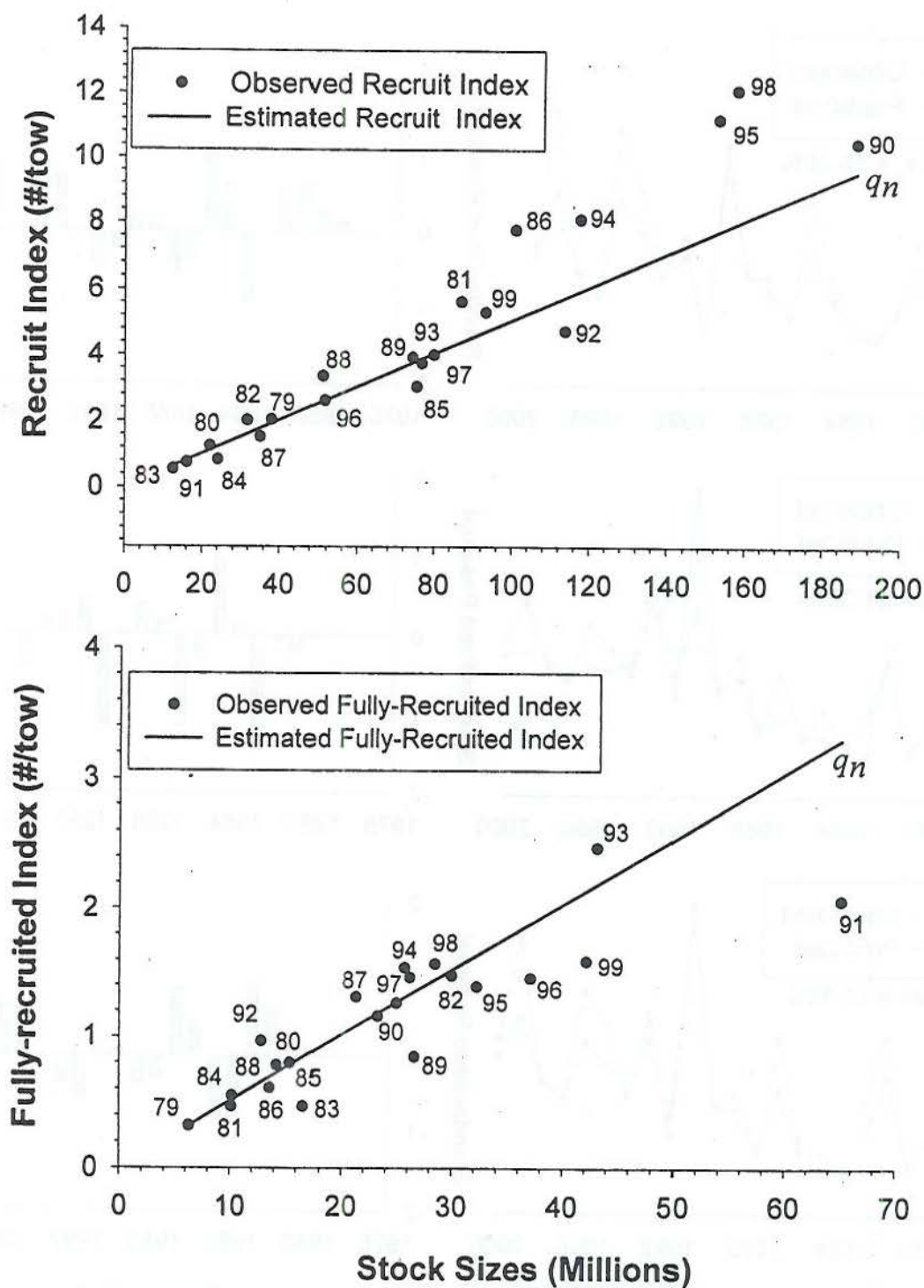


Figure 15. Observed indices for recruit and fully-recruited Delaware Bay blue crab plotted against stock sizes estimated by the modified Delury model. The solid line shows the estimated catchability relationship between abundance indices and stock sizes. Vertical discrepancies between the observed values and the catchability line represent measurement errors.

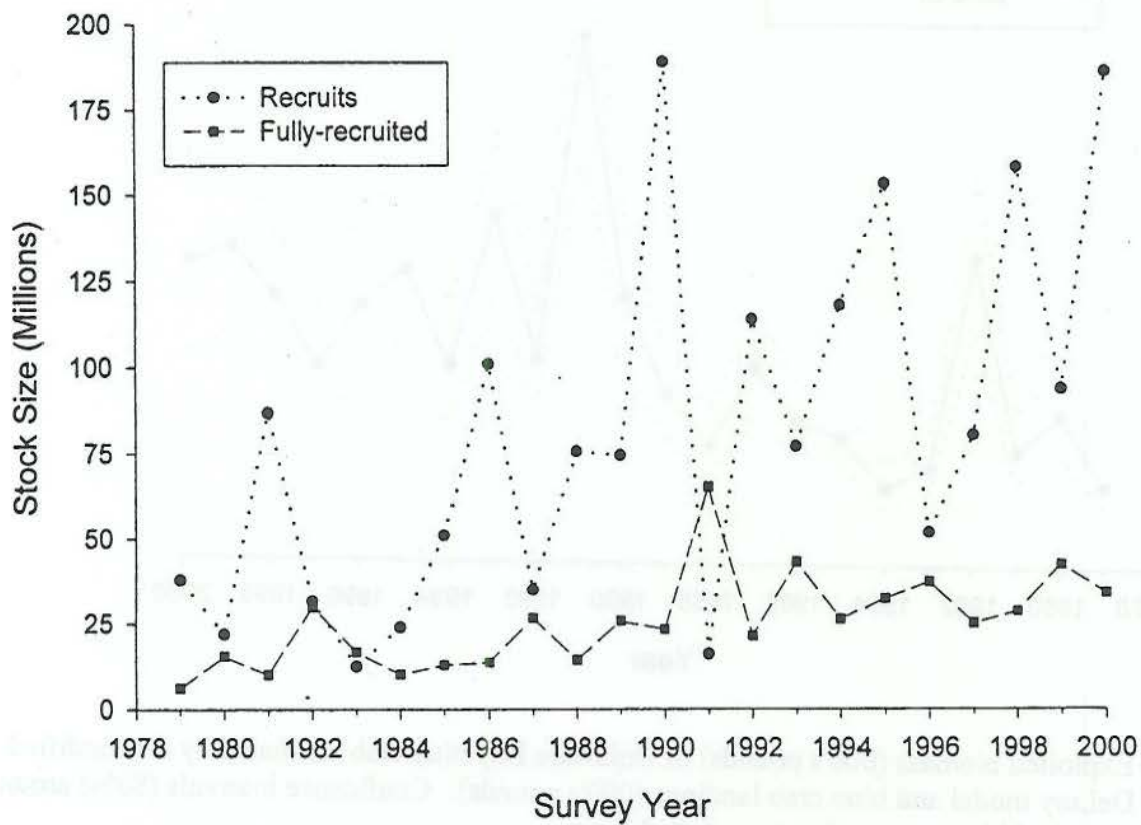


Figure 16 . Stock sizes (in millions of crabs) for recruit and fully-recruited Delaware Bay blue crab estimated by the modified Delury model, 1979- 2000. Value of recruits in 2000 is not estimated by the model, but rather calculated from the catchability coefficient, q_n .

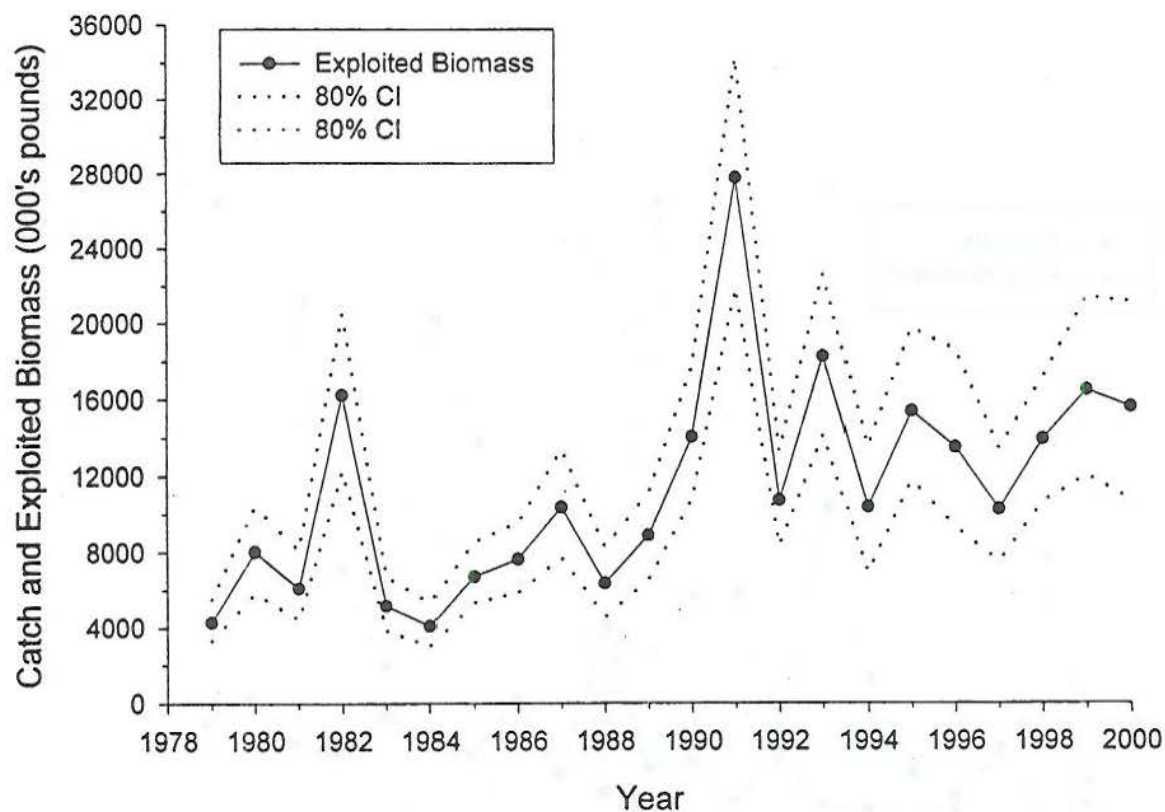


Figure 17. Exploited biomass (000's pounds) of Delaware Bay blue crab estimated by the modified DeLury model and blue crab landings (000's pounds). Confidence intervals (80%) around exploited biomass are shown as dotted lines.

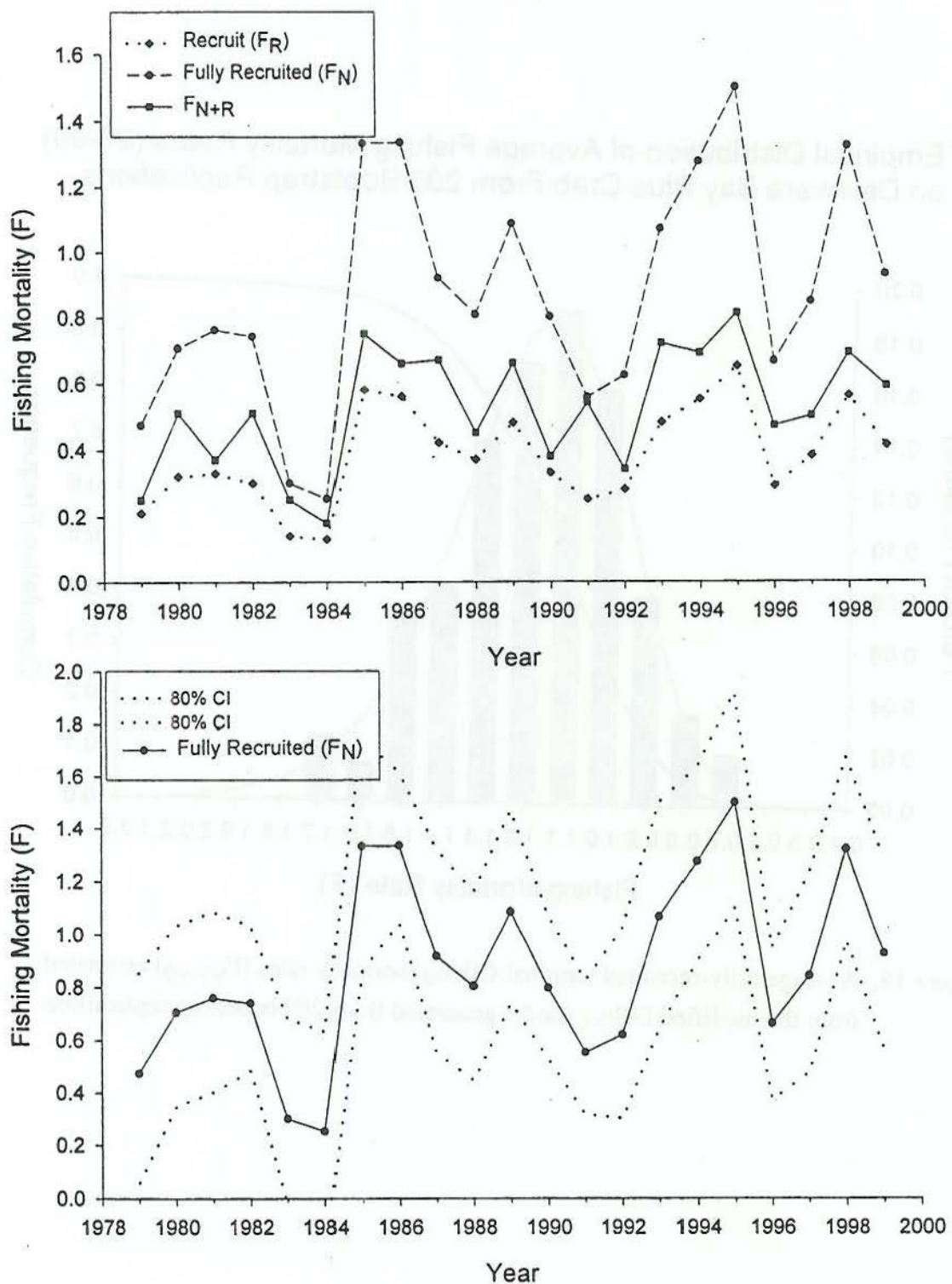


Figure 18. Instantaneous fishing mortality rates (F) on Delaware Bay blue crab of recruit size and greater (F_{N+R}), recruit size (F_R) and fully-recruited size (F_N) estimated by the modified DeLury model. Bottom Panel shows 80% confidence intervals around F_N estimated from 200 bootstraps.

Empirical Distribution of Average Fishing Mortality Rates (97-99)
on Delaware Bay Blue Crab From 200 Bootstrap Replications

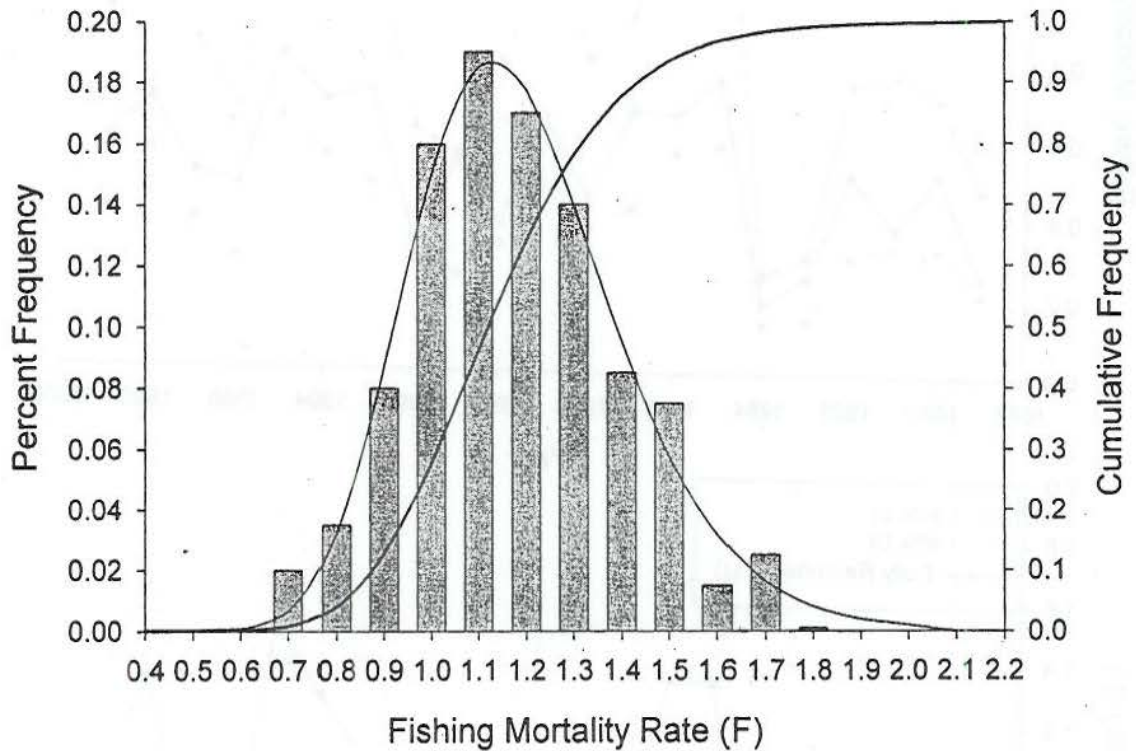


Figure 19. Average fully-recruited terminal fishing mortality rates (F_{97-99}) estimated from the modified Delury model generated from 200 bootstrap replications.

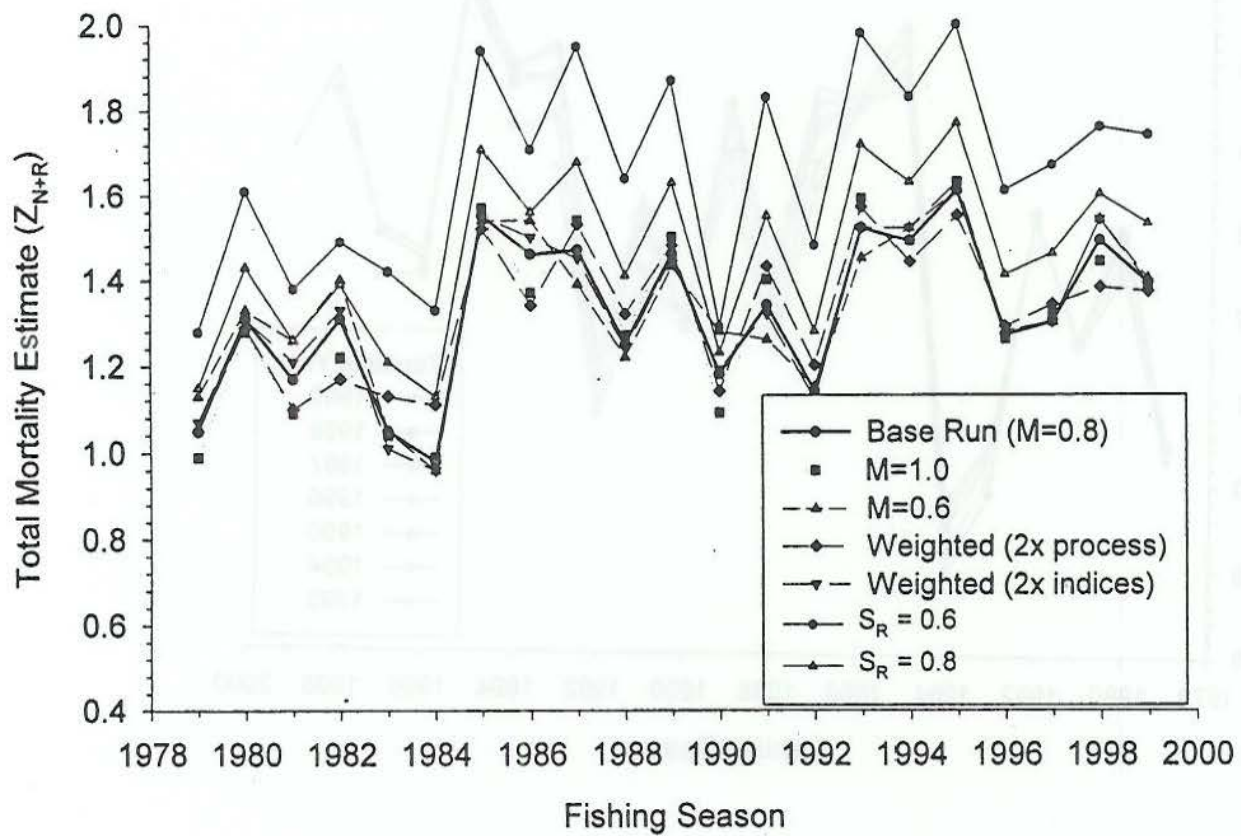


Figure 20. Delaware Bay blue crab deLury model sensitivity analysis of instantaneous total mortality rates to different assumptions of natural mortality (M), relative selectivity of recruits (S_R) and statistical weighting.

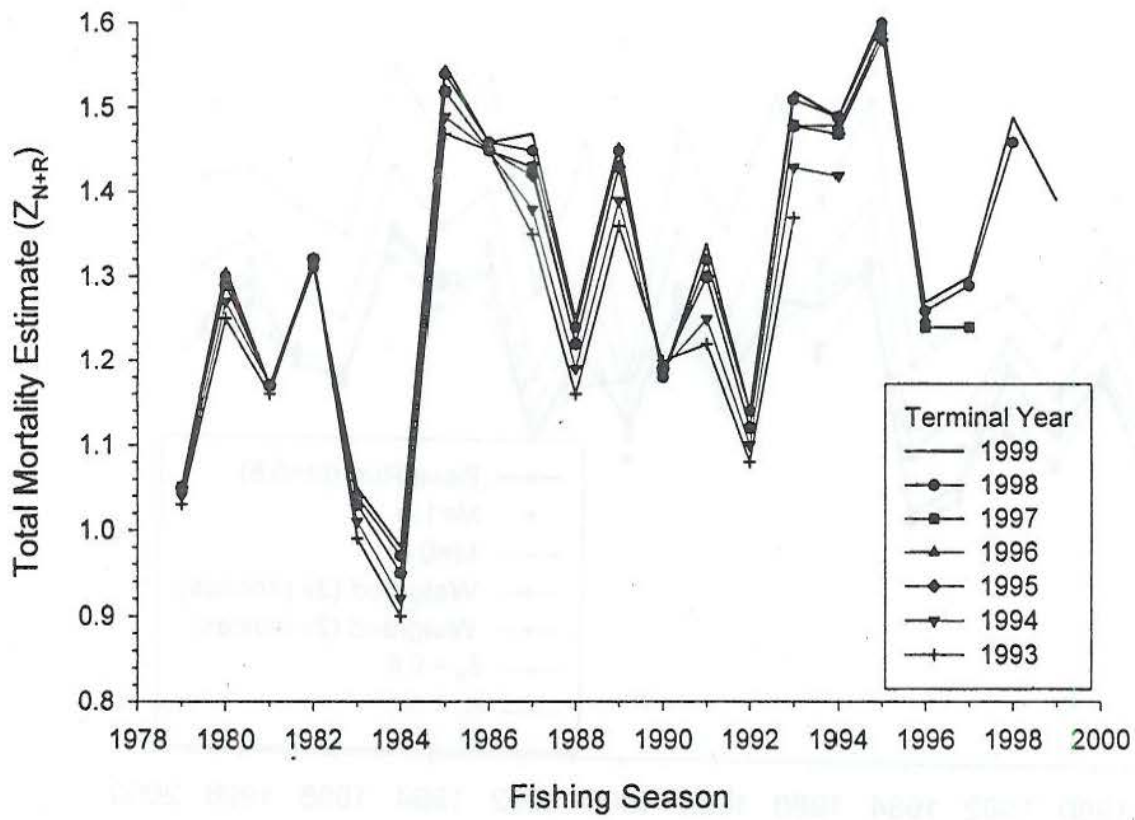


Figure 21. Retrospective DeLury model estimates of total mortality for Delaware Bay blue crab.

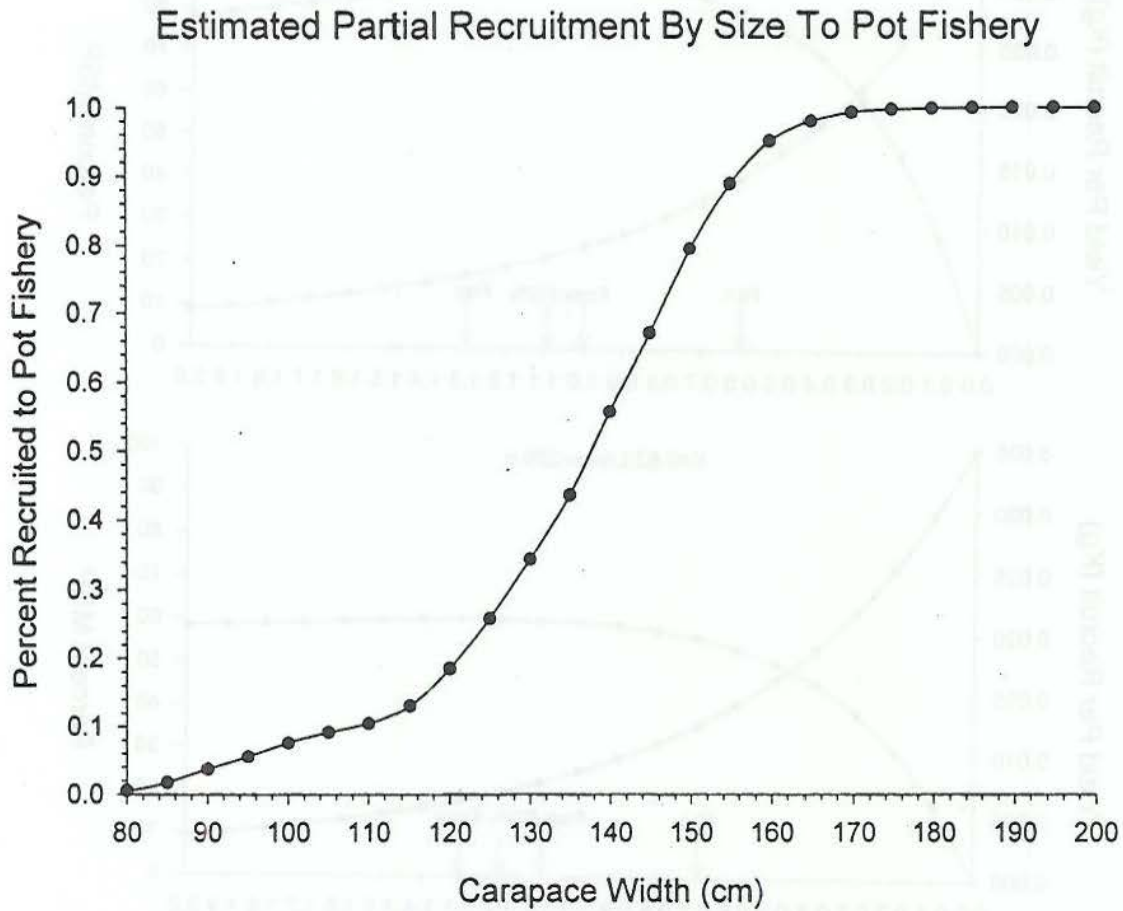


Figure 22 . Partial recruitment pattern by size to the crab pot fishery for Delaware Bay blue crab estimated from at sea length frequency samples, minimum crab size limits and total catch (in number) of crabs by market category.

Yield Per Recruit and % MSP for Delaware Bay Blue Crab

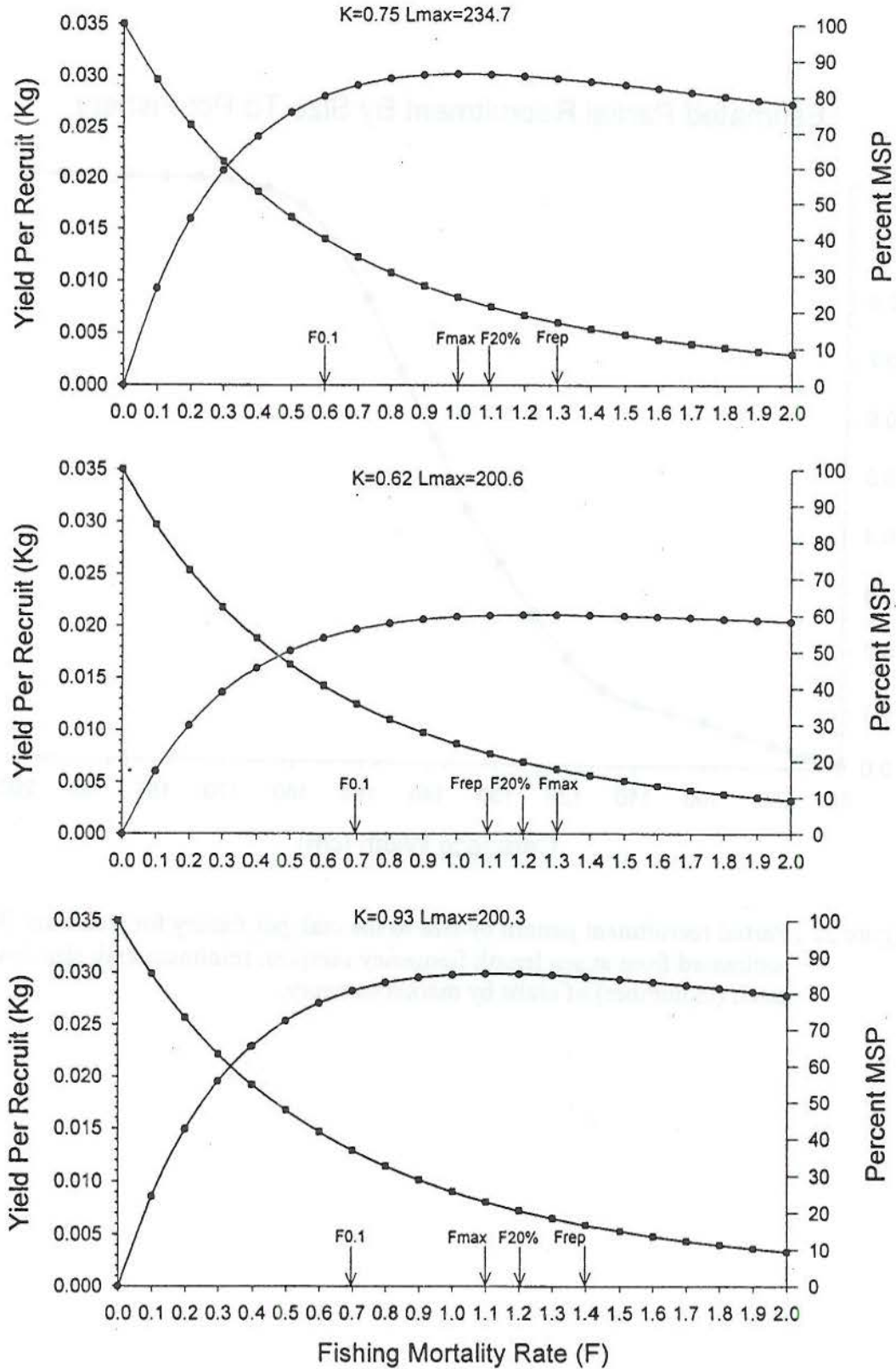


Figure 23. Results of Thompson and Bell yield and SSB-per-recruit analyses of Delaware Bay blue crab from three different assumptions of crab growth. Inputs of analyses are given in Appendix.

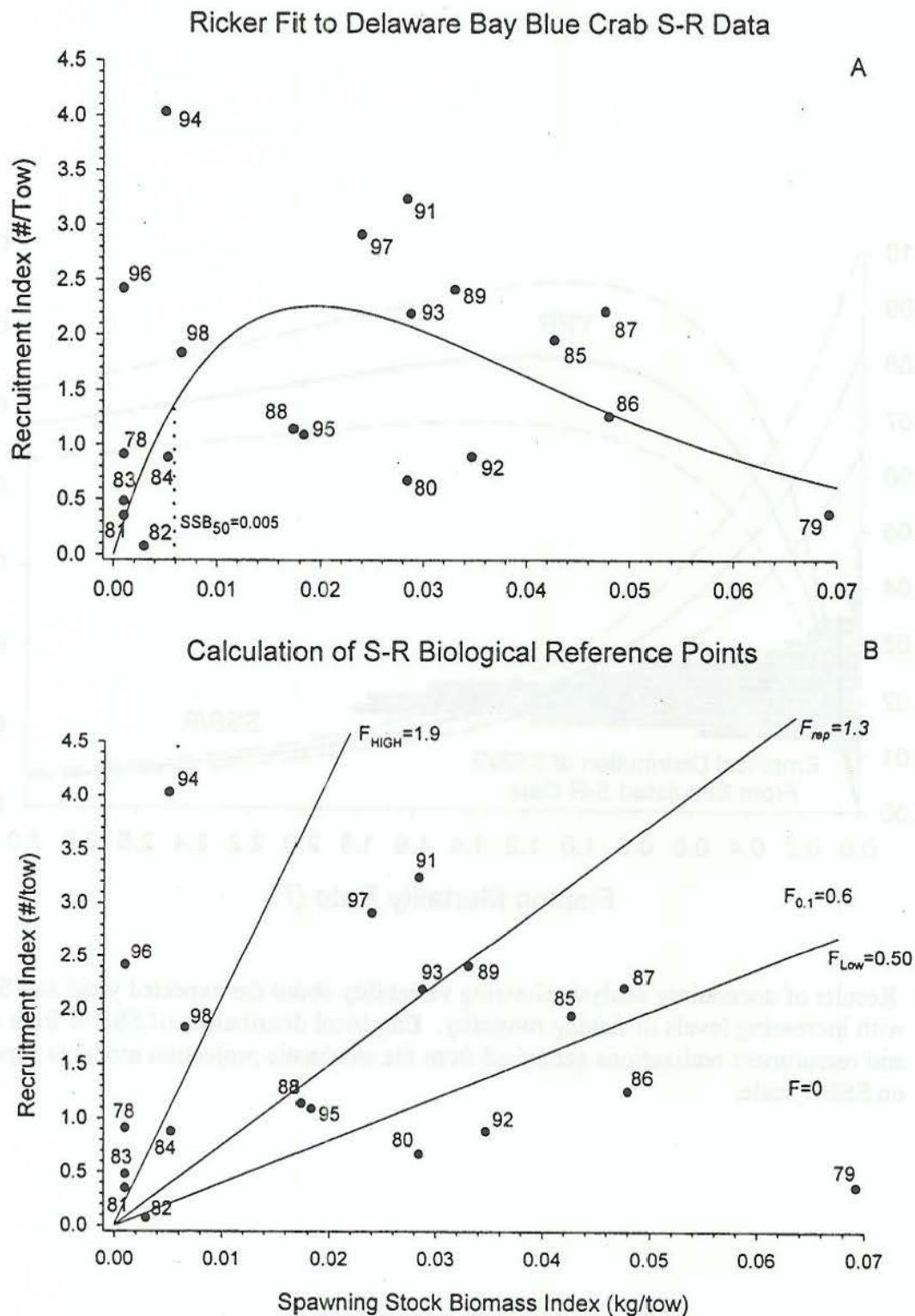


Figure 24. Calculation of biological reference points (F_{REP} , F_{HIGH} , and F_{LOW}) from SSB-per-recruit analyses coupled with standard spawning stock biomass and recruitment plots based on research surveys.

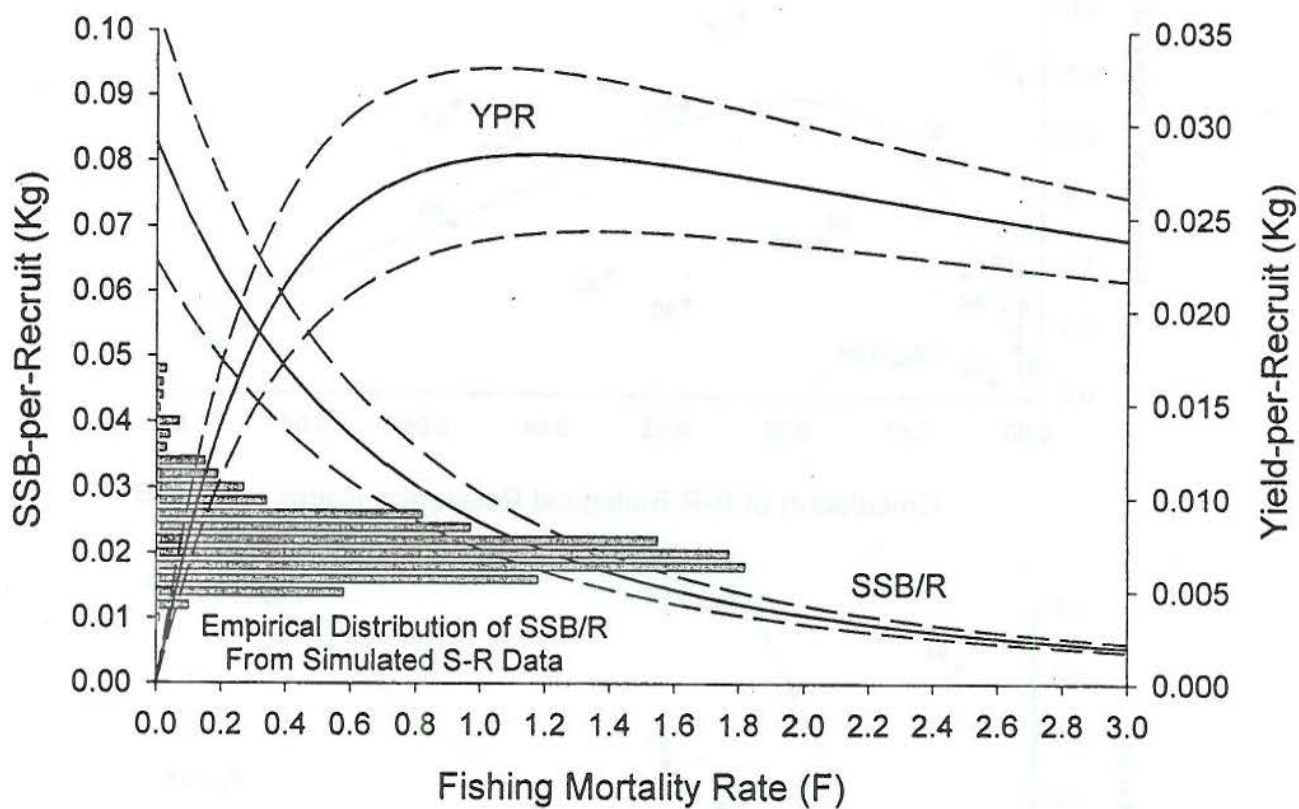


Figure 25. Results of uncertainty analysis showing variability about the expected yield and SSB-per-recruit with increasing levels of fishing mortality. Empirical distribution of SSB/R from simulated stock and recruitment realizations generated from the stochastic projection model is superimposed on SSB/R scale.

Probability Density Functions for Estimated Fully-recruited F (ave. 97-99) and F_{REP} .

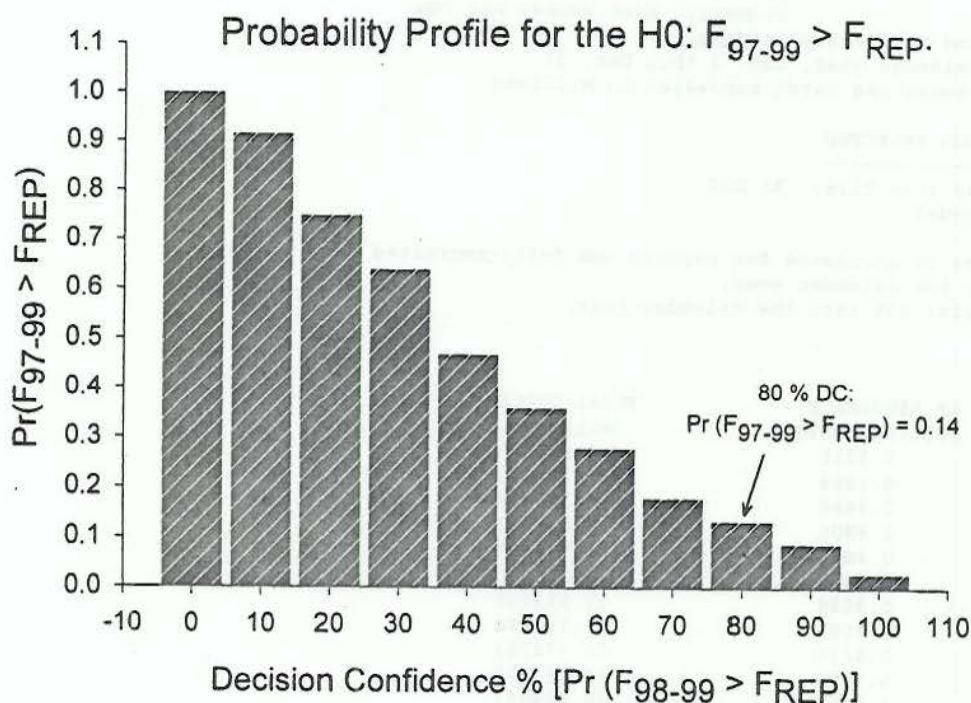
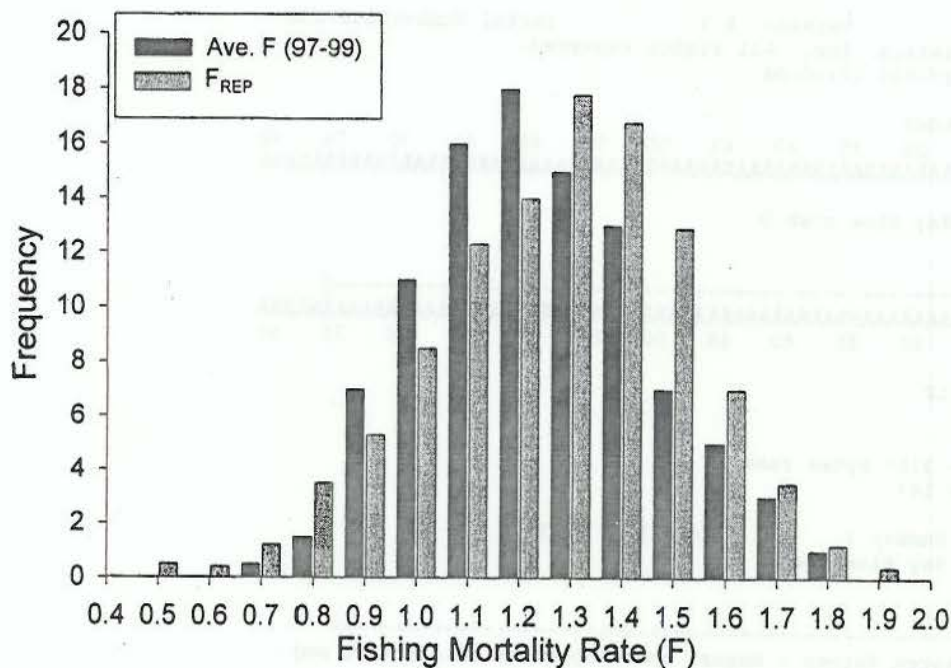


Figure 26. Probability density functions for the estimate of 1997-1999 average fully-recruited fishing mortality (F_{97-99}) and the estimate of the replacement fishing mortality rate (F_{REP}) for Delaware Bay blue crab. Probability profile specifying $\Pr(F_{97-99} > F_{REP})$ for various decision confidence levels along the X-axis. For example, at the 80% decision confidence level $\Pr(F_{97-99} > F_{REP})$ is only 14%.

APPENDIX A : MODIFIED DELURY ANALYSIS OF DELAWARE BAY BLUE CRAB

APL*PLUS II for the 80386 Version 5.1 Serial Number 5407538
 Copyright 1984-1992, Manugistics, Inc. All rights reserved.
 C:\DELURY\DEL20 SAVED 04/13/1995 12:40:04

FIRST 5 RECORDS ARE AS FOLLOWS

5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
 AA

ID0

Delury model for Delaware Bay Blue crab.0

0

Data Used0

-----0
 AA

5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80

0 = CR,LF

Press ENTER to continue

File read was successful - 3157 bytes read
 Number of records found is 147

DELURY v2.0 Oct94 Run Number 1 2000 3 20 11 59 2

Delury model for Delaware Bay Blue crab.

Data Used

 Tuning Index: Trawl Research Survey - August thru September cutoff (120 mm) -
 Indices lagged to next year.
 Geometric Mean Number per Tow

Catch Data: Delaware and New Jersey Landings
 Based on Calendar year, Jan. 1 thru Dec. 31
 1000 mt assumed and Catch expressed in Millions

INPUT PARAMETERS AND OPTIONS SELECTED

 Input data and options read from file: R1.DAT
 Data used in fitting the model:

The survey provides indices of abundance for recruit and fully-recruited
 numbers at a point 0% into the calendar year.
 The catch is taken at a point 60% into the calendar year.

Natural mortality is 0.8

CALENDAR	-- INDICES OF ABUNDANCE --	TOTAL CATCH
YEAR	RECRUITS FULLY-RECRUITED	(millions)
1979	2.0453 0.3215	4.962943
1980	1.2429 0.7984	7.395094
1981	5.6438 0.4686	7.366287
1982	2.0182 1.4805	4.425242
1983	0.5445 0.4689	6.734627
1984	0.8334 0.5469	8.399280
1985	3.3573 0.9648	17.013898
1986	7.7959 0.6088	18.569186
1987	1.5283 0.8476	20.772159
1988	3.0433 0.7794	24.961535
1989	3.9328 1.5408	28.849537
1990	10.4935 1.1600	34.544808
1991	0.7382 2.0649	26.838075
1992	4.7499 1.3115	32.009158
1993	3.7585 2.4699	38.976844
1994	8.1238 1.4642	32.493720
1995	11.2166 1.3925	48.530518
1996	2.6204 1.4587	20.369843
1997	4.0091 1.2629	25.951093
1998	12.1192 1.5719	32.828428
1999	5.3159 1.5903	31.935066
2000	9.4112 1.5452	

Indices of relative abundance are from Delaware research trawl survey in August and September. Indices lagged to next calendar year. Geometric Mean used to estimate index.

Note that the recruit abundance index for the last year is NOT used in the least squares estimation. It is, however, used in conjunction with the least squares estimate of q_n and the selectivity of the recruits to calculate recruit population size in 2000 (see RESULTS section).

MEAN WEIGHT (kg) AT THE TIME OF THE SURVEY

CALENDAR YEAR	RECRUITS	FULLY-RECRUITED
1979	0.030	0.149
1980	0.008	0.166
1981	0.011	0.155
1982	0.033	0.163
1983	0.022	0.176
1984	0.017	0.165
1985	0.031	0.167
1986	0.029	0.141
1987	0.031	0.146
1988	0.022	0.135
1989	0.009	0.131
1990	0.025	0.164
1991	0.017	0.181
1992	0.030	0.142
1993	0.029	0.155
1994	0.011	0.141
1995	0.029	0.139
1996	0.031	0.131
1997	0.025	0.136
1998	0.027	0.139
1999	0.025	0.138
2000	0.022	0.138

SELECTIVITY OF RECRUITS TO THE SURVEY GEAR

Selectivity of the recruits (relative to the fully-recruited animals) to the survey gear is set at:

1979	1.0000
1980	1.0000
1981	1.0000
1982	1.0000
1983	1.0000
1984	1.0000
1985	1.0000
1986	1.0000
1987	1.0000
1988	1.0000
1989	1.0000
1990	1.0000
1991	1.0000
1992	1.0000
1993	1.0000
1994	1.0000
1995	1.0000
1996	1.0000
1997	1.0000
1998	1.0000
1999	1.0000
2000	1.0000

PARTIAL RECRUITMENT (OF RECRUITS) TO THE COMMERCIAL FISHERY

A survey year (SY) is the period between successive annual surveys. Partial recruitment (PR) of the recruits to the commercial fishery is a function of month during the survey year. As animals grow in size, partial recruitment increases, eventually reaching 1.0 at the end of each survey year. The PR function may vary over SYs due to changes in regulations and/or unusually small (or large) mean size of the recruits. The following table gives the input PR functions for each survey year. The rows of the table represent the percent of the SY completed, e.g. 0 represents the beginning of the SY and 100 (**) represents the end of the SY. The annual average partial recruitment (shown after this table) results from integrating the annual PR functions with respect to time during the SY.

PARTIAL RECRUITMENT DURING EACH SURVEY YEAR

	p	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
0	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
42	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	p	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
58	p	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
67	p	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76
75	p	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
83	p	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
92	p	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
**	p	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

	p	1994	1995	1996	1997	1998	1999	2000
0	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00
42	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	p	0.36	0.36	0.36	0.36	0.36	0.36	0.36
58	p	0.50	0.50	0.50	0.50	0.50	0.50	0.50
67	p	0.76	0.76	0.76	0.76	0.76	0.76	0.76
75	p	0.89	0.89	0.89	0.89	0.89	0.89	0.89
83	p	1.00	1.00	1.00	1.00	1.00	1.00	1.00
92	p	1.00	1.00	1.00	1.00	1.00	1.00	1.00
**	p	1.00	1.00	1.00	1.00	1.00	1.00	1.00

AVERAGE PARTIAL RECRUITMENT OF RECRUITS TO THE COMMERCIAL FISHERY

Survey Year	Average Partial Recruitment
1979	0.418
1980	0.418
1981	0.418
1982	0.418
1983	0.418
1984	0.418
1985	0.418
1986	0.418
1987	0.418
1988	0.418
1989	0.418
1990	0.418
1991	0.418
1992	0.418
1993	0.418

1994	0.418
1995	0.418
1996	0.418
1997	0.418
1998	0.418
1999	0.418
2000	0.418

OTHER INPUT DATA AND OPTIONS

Measurement error in the abundance indices for both the recruits and the fully-recruited is assumed to be lognormally distributed. Process error is assumed to follow a lognormal distribution.

The input objective function weights are normalized (so that they will sum to 1.0) prior to their use in the estimation. Both the original input weights and the normalized weights are given below. The square root of the normalized weights is printed in the residual tables near the end of the RESULTS section (under the heading "WEIGHT").

YEAR	-- ORIGINAL INPUT WEIGHTS --			---- NORMALIZED WEIGHTS ----		
	Measurement Error n Index	Process Error r Index	Error	Measurement Error n Index	Process Error r Index	Error
1979	1.0000	1.0000	¥999.0000	0.0156	0.0156	¥999.0000
1980	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1981	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1982	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1983	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1984	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1985	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1986	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1987	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1988	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1989	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1990	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1991	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1992	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1993	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1994	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1995	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1996	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1997	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1998	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
1999	1.0000	1.0000	1.0000	0.0156	0.0156	0.0156
2000	1.0000	¥999.0000	1.0000	0.0156	¥999.0000	0.0156

¥999 indicates that no weighting is used for that year-error type combination

Initial estimates of parameters for the Marquardt algorithm and lower and upper bounds on the parameter estimates:

	Parameter	Initial Est	Lower Bnd	Upper Bnd
1	n 2+ 1979	3.2147804E¥1	1.0000000E¥10	1.0000000E6
2	n 2+ 1980	7.9842365E¥1	1.0000000E¥10	1.0000000E6
3	n 2+ 1981	4.6861458E¥1	1.0000000E¥10	1.0000000E6
4	n 2+ 1982	1.4804809E0	1.0000000E¥10	1.0000000E6
5	n 2+ 1983	4.6892669E¥1	1.0000000E¥10	1.0000000E6
6	n 2+ 1984	5.4690237E¥1	1.0000000E¥10	1.0000000E6
7	n 2+ 1985	9.6478088E¥1	1.0000000E¥10	1.0000000E6
8	n 2+ 1986	6.0882814E¥1	1.0000000E¥10	1.0000000E6
9	n 2+ 1987	8.4764424E¥1	1.0000000E¥10	1.0000000E6
10	n 2+ 1988	7.7935546E¥1	1.0000000E¥10	1.0000000E6
11	n 2+ 1989	1.5408005E0	1.0000000E¥10	1.0000000E6
12	n 2+ 1990	1.1600350E0	1.0000000E¥10	1.0000000E6
13	n 2+ 1991	2.0649045E0	1.0000000E¥10	1.0000000E6
14	n 2+ 1992	1.3115100E0	1.0000000E¥10	1.0000000E6
15	n 2+ 1993	2.4699145E0	1.0000000E¥10	1.0000000E6
16	n 2+ 1994	1.4642287E0	1.0000000E¥10	1.0000000E6

17	n 2+	1995	1.3924563E0	1.0000000EY10	1.0000000E6
18	n 2+	1996	1.4586743E0	1.0000000EY10	1.0000000E6
19	n 2+	1997	1.2628600E0	1.0000000EY10	1.0000000E6
20	n 2+	1998	1.5718600E0	1.0000000EY10	1.0000000E6
21	n 2+	1999	1.5902500E0	1.0000000EY10	1.0000000E6
22	n 2+	2000	1.5452000E0	1.0000000EY10	1.0000000E6
23	r 1	1979	2.0453446E0	1.0000000EY10	1.0000000E6
24	r 1	1980	1.2428788E0	1.0000000EY10	1.0000000E6
25	r 1	1981	5.6437959E0	1.0000000EY10	1.0000000E6
26	r 1	1982	2.0181845E0	1.0000000EY10	1.0000000E6
27	r 1	1983	5.4453684EY1	1.0000000EY10	1.0000000E6
28	r 1	1984	8.3343906EY1	1.0000000EY10	1.0000000E6
29	r 1	1985	3.3572986E0	1.0000000EY10	1.0000000E6
30	r 1	1986	7.7959008E0	1.0000000EY10	1.0000000E6
31	r 1	1987	1.5283138E0	1.0000000EY10	1.0000000E6
32	r 1	1988	3.0432744E0	1.0000000EY10	1.0000000E6
33	r 1	1989	3.9327780E0	1.0000000EY10	1.0000000E6
34	r 1	1990	1.0493495E1	1.0000000EY10	1.0000000E6
35	r 1	1991	7.3815882EY1	1.0000000EY10	1.0000000E6
36	r 1	1992	4.7499042E0	1.0000000EY10	1.0000000E6
37	r 1	1993	3.7585139E0	1.0000000EY10	1.0000000E6
38	r 1	1994	8.1238042E0	1.0000000EY10	1.0000000E6
39	r 1	1995	1.1216573E1	1.0000000EY10	1.0000000E6
40	r 1	1996	2.6203879E0	1.0000000EY10	1.0000000E6
41	r 1	1997	4.0091000E0	1.0000000EY10	1.0000000E6
42	r 1	1998	1.2119200E1	1.0000000EY10	1.0000000E6
43	r 1	1999	5.3159000E0	1.0000000EY10	1.0000000E6
44	Surv q_n		1.0000000EY3	1.0000000EY10	1.0000000E3

BEGIN MARQUARDT ALGORITHM

LAMBDA 1.00000EY2
 RSS 2.14988EY1
 NPFI 2.14988EY1

par
 3.21478EY1 7.98424EY1 4.68615EY1 1.48048E0 4.68927EY1 5.
 46902EY1 9.64781EY1 6.08828EY1 8.47644EY1 7.79355EY1 1
 .54080E0 1.16003E0 2.06490E0 1.31151E0 2.46991E0
 1.46423E0 1.39246E0 1.45867E0 1.26286E0 1.57186E0
 1.59025E0 1.54520E0 2.04534E0 1.24288E0 5.64380E0
 2.01818E0 5.44537EY1 8.33439EY1 3.35730E0 7.79590E0
 1.52831E0 3.04327E0 3.93278E0 1.04935E1 7.38159EY1
 4.74990E0 3.75851E0 8.12380E0 1.12166E1 2.62039E0
 4.00910E0 1.21192E1 5.31590E0 1.00000EY3

LAMBDA 1.00000EY3
 RSS 5.96355EY2
 NPFI 5.96355EY2

par
 3.18628EY1 7.98029EY1 5.36978EY1 1.57937E0 7.32125EY1 4.
 82406EY1 5.22061EY1 7.67555EY1 1.26502E0 7.18216EY1 1
 .24778E0 1.26803E0 2.85866E0 9.81322EY1 2.06746E0
 1.46032E0 1.78947E0 2.00417E0 1.30751E0 1.53067E0
 2.21233E0 1.78660E0 1.93048E0 1.11679E0 4.33473E0
 1.51262E0 6.26272EY1 1.03351E0 2.58526E0 4.51368E0
 1.63954E0 3.43246E0 3.61750E0 8.85546E0 7.94341EY1
 5.29010E0 3.64827E0 5.84775E0 7.30963E0 2.55063E0
 3.93739E0 7.51078E0 4.67086E0 5.08642EY2

LAMBDA 1.00000EY4
 RSS 5.10746EY2
 NPFI 5.10746EY2

par
 3.18242EY1 7.82315EY1 5.15601EY1 1.50968E0 8.35479EY1 5.
 26934EY1 6.53626EY1 6.76756EY1 1.34761E0 7.35277EY1 1

n 2+ 1985	0.9648	0.6526	0.1250	0.0489	0.9680	4.7
n 2+ 1986	0.6088	0.6914	0.1250	y0.0159	y0.3148	0.5
n 2+ 1987	0.8476	1.3526	0.1250	y0.0584	y1.1572	6.7
n 2+ 1988	0.7794	0.7220	0.1250	0.0096	0.1892	0.2
n 2+ 1989	1.5408	1.3071	0.1250	0.0206	0.4073	0.8
n 2+ 1990	1.1600	1.1823	0.1250	y0.0024	y0.0471	0.0
n 2+ 1991	2.0649	3.3032	0.1250	y0.0587	y1.1633	6.8
n 2+ 1992	1.3115	1.0826	0.1250	0.0240	0.4750	1.1
n 2+ 1993	2.4699	2.1868	0.1250	0.0152	0.3014	0.5
n 2+ 1994	1.4642	1.3313	0.1250	0.0119	0.2356	0.3
n 2+ 1995	1.3925	1.6374	0.1250	y0.0203	y0.4012	0.8
n 2+ 1996	1.4587	1.8842	0.1250	y0.0320	y0.6338	2.0
n 2+ 1997	1.2629	1.2693	0.1250	y0.0006	y0.0127	0.0
n 2+ 1998	1.5719	1.4464	0.1250	0.0104	0.2060	0.2
n 2+ 1999	1.5903	2.1398	0.1250	y0.0371	y0.7350	2.7
n 2+ 2000	1.5452	1.7174	0.1250	y0.0132	y0.2615	0.3
SUM				y0.1763	y3.4916	38.6

MEASUREMENT ERROR -- Recruit index with lognormal errors

ERROR TERM	OBSERVED	PREDICTED	WEIGHT	RESIDUAL	STD RES	%SS
r 1 1979	2.0453	1.9304	0.1250	0.0072	0.1432	0.1
r 1 1980	1.2429	1.1177	0.1250	0.0133	0.2628	0.3
r 1 1981	5.6438	4.4067	0.1250	0.0309	0.6126	1.9
r 1 1982	2.0182	1.6102	0.1250	0.0282	0.5592	1.6
r 1 1983	0.5445	0.6329	0.1250	y0.0188	y0.3724	0.7
r 1 1984	0.8334	1.2195	0.1250	y0.0476	y0.9425	4.4
r 1 1985	3.3573	2.5922	0.1250	0.0323	0.6404	2.1
r 1 1986	7.7959	5.1152	0.1250	0.0527	1.0433	5.4
r 1 1987	1.5283	1.7754	0.1250	y0.0187	y0.3711	0.7
r 1 1988	3.0433	3.8283	0.1250	y0.0287	y0.5682	1.6
r 1 1989	3.9328	3.7701	0.1250	0.0053	0.1046	0.1
r 1 1990	10.4935	9.5778	0.1250	0.0114	0.2261	0.3
r 1 1991	0.7382	0.8143	0.1250	y0.0123	y0.2430	0.3
r 1 1992	4.7499	5.7653	0.1250	y0.0242	y0.4797	1.2
r 1 1993	3.7585	3.8944	0.1250	y0.0044	y0.0879	0.0
r 1 1994	8.1238	5.9644	0.1250	0.0386	0.7651	2.9
r 1 1995	11.2166	7.7643	0.1250	0.0460	0.9108	4.1
r 1 1996	2.6204	2.6159	0.1250	0.0002	0.0043	0.0
r 1 1997	4.0091	4.0508	0.1250	y0.0013	y0.0256	0.0
r 1 1998	12.1192	8.0042	0.1250	0.0519	1.0271	5.3
r 1 1999	5.3159	4.7259	0.1250	0.0147	0.2913	0.4
SUM				0.1767	3.5003	33.4

PROCESS ERROR -- DeLury equation with lognormal errors

ERROR TERM	CALCULATED	PREDICTED	WEIGHT	RESIDUAL	STD RES	%SS
n 2+ 1980	0.8276	0.7832	0.1250	0.0069	0.1366	0.1
n 2+ 1981	0.5818	0.5146	0.1250	0.0153	0.3036	0.5
n 2+ 1982	1.9400	1.5225	0.1250	0.0303	0.6000	1.8
n 2+ 1983	1.2446	0.8442	0.1250	0.0485	0.9610	4.6
n 2+ 1984	0.4157	0.5172	0.1250	y0.0273	y0.5411	1.5
n 2+ 1985	0.4710	0.6526	0.1250	y0.0408	y0.8075	3.3
n 2+ 1986	0.8313	0.6914	0.1250	0.0230	0.4563	1.0
n 2+ 1987	1.9251	1.3526	0.1250	0.0441	0.8738	3.8
n 2+ 1988	0.6404	0.7220	0.1250	y0.0150	y0.2971	0.4
n 2+ 1989	1.1252	1.3071	0.1250	y0.0187	y0.3711	0.7
n 2+ 1990	1.2187	1.1823	0.1250	0.0038	0.0750	0.0
n 2+ 1991	3.5624	3.3032	0.1250	0.0094	0.1870	0.2
n 2+ 1992	0.8616	1.0826	0.1250	y0.0285	y0.5654	1.6
n 2+ 1993	1.8979	2.1868	0.1250	y0.0177	y0.3509	0.6
n 2+ 1994	1.2968	1.3313	0.1250	y0.0033	y0.0651	0.0
n 2+ 1995	2.0813	1.6374	0.1250	0.0300	0.5939	1.8
n 2+ 1996	2.4369	1.8842	0.1250	0.0322	0.6368	2.0
n 2+ 1997	1.2717	1.2693	0.1250	0.0002	0.0046	0.0
n 2+ 1998	1.4346	1.4464	0.1250	y0.0010	y0.0202	0.0
n 2+ 1999	3.0372	2.1398	0.1250	0.0438	0.8671	3.8
n 2+ 2000	1.9087	1.7174	0.1250	0.0132	0.2615	0.3
SUM				0.1484	2.9388	28.0

64 residual error terms

1979	1.149	0.937	2.086	1.417	0.692
1980	0.172	2.557	2.729	2.629	1.086
1981	0.930	1.567	2.497	1.956	1.051
1982	1.044	4.880	5.925	5.316	0.668
1983	0.270	2.931	3.200	3.043	1.008
1984	0.401	1.683	2.085	1.851	1.233
1985	1.584	2.147	3.731	2.809	2.510
1986	2.934	1.927	4.862	3.153	2.620
1987	1.092	3.885	4.977	4.341	2.990
1988	1.691	1.914	3.605	2.620	3.420
1989	0.684	3.383	4.067	3.669	4.110
1990	4.777	3.825	8.602	5.820	4.880
1991	0.279	11.787	12.066	11.903	4.030
1992	3.398	3.026	6.425	4.445	4.230
1993	2.203	6.699	8.903	7.620	5.610
1994	1.305	3.687	4.993	4.232	4.440
1995	4.393	4.500	8.893	6.334	6.480
1996	1.604	4.877	6.481	5.547	3.025
1997	1.964	3.396	5.360	4.216	3.702
1998	4.229	3.961	8.189	5.727	4.554
1999	2.283	5.834	8.117	6.787	4.623
2000	4.082	4.672	8.754	6.377	

CALENDAR YEAR	EXPLOITED BIOMASS	1000 Metric Tons DELTA B	CATCH	SURPLUS PRODUCTION	PROD-BIOMASS RATIO
1979	1.417	1.212	0.692	1.904	1.3433
1980	2.629	y0.673	1.086	0.413	0.1571
1981	1.956	3.361	1.051	4.412	2.2560
1982	5.316	y2.273	0.668	y1.605	y0.3019
1983	3.043	y1.192	1.008	y0.184	y0.0606
1984	1.851	0.958	1.233	2.191	1.1835
1985	2.809	0.344	2.510	2.854	1.0161
1986	3.153	1.189	2.620	3.809	1.2080
1987	4.341	y1.721	2.990	1.269	0.2924
1988	2.620	1.048	3.420	4.468	1.7053
1989	3.669	2.151	4.110	6.261	1.7065
1990	5.820	6.084	4.880	10.964	1.8839
1991	11.903	y7.458	4.030	y3.428	y0.2880
1992	4.445	3.174	4.230	7.404	1.6656
1993	7.620	y3.387	5.610	2.223	0.2917
1994	4.232	2.102	4.440	6.542	1.5456
1995	6.334	y0.787	6.480	5.693	0.8987
1996	5.547	y1.331	3.025	1.694	0.3054
1997	4.216	1.510	3.702	5.212	1.2363
1998	5.727	1.061	4.554	5.615	0.9805
1999	6.787	y0.411	4.623	4.212	0.6206
2000	6.377				

The SURPLUS PRODUCTION table, above, assumes that DELTA B over the course of a calendar year can be approximated by differencing the successive EXPLOITED BIOMASS estimates at time of the survey. More specifically, this assumes that the change in EXPLOITED BIOMASS between Jan 1 and the time of the survey is constant in successive years. Note also that the PRODUCTION-BIOMASS RATIO is with respect to exploited biomass at time of the survey.

SUMMARY OF RESIDUALS FROM THE FITTED MODEL

MEASUREMENT ERROR -- Fully-recruited index with lognormal errors

ERROR TERM	OBSERVED	PREDICTED	WEIGHT	RESIDUAL	STD RES	%SS
n 2+ 1979	0.3215	0.3184	0.1250	0.0012	0.0237	0.0
n 2+ 1980	0.7984	0.7832	0.1250	0.0024	0.0476	0.0
n 2+ 1981	0.4686	0.5146	0.1250	y0.0117	y0.2319	0.3
n 2+ 1982	1.4805	1.5225	0.1250	y0.0035	y0.0693	0.0
n 2+ 1983	0.4689	0.8442	0.1250	y0.0735	y1.4559	10.6
n 2+ 1984	0.5469	0.5172	0.1250	0.0070	0.1383	0.1

13	p	0.00	0.00	y0.03	0.00	0.02	y0.03	y0.03	y0.03	0.02	y0.04	y0.02	0.00
14	p	0.00	0.00	0.02	0.00	y0.01	0.02	0.02	0.02	y0.01	0.03	0.01	0.04
15	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	p	0.00	0.00	0.02	0.00	y0.01	0.02	0.02	0.02	y0.01	0.03	0.01	0.02
17	p	0.00	0.00	0.01	0.00	y0.01	0.01	0.01	0.01	y0.01	0.01	0.01	0.01
18	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01
19	p	0.00	0.00	0.01	0.00	y0.01	0.01	0.01	0.01	y0.01	0.02	0.01	0.01
20	p	0.00	0.00	0.01	0.00	y0.01	0.01	0.01	0.01	y0.01	0.02	0.01	0.02
21	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01
22	p	0.00	0.00	0.01	0.00	y0.01	0.01	0.01	0.02	y0.01	0.02	0.01	0.02
23	p	y0.08	0.49	0.09	0.00	0.01	y0.01	y0.01	y0.01	0.01	y0.01	y0.01	y0.01
24	p	y0.01	y0.17	0.39	0.02	0.01	y0.01	y0.01	y0.01	0.01	y0.02	y0.01	y0.01
25	p	0.00	y0.01	y0.05	0.48	0.11	0.03	0.00	y0.01	0.00	y0.01	0.00	y0.01
26	p	0.00	0.00	y0.01	y0.13	0.29	0.09	0.01	y0.01	0.00	y0.01	0.00	y0.01
27	p	0.00	0.00	y0.01	y0.04	y0.19	0.29	0.03	y0.01	0.01	y0.02	y0.01	y0.01
28	p	0.00	0.00	y0.02	y0.01	y0.04	y0.19	0.46	0.02	0.02	y0.03	y0.01	y0.03
29	p	0.00	0.00	y0.03	0.00	0.01	y0.04	y0.17	0.51	0.04	y0.03	y0.02	y0.03
30	p	0.00	0.00	y0.02	0.00	0.01	y0.02	y0.03	y0.09	0.51	0.09	y0.01	y0.02
31	p	0.00	0.00	y0.03	0.00	0.02	y0.03	y0.03	y0.05	y0.29	0.36	0.01	y0.03
32	p	0.00	0.00	y0.03	0.00	0.02	y0.03	y0.03	y0.03	y0.01	y0.17	0.52	0.03
33	p	0.00	0.00	y0.03	0.00	0.02	y0.03	y0.03	y0.03	0.02	y0.05	y0.21	0.48
34	p	0.00	0.00	y0.03	0.00	0.02	y0.03	y0.03	y0.03	0.02	y0.04	y0.03	y0.11
35	p	0.00	0.00	y0.01	0.00	0.01	y0.01	y0.01	y0.01	0.01	y0.01	y0.01	y0.02
36	p	0.00	0.00	y0.03	0.00	0.02	y0.02	y0.03	y0.03	0.02	y0.04	y0.02	y0.03
37	p	0.00	0.00	y0.03	0.00	0.02	y0.03	y0.03	y0.03	0.02	y0.05	y0.02	y0.04
38	p	0.00	0.00	y0.02	0.00	0.01	y0.02	y0.02	y0.02	0.01	y0.03	y0.01	y0.02
39	p	0.00	0.00	y0.03	0.00	0.02	y0.03	y0.03	y0.03	0.02	y0.04	y0.02	y0.03
40	p	0.00	0.00	y0.02	0.00	0.01	y0.01	y0.02	y0.02	0.01	y0.02	y0.01	y0.02
41	p	0.00	0.00	y0.02	0.00	0.01	y0.02	y0.02	y0.02	0.02	y0.03	y0.01	y0.03
42	p	0.00	0.00	y0.02	0.00	0.01	y0.01	y0.01	y0.02	0.01	y0.02	y0.01	y0.02
43	p	0.00	0.00	y0.02	0.00	0.01	y0.02	y0.02	y0.02	0.01	y0.03	y0.01	y0.02
44	p	0.01	0.00	y0.11	0.00	0.06	y0.10	y0.11	y0.12	0.08	y0.17	y0.07	y0.13

p	13	14	15	16	17	18	19	20	21	22	23	24
1	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	y0.08	y0.01
2	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.49	y0.17
3	p	y0.03	0.02	0.00	0.02	0.01	0.00	0.01	0.01	0.00	0.01	0.09
4	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
5	p	0.02	y0.01	0.00	y0.01	y0.01	0.00	y0.01	y0.01	0.00	y0.01	0.01
6	p	y0.03	0.02	0.00	0.02	0.01	0.00	0.01	0.01	0.00	0.01	y0.01
7	p	y0.03	0.02	0.00	0.02	0.01	0.00	0.01	0.01	0.00	0.01	y0.01
8	p	y0.03	0.02	0.00	0.02	0.01	0.01	0.01	0.01	0.00	0.02	y0.01
9	p	0.02	y0.01	0.00	y0.01	y0.01	0.00	y0.01	y0.01	0.00	y0.01	0.01
10	p	y0.04	0.03	0.00	0.03	0.01	0.01	0.02	0.02	0.01	0.02	y0.01
11	p	y0.02	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01	y0.01
12	p	0.00	0.04	0.00	0.02	0.01	0.01	0.01	0.02	0.01	0.02	y0.01
13	p	1.00	0.47	0.03	y0.04	y0.02	y0.01	y0.03	y0.03	y0.01	y0.03	0.02
14	p	0.47	1.00	0.06	0.04	0.01	0.01	0.02	0.02	0.01	0.02	y0.01
15	p	0.03	0.06	1.00	0.18	0.01	0.00	0.00	0.00	0.00	0.00	0.00
16	p	y0.04	0.04	0.18	1.00	0.09	0.01	0.02	0.02	0.01	0.02	y0.01
17	p	y0.02	0.01	0.01	0.09	1.00	0.07	0.03	0.01	0.00	0.01	y0.01
18	p	y0.01	0.01	0.00	0.01	0.07	1.00	0.23	0.03	0.00	0.01	0.00
19	p	y0.03	0.02	0.00	0.02	0.03	0.23	1.00	0.12	0.01	0.02	y0.01
20	p	y0.03	0.02	0.00	0.02	0.01	0.03	0.12	1.00	0.07	0.02	y0.01
21	p	y0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.07	1.00	0.16	0.00
22	p	y0.03	0.02	0.00	0.02	0.01	0.01	0.02	0.02	0.16	1.00	y0.01
23	p	0.02	y0.01	0.00	y0.01	y0.01	0.00	y0.01	y0.01	0.00	y0.01	1.00
24	p	0.02	y0.02	0.00	y0.02	y0.01	0.00	y0.01	y0.01	0.00	y0.01	y0.08
25	p	0.01	y0.01	0.00	y0.01	0.00	0.00	y0.01	y0.01	0.00	y0.01	0.00
26	p	0.01	y0.01	0.00	y0.01	0.00	0.00	y0.01	y0.01	0.00	y0.01	0.00
27	p	0.03	y0.02	0.00	y0.02	y0.01	0.00	y0.01	y0.01	0.00	y0.01	0.01
28	p	0.05	y0.03	0.00	y0.03	y0.02	y0.01	y0.02	y0.02	y0.01	y0.03	0.01
29	p	0.06	y0.04	0.00	y0.04	y0.02	y0.01	y0.03	y0.03	y0.01	y0.03	0.02
30	p	0.05	y0.03	0.00	y0.03	y0.01	y0.01	y0.02	y0.02	y0.01	y0.02	0.01
31	p	0.07	y0.05	0.00	y0.04	y0.02	y0.01	y0.03	y0.03	y0.01	y0.04	0.02
32	p	0.07	y0.05	0.00	y0.04	y0.02	y0.01	y0.03	y0.03	y0.01	y0.04	0.02
33	p	0.08	y0.03	0.00	y0.04	y0.02	y0.01	y0.03	y0.03	y0.01	y0.03	0.02
34	p	0.45	0.17	0.01	y0.04	y0.02	y0.01	y0.03	y0.03	y0.01	y0.03	0.02
35	p	y0.18	0.10	0.01	y0.01	y0.01	0.00	y0.01	y0.01	0.00	y0.01	0.01
36	p	0.01	y0.15	0.52	0.06	y0.01	y0.01	y0.03	y0.03	y0.01	y0.03	0.02

.31811E0	1.18497E0	3.26792E0	1.10700E0	2.19341E0
1.32942E0	1.62242E0	1.88166E0	1.27241E0	1.43922E0
2.13771E0	1.72512E0	1.92428E0	1.11405E0	4.38528E0
1.61957E0	6.42606EY1	1.20749E0	2.53199E0	5.05999E0
1.75960E0	3.78128E0	3.72219E0	9.49936E0	8.22377EY1
5.70256E0	3.82561E0	5.92828E0	7.70353E0	2.60173E0
4.00970E0	7.95787E0	4.70725E0	4.94544EY2	

LAMBDA 1.00000EY5
RSS 5.09771EY2
NPHI 5.09771EY2

par

3.18446EY1	7.83538EY1	5.14532EY1	1.52483E0	8.42534EY1	5.
16519EY1	6.49008EY1	6.91585EY1	1.35311E0	7.20451EY1	1
.30366E0	1.18110E0	3.29430E0	1.07797E0	2.18375E0	
1.32891E0	1.63941E0	1.88681E0	1.26901E0	1.44540E0	
2.14244E0	1.71747E0	1.93191E0	1.11940E0	4.41360E0	
1.60712E0	6.33398EY1	1.21255E0	2.60182E0	5.12343E0	
1.77457E0	3.82453E0	3.77814E0	9.57583E0	8.14850EY1	
5.76308E0	3.89987E0	5.98575E0	7.79123E0	2.61737E0	
4.05462E0	8.02831E0	4.73428E0	5.09183EY2		

LAMBDA 1.00000EY5
RSS 5.09737EY2
NPHI 5.09737EY2

par

3.18414EY1	7.83227EY1	5.14625EY1	1.52250E0	8.44245EY1	5.
17200EY1	6.52598EY1	6.91379EY1	1.35264E0	7.22014EY1	1
.30709E0	1.18230E0	3.30324E0	1.08255E0	2.18682E0	
1.33130E0	1.63742E0	1.88422E0	1.26935E0	1.44638E0	
2.13982E0	1.71735E0	1.93039E0	1.11773E0	4.40670E0	
1.61020E0	6.32916EY1	1.21954E0	2.59221E0	5.11521E0	
1.77540E0	3.82833E0	3.77009E0	9.57783E0	8.14285EY1	
5.76531E0	3.89437E0	5.96439E0	7.76434E0	2.61586E0	
4.05082E0	8.00420E0	4.72590E0	5.07260EY2		

RELATIVE CHANGE IN RESIDUAL SUM OF SQUARES LESS THAN 0.00001

RESULTS

APPROXIMATE STATISTICS ASSUMING LINEARITY NEAR SOLUTION

SUM OF SQUARES	0.050974
ORTHOGONALITY OFFSET.....	0.008616
MEAN SQUARE RESIDUALS	0.002549

	PARAMETER	PAR. EST.	STD. ERR.	T-STATISTIC	C.V.
1	n 2+ 1979	3.18414EY1	1.28600EY1	2.47601E0	0.40
2	n 2+ 1980	7.83227EY1	2.51017EY1	3.12022E0	0.32
3	n 2+ 1981	5.14625EY1	1.71290EY1	3.00440E0	0.33
4	n 2+ 1982	1.52250E0	4.83543EY1	3.14864E0	0.32
5	n 2+ 1983	8.44245EY1	2.43097EY1	3.47288E0	0.29
6	n 2+ 1984	5.17200EY1	1.67832EY1	3.08165E0	0.32
7	n 2+ 1985	6.52598EY1	2.22867EY1	2.92820E0	0.34
8	n 2+ 1986	6.91379EY1	2.44383EY1	2.82908E0	0.35
9	n 2+ 1987	1.35264E0	4.26801EY1	3.16926E0	0.32
10	n 2+ 1988	7.22014EY1	2.57343EY1	2.80565E0	0.36
11	n 2+ 1989	1.30709E0	4.57092EY1	2.85959E0	0.35
12	n 2+ 1990	1.18230E0	4.19780EY1	2.81648E0	0.36
13	n 2+ 1991	3.30324E0	8.34621EY1	3.95777E0	0.25
14	n 2+ 1992	1.08255E0	3.87637EY1	2.79270E0	0.36
15	n 2+ 1993	2.18682E0	7.25767EY1	3.01312E0	0.33
16	n 2+ 1994	1.33130E0	4.74386EY1	2.80637E0	0.36
17	n 2+ 1995	1.63742E0	5.65337EY1	2.89636E0	0.35
18	n 2+ 1996	1.88422E0	6.29293EY1	2.99419E0	0.33
19	n 2+ 1997	1.26935E0	4.23313EY1	2.99860E0	0.33

20	n 2+	1998	1.44638E0	5.02773Ey1	2.87681E0	0.35
21	n 2+	1999	2.13982E0	7.12134Ey1	3.00480E0	0.33
22	n 2+	2000	1.71735E0	5.91374Ey1	2.90401E0	0.34
23	r 1	1979	1.93039E0	6.26315Ey1	3.08213E0	0.32
24	r 1	1980	1.11773E0	3.94865Ey1	2.83067E0	0.35
25	r 1	1981	4.40670E0	1.43748E0	3.06558E0	0.33
26	r 1	1982	1.61020E0	6.04015Ey1	2.66583E0	0.38
27	r 1	1983	6.32916Ey1	2.36613Ey1	2.67490E0	0.37
28	r 1	1984	1.21954E0	3.94814Ey1	3.08891E0	0.32
29	r 1	1985	2.59221E0	7.75650Ey1	3.34198E0	0.30
30	r 1	1986	5.11521E0	1.57994E0	3.23760E0	0.31
31	r 1	1987	1.77540E0	5.94465Ey1	2.98655E0	0.33
32	r 1	1988	3.82833E0	1.10215E0	3.47350E0	0.29
33	r 1	1989	3.77009E0	1.15214E0	3.27223E0	0.31
34	r 1	1990	9.57783E0	2.83459E0	3.37891E0	0.30
35	r 1	1991	8.14285Ey1	3.24432Ey1	2.50988E0	0.40
36	r 1	1992	5.76531E0	1.72191E0	3.34821E0	0.30
37	r 1	1993	3.89437E0	1.24805E0	3.12036E0	0.32
38	r 1	1994	5.96439E0	1.83145E0	3.25666E0	0.31
39	r 1	1995	7.76434E0	2.27376E0	3.41476E0	0.29
40	r 1	1996	2.61586E0	9.16669Ey1	2.85365E0	0.35
41	r 1	1997	4.05082E0	1.26171E0	3.21058E0	0.31
42	r 1	1998	8.00420E0	2.50468E0	3.19570E0	0.31
43	r 1	1999	4.72590E0	1.55067E0	3.04766E0	0.33
44	Surv a n		5.07260Ey2	1.14054Ey2	4.44752E0	0.22

[illegible]

r 1	1992	2.832E0	4.368E0	4.809E0	5.486E0	6.273E0	7.018E0	9.398E0
r 1	1993	1.923E0	2.839E0	3.258E0	3.710E0	4.193E0	4.672E0	6.151E0
r 1	1994	3.282E0	4.653E0	5.149E0	5.857E0	6.540E0	7.138E0	9.940E0
r 1	1995	4.814E0	6.186E0	6.816E0	7.560E0	8.350E0	9.098E0	1.134E1
r 1	1996	1.096E0	1.851E0	2.137E0	2.523E0	2.983E0	3.292E0	4.079E0
r 1	1997	2.447E0	3.065E0	3.407E0	3.839E0	4.445E0	4.993E0	6.778E0
r 1	1998	5.060E0	6.324E0	6.979E0	7.859E0	8.723E0	9.640E0	1.187E1
r 1	1999	2.736E0	3.478E0	3.933E0	4.629E0	5.262E0	5.873E0	7.070E0

PARAMETER	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE	
r 1	1983	0.00000000	0.01344741	0.00	0.7089	0.27
r 1	1984	0.00000000	0.01773951	0.00	1.2083	0.21
r 1	1985	0.00000000	0.02966388	0.00	2.5525	0.16
r 1	1986	0.00000000	0.05964320	0.00	5.0466	0.17
r 1	1987	0.00000000	0.02603069	0.00	1.7043	0.22
r 1	1988	0.00000000	0.04879603	0.00	3.6946	0.19
r 1	1989	0.00000000	0.04955326	0.00	3.6725	0.19
r 1	1990	0.00000000	0.10805342	0.00	9.2885	0.16
r 1	1991	0.00000000	0.01677541	0.00	0.8033	0.30
r 1	1992	0.00000000	0.07575091	0.00	5.5885	0.19
r 1	1993	0.00000000	0.05273004	0.00	3.7628	0.20
r 1	1994	0.00000000	0.07281285	0.00	5.8927	0.17
r 1	1995	0.00000000	0.08265706	0.00	7.6315	0.15
r 1	1996	0.00000000	0.04091861	0.00	2.5633	0.23
r 1	1997	0.00000000	0.05264352	0.00	3.9600	0.19
r 1	1998	0.00000000	0.09243937	0.00	7.9511	0.16
r 1	1999	0.00000000	0.06648555	0.00	4.6562	0.20

BOOTSTRAP OUTPUT VARIABLE: q_hat
Catchability of the fully-recruited animals to the survey gear

PARAMETER	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
Surv q_n	4.643Ey2	4.643Ey2	6.678Ey3	0.14

PARAMETER	MIN	10	25	MEDIAN	75	90	MAX
Surv q_n	2.749Ey2	3.848Ey2	4.144Ey2	4.557Ey2	5.156Ey2	5.532Ey2	6.975Ey2

PARAMETER	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE
Surv q_n	6.384Ey18	4.722Ey4	0.00	4.643Ey2	0.14

BOOTSTRAP OUTPUT VARIABLE: msr
Estimated variance, i.e. the mse from the nonlinear least squares regression

PARAMETER	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
msr	3.300Ey3	3.300Ey3	4.773Ey4	0.14

PARAMETER	MIN	10	25	MEDIAN	75	90	MAX
msr	2.375Ey3	2.751Ey3	2.921Ey3	3.238Ey3	3.635Ey3	3.902Ey3	5.513Ey3

PARAMETER	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE
msr	2.711Ey19	3.375Ey5	0.00	3.300Ey3	0.14

BOOTSTRAP OUTPUT VARIABLE: n_calculated

Forward-calculated indices of abundance for the fully-recruited group
(using the DeLury difference equation)

YEAR	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
1984	3.533Ey1	3.533Ey1	8.766Ey2	0.25
1985	4.723Ey1	4.723Ey1	1.099Ey1	0.23
1986	8.662Ey1	8.662Ey1	1.809Ey1	0.21
1987	1.958E0	1.958E0	3.703Ey1	0.19
1988	6.699Ey1	6.699Ey1	1.911Ey1	0.29
1989	1.150E0	1.150E0	2.947Ey1	0.26
1990	1.268E0	1.268E0	3.013Ey1	0.24
1991	3.550E0	3.550E0	6.632Ey1	0.19
1992	8.940Ey1	8.940Ey1	2.522Ey1	0.28
1993	1.926E0	1.926E0	4.348Ey1	0.23
1994	1.357E0	1.357E0	3.217Ey1	0.24
1995	2.163E0	2.163E0	4.584Ey1	0.21
1996	2.541E0	2.541E0	5.475Ey1	0.22
1997	1.323E0	1.323E0	3.156Ey1	0.24
1998	1.484E0	1.484E0	3.387Ey1	0.23
1999	3.126E0	3.126E0	5.683Ey1	0.18
2000	1.987E0	1.987E0	4.934Ey1	0.25

YEAR	PERCENTILES						MAX
	MIN	10	25	MEDIAN	75	90	
1984	1.708Ey1	2.496Ey1	2.908Ey1	3.410Ey1	3.987Ey1	4.736Ey1	6.871Ey1
1985	2.375Ey1	3.391Ey1	3.960Ey1	4.706Ey1	5.392Ey1	6.238Ey1	7.782Ey1
1986	4.668Ey1	6.353Ey1	7.294Ey1	8.551Ey1	9.822Ey1	1.109E0	1.553E0
1987	1.168E0	1.527E0	1.696E0	1.912E0	2.175E0	2.407E0	3.049E0
1988	3.386Ey1	4.242Ey1	5.371Ey1	6.594Ey1	7.895Ey1	9.163Ey1	1.301E0
1989	4.908Ey1	8.014Ey1	9.545Ey1	1.132E0	1.343E0	1.500E0	2.705E0
1990	5.966Ey1	9.150Ey1	1.089E0	1.237E0	1.414E0	1.638E0	2.192E0
1991	2.245E0	2.813E0	3.121E0	3.469E0	3.902E0	4.429E0	6.212E0
1992	3.652Ey1	5.905Ey1	7.220Ey1	8.700Ey1	1.060E0	1.225E0	1.857E0
1993	1.045E0	1.383E0	1.614E0	1.902E0	2.191E0	2.474E0	3.414E0
1994	6.511Ey1	9.606Ey1	1.135E0	1.355E0	1.556E0	1.735E0	2.482E0
1995	1.210E0	1.632E0	1.814E0	2.141E0	2.410E0	2.733E0	4.001E0
1996	1.324E0	1.857E0	2.137E0	2.528E0	2.844E0	3.350E0	4.343E0
1997	7.267Ey1	9.589Ey1	1.076E0	1.284E0	1.558E0	1.720E0	2.104E0
1998	7.616Ey1	1.053E0	1.230E0	1.476E0	1.712E0	1.931E0	2.941E0
1999	1.905E0	2.412E0	2.737E0	3.090E0	3.473E0	3.871E0	4.779E0
2000	1.000E0	1.366E0	1.628E0	1.931E0	2.348E0	2.641E0	3.362E0

YEAR	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE
1984	6.772Ey17	6.199Ey3	0.00	3.533Ey1	0.25
1985	y1.527Ey16	7.771Ey3	0.00	4.723Ey1	0.23
1986	3.308Ey16	1.279Ey2	0.00	8.662Ey1	0.21
1987	1.060Ey15	2.619Ey2	0.00	1.958E0	0.19
1988	y2.698Ey16	1.352Ey2	0.00	6.699Ey1	0.29
1989	y3.497Ey17	2.084Ey2	0.00	1.150E0	0.26
1990	3.753Ey16	2.131Ey2	0.00	1.268E0	0.24
1991	y8.260Ey16	4.689Ey2	0.00	3.550E0	0.19
1992	y1.660Ey16	1.783Ey2	0.00	8.940Ey1	0.28
1993	y9.748Ey16	3.074Ey2	0.00	1.926E0	0.23

37	p	0.07	y0.07	y0.28	0.40	0.01	y0.01	y0.03	y0.03	y0.01	y0.04	0.02	0.03
38	p	0.05	y0.03	y0.02	y0.15	0.51	0.03	y0.01	y0.02	y0.01	y0.02	0.01	0.02
39	p	0.07	y0.04	0.00	y0.05	y0.15	0.51	0.09	y0.02	y0.01	y0.03	0.02	0.02
40	p	0.04	y0.03	0.00	y0.03	y0.03	y0.22	0.38	0.02	0.00	y0.02	0.01	0.01
41	p	0.05	y0.03	0.00	y0.03	y0.02	y0.04	y0.17	0.49	0.02	y0.02	0.01	0.02
42	p	0.04	y0.02	0.00	y0.02	y0.01	y0.01	y0.02	y0.10	0.51	0.06	0.01	0.01
43	p	0.04	y0.03	0.00	y0.02	y0.01	y0.01	y0.02	y0.03	y0.18	0.45	0.01	0.01
44	p	0.26	y0.17	0.00	y0.16	y0.08	y0.04	y0.11	y0.12	y0.04	y0.13	0.08	0.10

	p	25	26	27	28	29	30	31	32	33	34	35	36
- 1	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	p	y0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	p	y0.05	y0.01	y0.01	y0.02	y0.03	y0.02	y0.03	y0.03	y0.03	y0.03	y0.01	y0.03
4	p	0.48	y0.13	y0.04	y0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	p	0.11	0.29	y0.19	y0.04	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.02
6	p	0.03	0.09	0.29	y0.19	y0.04	y0.02	y0.03	y0.03	y0.03	y0.03	y0.01	y0.02
7	p	0.00	0.01	0.03	0.46	y0.17	y0.03	y0.03	y0.03	y0.03	y0.03	y0.01	y0.03
8	p	y0.01	y0.01	y0.01	0.02	0.51	y0.09	y0.05	y0.03	y0.03	y0.03	y0.01	y0.03
9	p	0.00	0.00	0.01	0.02	0.04	0.51	y0.29	y0.01	0.02	0.02	0.01	0.02
10	p	y0.01	y0.01	y0.02	y0.03	y0.03	0.09	0.36	y0.17	y0.05	y0.04	y0.01	y0.04
11	p	0.00	0.00	y0.01	y0.01	y0.02	y0.01	0.01	0.52	y0.21	y0.03	y0.01	y0.02
12	p	y0.01	y0.01	y0.01	y0.03	y0.03	y0.02	y0.03	0.03	0.48	y0.11	y0.02	y0.03
13	p	0.01	0.01	0.03	0.05	0.06	0.05	0.07	0.07	0.08	0.45	y0.18	0.01
14	p	y0.01	y0.01	y0.02	y0.03	y0.04	y0.03	y0.05	y0.05	y0.03	0.17	0.10	y0.15
15	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.52
16	p	y0.01	y0.01	y0.02	y0.03	y0.04	y0.03	y0.04	y0.04	y0.04	y0.04	y0.01	0.06
17	p	0.00	0.00	y0.01	y0.02	y0.02	y0.01	y0.02	y0.02	y0.02	y0.02	y0.01	y0.01
18	p	0.00	0.00	0.00	y0.01	y0.01	y0.01	y0.01	y0.01	y0.01	y0.01	0.00	y0.01
19	p	y0.01	y0.01	y0.01	y0.02	y0.03	y0.02	y0.03	y0.03	y0.03	y0.03	y0.01	y0.03
20	p	y0.01	y0.01	y0.01	y0.02	y0.03	y0.02	y0.03	y0.03	y0.03	y0.03	y0.01	y0.03
21	p	0.00	0.00	0.00	y0.01	y0.01	y0.01	y0.01	y0.01	y0.01	y0.01	0.00	y0.01
22	p	y0.01	y0.01	y0.01	y0.03	y0.03	y0.02	y0.04	y0.04	y0.03	y0.03	y0.01	y0.03
23	p	0.00	0.00	0.01	0.01	0.02	0.01	0.02	0.02	0.02	0.02	0.01	0.02
24	p	y0.01	0.00	0.01	0.02	0.02	0.02	0.03	0.03	0.02	0.02	0.01	0.02
25	p	1.00	y0.06	y0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.00	0.01
26	p	y0.06	1.00	y0.05	y0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.00	0.01
27	p	y0.01	y0.05	1.00	y0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.01	0.03
28	p	0.01	y0.01	y0.03	1.00	y0.02	0.03	0.05	0.05	0.05	0.05	0.02	0.05
29	p	0.01	0.01	0.02	y0.02	1.00	0.00	0.05	0.06	0.06	0.06	0.02	0.06
30	p	0.01	0.01	0.02	0.03	0.00	1.00	y0.11	0.04	0.04	0.05	0.01	0.04
31	p	0.02	0.02	0.03	0.05	0.05	y0.11	1.00	0.03	0.07	0.07	0.02	0.07
32	p	0.02	0.02	0.03	0.05	0.06	0.04	0.03	1.00	y0.03	0.07	0.02	0.07
33	p	0.01	0.01	0.03	0.05	0.06	0.04	0.07	y0.03	1.00	0.03	0.02	0.06
34	p	0.01	0.01	0.03	0.05	0.06	0.05	0.07	0.07	0.03	1.00	y0.06	0.04
35	p	0.00	0.00	0.01	0.02	0.02	0.01	0.02	0.02	0.02	y0.06	1.00	0.01
36	p	0.01	0.01	0.03	0.05	0.06	0.04	0.07	0.07	0.06	0.04	0.01	1.00
37	p	0.02	0.02	0.03	0.06	0.07	0.05	0.08	0.08	0.07	0.07	0.02	y0.07
38	p	0.01	0.01	0.02	0.04	0.04	0.03	0.05	0.05	0.05	0.05	0.01	0.03
39	p	0.01	0.01	0.03	0.05	0.06	0.05	0.07	0.07	0.07	0.07	0.02	0.06
40	p	0.01	0.01	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.01	0.04
41	p	0.01	0.01	0.02	0.04	0.04	0.03	0.05	0.06	0.05	0.05	0.02	0.05
42	p	0.01	0.01	0.01	0.03	0.03	0.02	0.04	0.04	0.03	0.03	0.01	0.03
43	p	0.01	0.01	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.01	0.04
44	p	0.06	0.05	0.11	0.19	0.23	0.18	0.28	0.28	0.25	0.25	0.08	0.25

	p	37	38	39	40	41	42	43	44
1	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
2	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	p	y0.03	y0.02	y0.03	y0.02	y0.02	y0.02	y0.02	y0.11
4	p	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	p	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.06
6	p	y0.03	y0.02	y0.03	y0.01	y0.02	y0.01	y0.02	y0.10
7	p	y0.03	y0.02	y0.03	y0.02	y0.02	y0.01	y0.02	y0.11
8	p	y0.03	y0.02	y0.03	y0.02	y0.02	y0.02	y0.02	y0.12
9	p	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.08
10	p	y0.05	y0.03	y0.04	y0.02	y0.03	y0.02	y0.03	y0.17
11	p	y0.02	y0.01	y0.02	y0.01	y0.01	y0.01	y0.01	y0.07
12	p	y0.04	y0.02	y0.03	y0.02	y0.03	y0.02	y0.02	y0.13
13	p	0.07	0.05	0.07	0.04	0.05	0.04	0.04	0.26

14	p	y0.07	y0.03	y0.04	y0.03	y0.03	y0.02	y0.03	y0.17
15	p	y0.28	y0.02	0.00	0.00	0.00	0.00	0.00	0.00
16	p	0.40	y0.15	y0.05	y0.03	y0.03	y0.02	y0.02	y0.16
17	p	0.01	0.51	y0.15	y0.03	y0.02	y0.01	y0.01	y0.08
18	p	y0.01	0.03	0.51	y0.22	y0.04	y0.01	y0.01	y0.04
19	p	y0.03	y0.01	0.09	0.38	y0.17	y0.02	y0.02	y0.11
20	p	y0.03	y0.02	y0.02	0.02	0.49	y0.10	y0.03	y0.12
21	p	y0.01	y0.01	y0.01	0.00	0.02	0.51	y0.18	y0.04
22	p	y0.04	y0.02	y0.03	y0.02	y0.02	0.06	0.45	y0.13
23	p	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.08
24	p	0.03	0.02	0.02	0.01	0.02	0.01	0.01	0.10
25	p	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.06
26	p	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.05
27	p	0.03	0.02	0.03	0.02	0.02	0.01	0.02	0.11
28	p	0.06	0.04	0.05	0.03	0.04	0.03	0.03	0.19
29	p	0.07	0.04	0.06	0.03	0.04	0.03	0.03	0.23
30	p	0.05	0.03	0.05	0.03	0.03	0.02	0.03	0.18
31	p	0.08	0.05	0.07	0.04	0.05	0.04	0.04	0.28
32	p	0.08	0.05	0.07	0.04	0.06	0.04	0.04	0.28
33	p	0.07	0.05	0.07	0.04	0.05	0.03	0.04	0.25
34	p	0.07	0.05	0.07	0.04	0.05	0.03	0.04	0.25
35	p	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.08
36	p	y0.07	0.03	0.06	0.04	0.05	0.03	0.04	0.25
37	p	1.00	0.00	0.07	0.04	0.06	0.04	0.04	0.29
38	p	0.00	1.00	y0.02	0.02	0.04	0.03	0.03	0.19
39	p	0.07	y0.02	1.00	y0.07	0.03	0.03	0.04	0.26
40	p	0.04	0.02	y0.07	1.00	y0.03	0.02	0.02	0.15
41	p	0.06	0.04	0.03	y0.03	1.00	y0.02	0.02	0.20
42	p	0.04	0.03	0.03	0.02	y0.02	1.00	y0.07	0.14
43	p	0.04	0.03	0.04	0.02	0.02	y0.07	1.00	0.15
44	p	0.29	0.19	0.26	0.15	0.20	0.14	0.15	1.00

CALENDAR YEAR	STOCK SIZE ESTIMATES (millions at time of survey)		MORTALITY RATES (between surveys)		
	RECRUITS	FULLY-RECRUITED	Z	F	F
			on sizes 1+	on size 1	on sizes 2+
1979	38.055	6.277	1.05	0.21	0.51
1980	22.035	15.440	1.31	0.32	0.77
1981	86.873	10.145	1.17	0.33	0.78
1982	31.743	30.014	1.31	0.30	0.73
1983	12.477	16.643	1.05	0.14	0.33
1984	24.042	10.196	0.98	0.13	0.30
1985	51.102	12.865	1.55	0.58	1.40
1986	100.840	13.630	1.46	0.56	1.35
1987	35.000	26.666	1.47	0.42	1.00
1988	75.471	14.234	1.25	0.37	0.88
1989	74.323	25.768	1.46	0.48	1.16
1990	188.815	23.308	1.18	0.33	0.79
1991	16.053	65.119	1.34	0.25	0.61
1992	113.656	21.341	1.14	0.28	0.67
1993	76.773	43.111	1.52	0.48	1.15
1994	117.581	26.245	1.49	0.55	1.33
1995	153.064	32.280	1.61	0.65	1.56
1996	51.568	37.145	1.27	0.29	0.70
1997	79.857	25.024	1.30	0.38	0.90
1998	157.793	28.514	1.49	0.56	1.35
1999	93.165	42.184	1.39	0.41	0.98
2000	185.530	33.856			

RECRUITS = SIZECLASS 1 FULLY-RECRUITED = SIZECLASS 2+

Note that the recruit population estimate for the last year (2000) is NOT a least squares estimate. It is calculated from the observed survey index, the least squares estimate of q , and the s_r .

---- BIOMASS ESTIMATES (at time of the survey) ----					CATCH BIOMASS DURING YEAR (1000 mt)
CALENDAR YEAR	RECRUITS	FULLY- RECRUITED	TOTAL BIOMASS	EXPLOITED BIOMASS	

n 2+ 1994	6.013Eý1	9.351Eý1	1.110E0	1.358E0	1.588E0	1.843E0	2.427E0
n 2+ 1995	7.252Eý1	1.178E0	1.361E0	1.630E0	1.904E0	2.181E0	3.136E0
n 2+ 1996	8.886Eý1	1.307E0	1.529E0	1.848E0	2.244E0	2.610E0	3.772E0
n 2+ 1997	6.418Eý1	9.278Eý1	1.077E0	1.243E0	1.467E0	1.720E0	2.580E0
n 2+ 1998	7.004Eý1	1.043E0	1.195E0	1.454E0	1.678E0	1.967E0	2.448E0
n 2+ 1999	8.591Eý1	1.518E0	1.831E0	2.119E0	2.470E0	2.837E0	3.963E0
n 2+ 2000	8.372Eý1	1.159E0	1.384E0	1.714E0	2.113E0	2.401E0	3.199E0

PARAMETER	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE
n 2+ 1983	ý2.603Eý16	1.091Eý2	0.00	5.827Eý1	0.26
n 2+ 1984	ý1.105Eý16	7.790Eý3	0.00	4.729Eý1	0.23
n 2+ 1985	ý3.400Eý16	1.009Eý2	0.00	6.519Eý1	0.22
n 2+ 1986	3.475Eý16	1.338Eý2	0.00	7.044Eý1	0.27
n 2+ 1987	5.951Eý16	2.360Eý2	0.00	1.345E0	0.25
n 2+ 1988	ý1.615Eý16	1.481Eý2	0.00	7.367Eý1	0.28
n 2+ 1989	1.138Eý16	2.115Eý2	0.00	1.315E0	0.23
n 2+ 1990	1.010Eý16	2.165Eý2	0.00	1.203E0	0.25
n 2+ 1991	ý1.088Eý15	3.837Eý2	0.00	3.200E0	0.17
n 2+ 1992	3.758Eý16	1.918Eý2	0.00	1.100E0	0.25
n 2+ 1993	ý9.326Eý17	3.271Eý2	0.00	2.182E0	0.21
n 2+ 1994	ý7.694Eý16	2.474Eý2	0.00	1.358E0	0.26
n 2+ 1995	ý1.318Eý15	2.981Eý2	0.00	1.664E0	0.25
n 2+ 1996	9.892Eý16	3.623Eý2	0.00	1.909E0	0.27
n 2+ 1997	ý3.247Eý16	2.203Eý2	0.00	1.290E0	0.24
n 2+ 1998	ý4.574Eý16	2.381Eý2	0.00	1.469E0	0.23
n 2+ 1999	4.430Eý16	3.607Eý2	0.00	2.162E0	0.24
n 2+ 2000	ý6.878Eý16	3.501Eý2	0.00	1.752E0	0.28

BOOTSTRAP OUTPUT VARIABLE: r_hat

Predicted indices of abundance for the recruits for years

1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998
1999

PARAMETER	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
r 1 1983	7.089Eý1	7.089Eý1	1.902Eý1	0.27
r 1 1984	1.208E0	1.208E0	2.509Eý1	0.21
r 1 1985	2.552E0	2.552E0	4.195Eý1	0.16
r 1 1986	5.047E0	5.047E0	8.435Eý1	0.17
r 1 1987	1.704E0	1.704E0	3.681Eý1	0.22
r 1 1988	3.695E0	3.695E0	6.901Eý1	0.19
r 1 1989	3.673E0	3.673E0	7.008Eý1	0.19
r 1 1990	9.289E0	9.289E0	1.528E0	0.16
r 1 1991	8.033Eý1	8.033Eý1	2.372Eý1	0.30
r 1 1992	5.588E0	5.588E0	1.071E0	0.19
r 1 1993	3.763E0	3.763E0	7.457Eý1	0.20
r 1 1994	5.893E0	5.893E0	1.030E0	0.17
r 1 1995	7.632E0	7.632E0	1.169E0	0.15
r 1 1996	2.563E0	2.563E0	5.787Eý1	0.23
r 1 1997	3.960E0	3.960E0	7.445Eý1	0.19
r 1 1998	7.951E0	7.951E0	1.307E0	0.16
r 1 1999	4.656E0	4.656E0	9.402Eý1	0.20

PARAMETER	MIN	10	25	MEDIAN	75	90	MAX
r 1 1983	3.279Eý1	4.813Eý1	5.889Eý1	6.965Eý1	8.114Eý1	9.426Eý1	1.427E0
r 1 1984	5.308Eý1	8.827Eý1	1.045E0	1.195E0	1.362E0	1.553E0	1.862E0
r 1 1985	1.607E0	2.011E0	2.262E0	2.542E0	2.847E0	3.089E0	3.968E0
r 1 1986	3.069E0	4.071E0	4.405E0	4.931E0	5.559E0	6.199E0	7.530E0
r 1 1987	8.530Eý1	1.266E0	1.448E0	1.698E0	1.936E0	2.150E0	2.862E0
r 1 1988	1.710E0	2.842E0	3.222E0	3.698E0	4.072E0	4.588E0	6.528E0
r 1 1989	1.904E0	2.825E0	3.182E0	3.628E0	4.048E0	4.580E0	6.046E0
r 1 1990	5.436E0	7.567E0	8.229E0	9.155E0	1.010E1	1.117E1	1.493E1
r 1 1991	3.416Eý1	5.015Eý1	6.289Eý1	7.667Eý1	9.413Eý1	1.101E0	1.518E0

APPENDIX B: BOOTSTRAP OF MODIFIED DELURY ANALYSIS OF DELAWARE BAY BLUE CRAB

BOOTSTRAP RESULTS FOR RUN NUMBER 99 2000 3 20 15 5 53
Delury model for Delaware Bay Blue crab.

Data Used

Tuning Index: Trawl Research Survey - August thru September cutoff (120 mm) -
Indices lagged to next year.
Geometric Mean Number per Tow
Catch Data: Delaware and New Jersey Landings
Based on Calendar year, Jan. 1 thru Dec. 31
1000 mt assumed and Catch expressed in Millions

BOOTSTRAP TYPE : LOB
BOOTSTRAP CLASS: parametric conditional
SEED FOR THE RANDOM NUMBER GENERATOR: 74747

MAIN LOOP LIMIT IN MARQUARDT ALGORITHM: 50
NUMBER OF BOOTSTRAP REPLICATIONS ATTEMPTED: 200
NUMBER FOR WHICH NLLS CONVERGED: 200
Results from the converged replications are used for computing the
statistics that follow. Other replications are ignored.

This bootstrap run finished running at timestamp: 2000 3 20 14 58 8 280
This bootstrap run was started at timestamp: 2000 3 20 14 57 29 60

BOOTSTRAP OUTPUT VARIABLE: n_hat
Predicted indices of abundance for the fully-recruited animals for years
1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998
1999 2000

PARAMETER	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
n 2+ 1983	5.827Ey1	5.827Ey1	1.542Ey1	0.26
n 2+ 1984	4.729Ey1	4.729Ey1	1.102Ey1	0.23
n 2+ 1985	6.519Ey1	6.519Ey1	1.427Ey1	0.22
n 2+ 1986	7.044Ey1	7.044Ey1	1.892Ey1	0.27
n 2+ 1987	1.345E0	1.345E0	3.337Ey1	0.25
n 2+ 1988	7.367Ey1	7.367Ey1	2.094Ey1	0.28
n 2+ 1989	1.315E0	1.315E0	2.991Ey1	0.23
n 2+ 1990	1.203E0	1.203E0	3.062Ey1	0.25
n 2+ 1991	3.200E0	3.200E0	5.426Ey1	0.17
n 2+ 1992	1.100E0	1.100E0	2.712Ey1	0.25
n 2+ 1993	2.182E0	2.182E0	4.626Ey1	0.21
n 2+ 1994	1.358E0	1.358E0	3.499Ey1	0.26
n 2+ 1995	1.664E0	1.664E0	4.216Ey1	0.25
n 2+ 1996	1.909E0	1.909E0	5.124Ey1	0.27
n 2+ 1997	1.290E0	1.290E0	3.116Ey1	0.24
n 2+ 1998	1.469E0	1.469E0	3.368Ey1	0.23
n 2+ 1999	2.162E0	2.162E0	5.101Ey1	0.24
n 2+ 2000	1.752E0	1.752E0	4.952Ey1	0.28

PARAMETER	MIN	PERCENTILES					MAX
		10	25	MEDIAN	75	90	
n 2+ 1983	2.190Ey1	4.133Ey1	4.703Ey1	5.657Ey1	6.677Ey1	7.722Ey1	1.176E0
n 2+ 1984	2.319Ey1	3.496Ey1	3.877Ey1	4.619Ey1	5.430Ey1	6.185Ey1	9.080Ey1
n 2+ 1985	3.647Ey1	4.868Ey1	5.522Ey1	6.348Ey1	7.372Ey1	8.323Ey1	1.260E0
n 2+ 1986	3.358Ey1	4.808Ey1	5.661Ey1	6.841Ey1	8.259Ey1	9.523Ey1	1.322E0
n 2+ 1987	6.167Ey1	9.482Ey1	1.107E0	1.326E0	1.511E0	1.811E0	2.499E0
n 2+ 1988	3.416Ey1	4.804Ey1	5.624Ey1	7.193Ey1	8.552Ey1	1.002E0	1.577E0
n 2+ 1989	6.664Ey1	9.721Ey1	1.123E0	1.287E0	1.463E0	1.683E0	2.438E0
n 2+ 1990	5.131Ey1	8.303Ey1	1.011E0	1.196E0	1.369E0	1.589E0	2.173E0
n 2+ 1991	1.941E0	2.542E0	2.798E0	3.150E0	3.551E0	3.895E0	5.094E0
n 2+ 1992	5.189Ey1	7.855Ey1	8.976Ey1	1.075E0	1.265E0	1.463E0	2.263E0
n 2+ 1993	1.065E0	1.576E0	1.842E0	2.130E0	2.493E0	2.808E0	3.595E0

1994	1.121Ey16	2.275Ey2	0.00	1.357E0	0.24
1995	4.663Ey16	3.241Ey2	0.00	2.163E0	0.21
1996	y8.871Ey16	3.871Ey2	0.00	2.541E0	0.22
1997	7.544Ey16	2.232Ey2	0.00	1.323E0	0.24
1998	1.088Ey16	2.395Ey2	0.00	1.484E0	0.23
1999	y3.997Ey16	4.018Ey2	0.00	3.126E0	0.18
2000	y3.220Ey17	3.489Ey2	0.00	1.987E0	0.25

BOOTSTRAP OUTPUT VARIABLE: R_0

Population size (in number) of the recruits at time of the survey
i.e. 0% into the calendar year

YEAR	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
1983	1.527E1	1.527E1	3.933E0	0.26
1984	2.603E1	2.603E1	5.368E0	0.21
1985	5.498E1	5.498E1	8.483E0	0.15
1986	1.087E2	1.087E2	1.735E1	0.16
1987	3.671E1	3.671E1	7.673E0	0.21
1988	7.958E1	7.958E1	1.410E1	0.18
1989	7.910E1	7.910E1	1.305E1	0.17
1990	2.001E2	2.001E2	3.255E1	0.16
1991	1.730E1	1.730E1	4.653E0	0.27
1992	1.204E2	1.204E2	1.988E1	0.17
1993	8.105E1	8.105E1	1.434E1	0.18
1994	1.269E2	1.269E2	2.070E1	0.16
1995	1.644E2	1.644E2	2.598E1	0.16
1996	5.521E1	5.521E1	1.157E1	0.21
1997	8.529E1	8.529E1	1.548E1	0.18
1998	1.713E2	1.713E2	2.826E1	0.17
1999	1.003E2	1.003E2	2.214E1	0.22
2000	2.027E2	2.027E2	2.279E1	0.11

YEAR	MIN	PERCENTILES					MAX
		10	25	MEDIAN	75	90	
1983	7.463E0	1.028E1	1.285E1	1.474E1	1.766E1	2.053E1	3.233E1
1984	1.419E1	2.000E1	2.189E1	2.568E1	2.945E1	3.263E1	4.379E1
1985	4.035E1	4.501E1	4.902E1	5.435E1	5.960E1	6.518E1	9.159E1
1986	7.389E1	8.701E1	9.715E1	1.055E2	1.209E2	1.314E2	1.647E2
1987	2.021E1	2.741E1	3.156E1	3.559E1	4.206E1	4.646E1	6.869E1
1988	5.249E1	6.455E1	6.957E1	7.855E1	8.841E1	9.610E1	1.628E2
1989	4.909E1	6.443E1	7.003E1	7.697E1	8.747E1	9.674E1	1.136E2
1990	1.450E2	1.636E2	1.776E2	1.950E2	2.174E2	2.416E2	3.333E2
1991	8.357E0	1.168E1	1.354E1	1.699E1	2.046E1	2.308E1	3.112E1
1992	7.648E1	9.660E1	1.076E2	1.179E2	1.319E2	1.445E2	1.876E2
1993	4.678E1	6.393E1	7.018E1	8.069E1	9.017E1	1.006E2	1.232E2
1994	8.760E1	1.037E2	1.102E2	1.230E2	1.398E2	1.568E2	1.924E2
1995	1.095E2	1.331E2	1.454E2	1.622E2	1.796E2	1.982E2	2.515E2
1996	3.076E1	4.118E1	4.687E1	5.419E1	6.228E1	7.268E1	8.444E1
1997	5.413E1	6.740E1	7.324E1	8.506E1	9.545E1	1.057E2	1.473E2
1998	1.149E2	1.395E2	1.519E2	1.679E2	1.886E2	2.047E2	2.614E2
1999	5.757E1	7.378E1	8.380E1	9.823E1	1.142E2	1.285E2	1.743E2
2000	1.459E2	1.745E2	1.843E2	2.028E2	2.182E2	2.310E2	2.979E2

YEAR	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE
1983	4.459Ey15	2.781Ey1	0.00	1.527E1	0.26
1984	y6.644Ey15	3.796Ey1	0.00	2.603E1	0.21
1985	2.984Ey15	5.998Ey1	0.00	5.498E1	0.15
1986	y9.258Ey14	1.227E0	0.00	1.087E2	0.16
1987	y1.556Ey14	5.426Ey1	0.00	3.671E1	0.21
1988	y5.329Ey15	9.969Ey1	0.00	7.958E1	0.18
1989	9.877Ey15	9.229Ey1	0.00	7.910E1	0.17
1990	y9.479Ey14	2.302E0	0.00	2.001E2	0.16
1991	9.326Ey16	3.290Ey1	0.00	1.730E1	0.27

1992	y8.953Ey15	1.406E0	0.00	1.204E2	0.17
1993	2.757Ey14	1.014E0	0.00	8.105E1	0.18
1994	2.345Ey15	1.464E0	0.00	1.269E2	0.16
1995	1.535Ey14	1.837E0	0.00	1.644E2	0.16
1996	4.032Ey15	8.181Ey1	0.00	5.521E1	0.21
1997	3.482Ey15	1.094E0	0.00	8.529E1	0.18
1998	y4.619Ey14	1.998E0	0.00	1.713E2	0.17
1999	y1.442Ey14	1.566E0	0.00	1.003E2	0.22
2000	y9.337Ey14	1.611E0	0.00	2.027E2	0.11

BOOTSTRAP OUTPUT VARIABLE: N_0

Popn size (in number) of fully-recruited animals at time of the survey
i.e. 0% into the calendar year

YEAR	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
1983	1.255E1	1.255E1	2.975E0	0.24
1984	1.019E1	1.019E1	2.524E0	0.25
1985	1.404E1	1.404E1	3.448E0	0.25
1986	1.517E1	1.517E1	4.506E0	0.30
1987	2.897E1	2.897E1	7.450E0	0.26
1988	1.587E1	1.587E1	5.004E0	0.32
1989	2.832E1	2.832E1	7.032E0	0.25
1990	2.592E1	2.592E1	6.542E0	0.25
1991	6.892E1	6.892E1	1.244E1	0.18
1992	2.370E1	2.370E1	6.361E0	0.27
1993	4.700E1	4.700E1	1.004E1	0.21
1994	2.926E1	2.926E1	7.949E0	0.27
1995	3.584E1	3.584E1	9.484E0	0.26
1996	4.112E1	4.112E1	1.209E1	0.29
1997	2.778E1	2.778E1	7.317E0	0.26
1998	3.164E1	3.164E1	8.272E0	0.26
1999	4.656E1	4.656E1	1.172E1	0.25
2000	3.774E1	3.774E1	1.168E1	0.31

YEAR	----- PERCENTILES -----						MAX
	MIN	10	25	MEDIAN	75	90	
1983	6.346E0	9.146E0	1.049E1	1.229E1	1.416E1	1.673E1	2.521E1
1984	4.871E0	7.215E0	8.510E0	9.896E0	1.138E1	1.356E1	2.132E1
1985	7.567E0	1.036E1	1.167E1	1.345E1	1.587E1	1.848E1	2.781E1
1986	6.376E0	1.028E1	1.175E1	1.448E1	1.770E1	2.124E1	3.415E1
1987	1.503E1	2.037E1	2.355E1	2.830E1	3.313E1	3.872E1	5.988E1
1988	6.877E0	1.015E1	1.185E1	1.530E1	1.866E1	2.211E1	3.400E1
1989	1.398E1	2.041E1	2.364E1	2.751E1	3.201E1	3.604E1	6.379E1
1990	1.212E1	1.732E1	2.135E1	2.543E1	3.066E1	3.530E1	4.467E1
1991	4.662E1	5.410E1	6.021E1	6.784E1	7.534E1	8.491E1	1.140E2
1992	1.206E1	1.681E1	1.908E1	2.273E1	2.699E1	3.203E1	4.776E1
1993	2.794E1	3.490E1	3.958E1	4.592E1	5.355E1	5.976E1	8.741E1
1994	1.325E1	1.856E1	2.349E1	2.865E1	3.455E1	3.970E1	5.457E1
1995	1.459E1	2.464E1	2.949E1	3.451E1	4.173E1	4.886E1	6.623E1
1996	1.806E1	2.693E1	3.207E1	3.969E1	4.889E1	5.809E1	8.091E1
1997	1.335E1	1.868E1	2.263E1	2.678E1	3.257E1	3.830E1	5.066E1
1998	1.513E1	2.166E1	2.476E1	3.129E1	3.678E1	4.275E1	5.794E1
1999	1.767E1	3.206E1	3.934E1	4.561E1	5.431E1	6.209E1	8.715E1
2000	1.593E1	2.327E1	2.875E1	3.694E1	4.612E1	5.386E1	7.236E1

YEAR	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE
1983	y8.571Ey15	2.104Ey1	0.00	1.255E1	0.24
1984	6.750Ey16	1.785Ey1	0.00	1.019E1	0.25
1985	6.795Ey15	2.438Ey1	0.00	1.404E1	0.25
1986	6.501Ey15	3.186Ey1	0.00	1.517E1	0.30
1987	2.949Ey15	5.268Ey1	0.00	2.897E1	0.26
1988	7.470Ey15	3.539Ey1	0.00	1.587E1	0.32
1989	y1.549Ey14	4.973Ey1	0.00	2.832E1	0.25

1990	y7.940Ey15	4.626Ey1	0.00	2.592E1	0.25
1991	2.451Ey14	8.796Ey1	0.00	6.892E1	0.18
1992	5.755Ey15	4.498Ey1	0.00	2.370E1	0.27
1993	4.459Ey15	7.097Ey1	0.00	4.700E1	0.21
1994	2.522Ey15	5.620Ey1	0.00	2.926E1	0.27
1995	8.349Ey16	6.707Ey1	0.00	3.584E1	0.26
1996	1.155Ey14	8.547Ey1	0.00	4.112E1	0.29
1997	2.904Ey15	5.174Ey1	0.00	2.778E1	0.26
1998	y5.507Ey16	5.849Ey1	0.00	3.164E1	0.26
1999	6.413Ey15	8.289Ey1	0.00	4.656E1	0.25
2000	1.984Ey14	8.257Ey1	0.00	3.774E1	0.31

BOOTSTRAP OUTPUT VARIABLE: F_R

Fishing mortality rate on the recruits during survey years

SURVEY YEAR	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
1983	0.1256	0.1256	0.1075	0.86
1984	0.1059	0.1059	0.1258	1.19
1985	0.5569	0.5569	0.1429	0.26
1986	0.5577	0.5577	0.1003	0.18
1987	0.3842	0.3842	0.1291	0.34
1988	0.3370	0.3370	0.1185	0.35
1989	0.4546	0.4546	0.1255	0.28
1990	0.3340	0.3340	0.0863	0.26
1991	0.2324	0.2324	0.0912	0.39
1992	0.2604	0.2604	0.1093	0.42
1993	0.4473	0.4473	0.1368	0.31
1994	0.5328	0.5328	0.1200	0.23
1995	0.6264	0.6264	0.1327	0.21
1996	0.2779	0.2779	0.0984	0.35
1997	0.3528	0.3528	0.1262	0.36
1998	0.5518	0.5518	0.1193	0.22
1999	0.3874	0.3874	0.1174	0.30

SURVEY YEAR	PERCENTILES						
	MIN	10	25	MEDIAN	75	90	MAX
1983	y0.1391	y0.0060	0.0519	0.1131	0.1930	0.2854	0.4774
1984	y0.2457	y0.0468	0.0322	0.1027	0.1847	0.2651	0.4653
1985	0.1888	0.3602	0.4548	0.5603	0.6577	0.7297	1.0384
1986	0.2504	0.4371	0.4953	0.5634	0.6248	0.6748	0.8892
1987	0.0801	0.2315	0.2917	0.3703	0.4824	0.5521	0.7517
1988	0.0191	0.1869	0.2749	0.3256	0.4160	0.4852	0.6753
1989	0.2167	0.3104	0.3652	0.4400	0.5261	0.6133	0.8361
1990	0.1351	0.2220	0.2806	0.3330	0.3852	0.4496	0.5623
1991	y0.0310	0.1323	0.1710	0.2292	0.2906	0.3449	0.5058
1992	y0.0228	0.1260	0.1841	0.2460	0.3246	0.4280	0.5097
1993	0.1356	0.2706	0.3448	0.4406	0.5324	0.6260	0.8810
1994	0.2138	0.3774	0.4483	0.5303	0.6022	0.6834	1.0169
1995	0.2604	0.4605	0.5388	0.6231	0.7260	0.8004	0.9931
1996	y0.0110	0.1558	0.2103	0.2795	0.3414	0.3974	0.5484
1997	0.0490	0.1995	0.2721	0.3455	0.4299	0.5130	0.7753
1998	0.2172	0.4072	0.4686	0.5572	0.6118	0.6977	0.9389
1999	0.1471	0.2364	0.3068	0.3754	0.4686	0.5376	0.7089

SURVEY YEAR	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE
1983	0.00000000	0.00760318	0.00	0.1256	0.86
1984	0.00000000	0.00889849	0.00	0.1059	1.19
1985	0.00000000	0.01010392	0.00	0.5569	0.26
1986	0.00000000	0.00708937	0.00	0.5577	0.18
1987	0.00000000	0.00912710	0.00	0.3842	0.34
1988	0.00000000	0.00837757	0.00	0.3370	0.35

1989	0.00000000	0.00887519	0.00	0.4546	0.28
1990	0.00000000	0.00610453	0.00	0.3340	0.26
1991	0.00000000	0.00644623	0.00	0.2324	0.39
1992	0.00000000	0.00772845	0.00	0.2604	0.42
1993	0.00000000	0.00967451	0.00	0.4473	0.31
1994	0.00000000	0.00848218	0.00	0.5328	0.23
1995	0.00000000	0.00938027	0.00	0.6264	0.21
1996	0.00000000	0.00695507	0.00	0.2779	0.35
1997	0.00000000	0.00892062	0.00	0.3528	0.36
1998	0.00000000	0.00843526	0.00	0.5518	0.22
1999	0.00000000	0.00830096	0.00	0.3874	0.30

BOOTSTRAP OUTPUT VARIABLE: F N

Fishing mortality rate on the fully-recruited animals during survey yrs

SURVEY YEAR	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
1983	0.3008	0.3008	0.2575	0.86
1984	0.2536	0.2536	0.3013	1.19
1985	1.3336	1.3336	0.3422	0.26
1986	1.3355	1.3355	0.2401	0.18
1987	0.9199	0.9199	0.3091	0.34
1988	0.8069	0.8069	0.2837	0.35
1989	1.0886	1.0886	0.3006	0.28
1990	0.7999	0.7999	0.2067	0.26
1991	0.5565	0.5565	0.2183	0.39
1992	0.6237	0.6237	0.2617	0.42
1993	1.0710	1.0710	0.3276	0.31
1994	1.2760	1.2760	0.2872	0.23
1995	1.5000	1.5000	0.3177	0.21
1996	0.6655	0.6655	0.2355	0.35
1997	0.8448	0.8448	0.3021	0.36
1998	1.3214	1.3214	0.2857	0.22
1999	0.9277	0.9277	0.2811	0.30

SURVEY YEAR	PERCENTILES						MAX
	MIN	10	25	MEDIAN	75	90	
1983	y0.3331	y0.0144	0.1242	0.2708	0.4621	0.6835	1.1432
1984	y0.5884	y0.1120	0.0770	0.2460	0.4422	0.6349	1.1141
1985	0.4520	0.8624	1.0892	1.3417	1.5750	1.7473	2.4866
1986	0.5995	1.0468	1.1860	1.3490	1.4961	1.6158	2.1293
1987	0.1919	0.5543	0.6986	0.8866	1.1551	1.3222	1.7999
1988	0.0456	0.4476	0.6582	0.7796	0.9962	1.1620	1.6171
1989	0.5188	0.7432	0.8746	1.0536	1.2598	1.4687	2.0021
1990	0.3236	0.5315	0.6719	0.7975	0.9224	1.0765	1.3464
1991	y0.0742	0.3169	0.4095	0.5489	0.6958	0.8260	1.2112
1992	y0.0546	0.3018	0.4409	0.5890	0.7774	1.0250	1.2206
1993	0.3247	0.6479	0.8257	1.0551	1.2749	1.4989	2.1096
1994	0.5119	0.9037	1.0734	1.2698	1.4421	1.6364	2.4351
1995	0.6235	1.1028	1.2902	1.4920	1.7385	1.9167	2.3781
1996	y0.0264	0.3730	0.5036	0.6694	0.8176	0.9515	1.3132
1997	0.1174	0.4776	0.6515	0.8273	1.0295	1.2284	1.8564
1998	0.5201	0.9751	1.1220	1.3342	1.4650	1.6708	2.2484
1999	0.3522	0.5662	0.7347	0.8989	1.1220	1.2873	1.6975

SURVEY YEAR	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE
1983	0.00000000	0.01820659	0.00	0.3008	0.86
1984	0.00000000	0.02130833	0.00	0.2536	1.19
1985	0.00000000	0.02419487	0.00	1.3336	0.26
1986	0.00000000	0.01697620	0.00	1.3355	0.18
1987	0.00000000	0.02185578	0.00	0.9199	0.34
1988	0.00000000	0.02006095	0.00	0.8069	0.35
1989	0.00000000	0.02125253	0.00	1.0886	0.28

1990	0.00000000	0.01461792	0.00	0.7999	0.26
1991	0.00000000	0.01543615	0.00	0.5565	0.39
1992	0.00000000	0.01850655	0.00	0.6237	0.42
1993	0.00000000	0.02316659	0.00	1.0710	0.31
1994	0.00000000	0.02031145	0.00	1.2760	0.23
1995	0.00000000	0.02246200	0.00	1.5000	0.21
1996	0.00000000	0.01665461	0.00	0.6655	0.35
1997	0.00000000	0.02136132	0.00	0.8448	0.36
1998	0.00000000	0.02019908	0.00	1.3214	0.22
1999	0.00000000	0.01987749	0.00	0.9277	0.30

BOOTSTRAP OUTPUT VARIABLE: F_RN

Fishing mortality rate for all animals of recruitment size and larger
i.e. recruits plus the fully-recruited group during survey years

SURVEY YEAR	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
1983	0.2046	0.2046	0.1658	0.81
1984	0.1475	0.1475	0.1663	1.13
1985	0.7149	0.7149	0.1750	0.24
1986	0.6530	0.6530	0.1206	0.18
1987	0.6205	0.6205	0.2041	0.33
1988	0.4151	0.4151	0.1404	0.34
1989	0.6217	0.6217	0.1713	0.28
1990	0.3875	0.3875	0.0983	0.25
1991	0.4915	0.4915	0.1874	0.38
1992	0.3202	0.3202	0.1310	0.41
1993	0.6762	0.6762	0.2029	0.30
1994	0.6721	0.6721	0.1472	0.22
1995	0.7828	0.7828	0.1712	0.22
1996	0.4434	0.4434	0.1490	0.34
1997	0.4737	0.4737	0.1622	0.34
1998	0.6718	0.6718	0.1429	0.21
1999	0.5587	0.5587	0.1737	0.31

SURVEY YEAR	PERCENTILES						
	MIN	10	25	MEDIAN	75	90	MAX
1983	y0.2110	0.0017	0.0830	0.1978	0.3146	0.4182	0.7518
1984	y0.3142	y0.0599	0.0545	0.1465	0.2470	0.3525	0.6032
1985	0.2565	0.4687	0.5932	0.7270	0.8371	0.9253	1.2283
1986	0.2928	0.5029	0.5769	0.6683	0.7296	0.7947	1.0331
1987	0.1023	0.3686	0.4721	0.6020	0.7818	0.8877	1.2404
1988	0.0232	0.2281	0.3362	0.4042	0.5060	0.5815	0.8250
1989	0.3038	0.4193	0.4968	0.5993	0.7244	0.8438	1.1581
1990	0.1621	0.2569	0.3239	0.3852	0.4475	0.5181	0.6628
1991	y0.0662	0.2895	0.3655	0.4874	0.6115	0.7231	1.0332
1992	y0.0227	0.1580	0.2287	0.3003	0.4013	0.5131	0.6793
1993	0.2104	0.4351	0.5206	0.6642	0.7904	0.9549	1.2696
1994	0.3039	0.4891	0.5573	0.6787	0.7585	0.8592	1.2049
1995	0.3256	0.5652	0.6677	0.7792	0.9054	0.9981	1.2666
1996	y0.0069	0.2572	0.3532	0.4431	0.5538	0.6451	0.8747
1997	0.0789	0.2725	0.3744	0.4621	0.5856	0.6785	0.9503
1998	0.2650	0.4935	0.5797	0.6787	0.7492	0.8443	1.1587
1999	0.2175	0.3335	0.4398	0.5510	0.6920	0.8075	1.0305

SURVEY YEAR	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE
1983	0.00000000	0.01172668	0.00	0.2046	0.81
1984	0.00000000	0.01176014	0.00	0.1475	1.13
1985	0.00000000	0.01237400	0.00	0.7149	0.24
1986	0.00000000	0.00852517	0.00	0.6530	0.18
1987	0.00000000	0.01443540	0.00	0.6205	0.33
1988	0.00000000	0.00992732	0.00	0.4151	0.34
1989	0.00000000	0.01210938	0.00	0.6217	0.28

1990	0.00000000	0.00695363	0.00	0.3875	0.25
1991	0.00000000	0.01325149	0.00	0.4915	0.38
1992	0.00000000	0.00926501	0.00	0.3202	0.41
1993	0.00000000	0.01434598	0.00	0.6762	0.30
1994	0.00000000	0.01040521	0.00	0.6721	0.22
1995	0.00000000	0.01210829	0.00	0.7828	0.22
1996	0.00000000	0.01053454	0.00	0.4434	0.34
1997	0.00000000	0.01146577	0.00	0.4737	0.34
1998	0.00000000	0.01010414	0.00	0.6718	0.21
1999	0.00000000	0.01228306	0.00	0.5587	0.31

BOOTSTRAP OUTPUT VARIABLE: F_RN_bar

Average fishing mortality rate for all animals of recruitment size and larger
i.e. recruits plus the fully-recruited group during survey years

Average fishing mortality rates on the fully-recruited animals

1st Row: F in 1999

2nd Row: Average F for 1998 1999

3rd Row: Average F for 1997 1998 1999

SURVEY YEAR(S)	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
1999 0	0.5587	0.5587	0.1737	0.31
1998 99	0.6153	0.6153	0.1288	0.21
1997 99	0.5681	0.5681	0.1169	0.21

SURVEY YEAR(S)	MIN	PERCENTILES					MAX
		10	25	MEDIAN	75	90	
1999 0	0.2175	0.3335	0.4398	0.5510	0.6920	0.8075	1.0305
1998 99	0.3236	0.4500	0.5273	0.6093	0.6959	0.7782	0.9929
1997 99	0.2813	0.4278	0.4909	0.5781	0.6415	0.7137	0.8861

SURVEY YEAR(S)	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE
1999 0	0.00000000	0.01228306	0.00	0.5587	0.31
1998 99	0.00000000	0.00910762	0.00	0.6153	0.21
1997 99	0.00000000	0.00826566	0.00	0.5681	0.21

BOOTSTRAP OUTPUT VARIABLE: F_N_bar

Average fishing mortality rates on fully-recruited animals during survey years

1st Row: F in 1999

2nd Row: Average F for 1998 1999

3rd Row: Average F for 1997 1998 1999

SURVEY YEAR(S)	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
1999 0	0.9277	0.9277	0.2811	0.30
1998 99	1.1245	1.1245	0.2426	0.22
1997 99	1.0313	1.0313	0.2227	0.22

SURVEY YEAR(S)	MIN	PERCENTILES					MAX
		10	25	MEDIAN	75	90	
1999 0	0.3522	0.5662	0.7347	0.8989	1.1220	1.2873	1.6975
1998 99	0.5682	0.8107	0.9639	1.1183	1.2618	1.4210	1.9218
1997 99	0.5004	0.7681	0.8811	1.0489	1.1614	1.2922	1.7127

SURVEY YEAR(S)	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE
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1999	0	0.00000000	0.01987749	0.00	0.9277	0.30
1998	99	0.00000000	0.01715204	0.00	1.1245	0.22
1997	99	0.00000000	0.01574717	0.00	1.0313	0.22

BOOTSTRAP OUTPUT VARIABLE: B_R_0

Population biomass of the recruits at time of the survey
i.e. 0% into the calendar year

YEAR	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
1983	3.298Ey1	3.298Ey1	8.496Ey2	0.26
1984	4.346Ey1	4.346Ey1	8.965Ey2	0.21
1985	1.704E0	1.704E0	2.630Ey1	0.15
1986	3.163E0	3.163E0	5.049Ey1	0.16
1987	1.145E0	1.145E0	2.394Ey1	0.21
1988	1.783E0	1.783E0	3.158Ey1	0.18
1989	7.277Ey1	7.277Ey1	1.201Ey1	0.17
1990	5.062E0	5.062E0	8.235Ey1	0.16
1991	3.011Ey1	3.011Ey1	8.097Ey2	0.27
1992	3.599E0	3.599E0	5.945Ey1	0.17
1993	2.326E0	2.326E0	4.116Ey1	0.18
1994	1.409E0	1.409E0	2.298Ey1	0.16
1995	4.718E0	4.718E0	7.457Ey1	0.16
1996	1.717E0	1.717E0	3.598Ey1	0.21
1997	2.098E0	2.098E0	3.808Ey1	0.18
1998	4.590E0	4.590E0	7.574Ey1	0.17
1999	2.457E0	2.457E0	5.425Ey1	0.22
2000	4.460E0	4.460E0	5.014Ey1	0.11

YEAR	MIN	PERCENTILES					MAX
		10	25	MEDIAN	75	90	
1983	1.612Ey1	2.220Ey1	2.776Ey1	3.183Ey1	3.814Ey1	4.434Ey1	6.983Ey1
1984	2.369Ey1	3.340Ey1	3.656Ey1	4.288Ey1	4.918Ey1	5.450Ey1	7.312Ey1
1985	1.251E0	1.395E0	1.520E0	1.685E0	1.847E0	2.021E0	2.839E0
1986	2.150E0	2.532E0	2.827E0	3.070E0	3.520E0	3.822E0	4.792E0
1987	6.305Ey1	8.553Ey1	9.846Ey1	1.110E0	1.312E0	1.449E0	2.143E0
1988	1.176E0	1.446E0	1.558E0	1.760E0	1.980E0	2.153E0	3.648E0
1989	4.516Ey1	5.927Ey1	6.442Ey1	7.081Ey1	8.047Ey1	8.900Ey1	1.045E0
1990	3.669E0	4.140E0	4.494E0	4.933E0	5.499E0	6.113E0	8.433E0
1991	1.454Ey1	2.032Ey1	2.356Ey1	2.956Ey1	3.559Ey1	4.016Ey1	5.414Ey1
1992	2.287E0	2.888E0	3.218E0	3.525E0	3.943E0	4.319E0	5.611E0
1993	1.343E0	1.835E0	2.014E0	2.316E0	2.588E0	2.888E0	3.536E0
1994	9.724Ey1	1.151E0	1.223E0	1.365E0	1.551E0	1.740E0	2.135E0
1995	3.142E0	3.821E0	4.172E0	4.655E0	5.155E0	5.689E0	7.219E0
1996	9.567Ey1	1.281E0	1.458E0	1.685E0	1.937E0	2.260E0	2.626E0
1997	1.332E0	1.658E0	1.802E0	2.093E0	2.348E0	2.600E0	3.623E0
1998	3.080E0	3.739E0	4.072E0	4.499E0	5.054E0	5.485E0	7.005E0
1999	1.410E0	1.808E0	2.053E0	2.407E0	2.798E0	3.147E0	4.271E0
2000	3.210E0	3.840E0	4.055E0	4.462E0	4.801E0	5.082E0	6.554E0

YEAR	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE
1983	2.558Ey16	6.008Ey3	0.00	3.298Ey1	0.26
1984	y1.152Ey16	6.339Ey3	0.00	4.346Ey1	0.21
1985	y4.563Ey16	1.860Ey2	0.00	1.704E0	0.15
1986	y1.887Ey16	3.570Ey2	0.00	3.163E0	0.16
1987	y1.843Ey16	1.693Ey2	0.00	1.145E0	0.21
1988	y7.150Ey16	2.233Ey2	0.00	1.783E0	0.18
1989	y4.086Ey16	8.491Ey3	0.00	7.277Ey1	0.17
1990	y2.021Ey16	5.823Ey2	0.00	5.062E0	0.16
1991	y6.189Ey17	5.725Ey3	0.00	3.011Ey1	0.27
1992	y1.430Ey15	4.204Ey2	0.00	3.599E0	0.17
1993	1.776Ey17	2.911Ey2	0.00	2.326E0	0.18
1994	y6.328Ey17	1.625Ey2	0.00	1.409E0	0.16

1995	1.303Ey15	5.273Ey2	0.00	4.718E0	0.16
1996	y1.815Ey16	2.544Ey2	0.00	1.717E0	0.21
1997	y1.221Ey16	2.692Ey2	0.00	2.098E0	0.18
1998	7.994Ey16	5.355Ey2	0.00	4.590E0	0.17
1999	4.285Ey16	3.836Ey2	0.00	2.457E0	0.22
2000	y3.777Ey15	3.545Ey2	0.00	4.460E0	0.11

BOOTSTRAP OUTPUT VARIABLE: B N_0

Population biomass of the fully-recruited animals at time of the survey
i.e. 0% into the calendar year

YEAR	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
1983	2.210E0	2.210E0	5.240Ey1	0.24
1984	1.682E0	1.682E0	4.167Ey1	0.25
1985	2.343E0	2.343E0	5.754Ey1	0.25
1986	2.145E0	2.145E0	6.372Ey1	0.30
1987	4.221E0	4.221E0	1.085E0	0.26
1988	2.134E0	2.134E0	6.731Ey1	0.32
1989	3.718E0	3.718E0	9.234Ey1	0.25
1990	4.253E0	4.253E0	1.073E0	0.25
1991	1.248E1	1.248E1	2.252E0	0.18
1992	3.361E0	3.361E0	9.019Ey1	0.27
1993	7.304E0	7.304E0	1.560E0	0.21
1994	4.111E0	4.111E0	1.117E0	0.27
1995	4.996E0	4.996E0	1.322E0	0.26
1996	5.400E0	5.400E0	1.587E0	0.29
1997	3.770E0	3.770E0	9.929Ey1	0.26
1998	4.395E0	4.395E0	1.149E0	0.26
1999	6.440E0	6.440E0	1.621E0	0.25
2000	5.208E0	5.208E0	1.611E0	0.31

YEAR	MIN	PERCENTILES					MAX
		10	25	MEDIAN	75	90	
1983	1.118E0	1.611E0	1.848E0	2.164E0	2.493E0	2.946E0	4.440E0
1984	8.042Ey1	1.191E0	1.405E0	1.634E0	1.879E0	2.239E0	3.519E0
1985	1.263E0	1.730E0	1.948E0	2.245E0	2.649E0	3.084E0	4.641E0
1986	9.015Ey1	1.453E0	1.661E0	2.048E0	2.503E0	3.003E0	4.829E0
1987	2.190E0	2.968E0	3.431E0	4.123E0	4.827E0	5.641E0	8.724E0
1988	9.249Ey1	1.365E0	1.594E0	2.058E0	2.510E0	2.974E0	4.573E0
1989	1.836E0	2.680E0	3.104E0	3.612E0	4.202E0	4.732E0	8.376E0
1990	1.988E0	2.843E0	3.503E0	4.173E0	5.031E0	5.793E0	7.330E0
1991	8.438E0	9.791E0	1.090E1	1.228E1	1.364E1	1.537E1	2.063E1
1992	1.711E0	2.383E0	2.705E0	3.224E0	3.828E0	4.541E0	6.772E0
1993	4.342E0	5.423E0	6.151E0	7.137E0	8.322E0	9.287E0	1.358E1
1994	1.861E0	2.607E0	3.301E0	4.026E0	4.855E0	5.577E0	7.667E0
1995	2.034E0	3.435E0	4.111E0	4.810E0	5.817E0	6.811E0	9.232E0
1996	2.372E0	3.536E0	4.211E0	5.211E0	6.419E0	7.627E0	1.062E1
1997	1.812E0	2.535E0	3.071E0	3.635E0	4.420E0	5.198E0	6.875E0
1998	2.101E0	3.009E0	3.440E0	4.347E0	5.109E0	5.939E0	8.048E0
1999	2.443E0	4.434E0	5.441E0	6.307E0	7.512E0	8.586E0	1.205E1
2000	2.199E0	3.211E0	3.967E0	5.098E0	6.365E0	7.433E0	9.985E0

YEAR	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE
1983	6.362Ey16	3.705Ey2	0.00	2.210E0	0.24
1984	2.109Ey17	2.946Ey2	0.00	1.682E0	0.25
1985	4.541Ey16	4.069Ey2	0.00	2.343E0	0.25
1986	1.034Ey15	4.505Ey2	0.00	2.145E0	0.30
1987	1.086Ey15	7.675Ey2	0.00	4.221E0	0.26
1988	y4.241Ey16	4.759Ey2	0.00	2.134E0	0.32
1989	y2.127Ey15	6.529Ey2	0.00	3.718E0	0.25
1990	y4.530Ey16	7.591Ey2	0.00	4.253E0	0.25
1991	5.862Ey15	1.592Ey1	0.00	1.248E1	0.18

1992	1.363Eý15	6.378Eý2	0.00	3.361E0	0.27
1993	9.548Eý16	1.103Eý1	0.00	7.304E0	0.21
1994	ý2.343Eý15	7.897Eý2	0.00	4.111E0	0.27
1995	ý5.751Eý16	9.349Eý2	0.00	4.996E0	0.26
1996	1.732Eý15	1.122Eý1	0.00	5.400E0	0.29
1997	1.140Eý15	7.021Eý2	0.00	3.770E0	0.26
1998	ý1.759Eý15	8.125Eý2	0.00	4.395E0	0.26
1999	4.758Eý15	1.146Eý1	0.00	6.440E0	0.25
2000	ý2.442Eý16	1.139Eý1	0.00	5.208E0	0.31

BOOTSTRAP OUTPUT VARIABLE: B_RN_0_expl
Exploited biomass at time of the survey
i.e. 0% into the calendar year

YEAR	NLLS ESTIMATE	BOOTSTRAP MEAN	BOOTSTRAP STD ERROR	C.V. FOR NLLS SOLN
1983	2.348E0	2.348E0	5.188Eý1	0.22
1984	1.863E0	1.863E0	4.196Eý1	0.23
1985	3.055E0	3.055E0	6.004Eý1	0.20
1986	3.466E0	3.466E0	7.135Eý1	0.21
1987	4.699E0	4.699E0	1.087E0	0.23
1988	2.879E0	2.879E0	7.060Eý1	0.25
1989	4.022E0	4.022E0	9.271Eý1	0.23
1990	6.367E0	6.367E0	1.179E0	0.19
1991	1.260E1	1.260E1	2.253E0	0.18
1992	4.864E0	4.864E0	9.518Eý1	0.20
1993	8.275E0	8.275E0	1.551E0	0.19
1994	4.699E0	4.699E0	1.132E0	0.24
1995	6.966E0	6.966E0	1.415E0	0.20
1996	6.117E0	6.117E0	1.605E0	0.26
1997	4.647E0	4.647E0	1.027E0	0.22
1998	6.311E0	6.311E0	1.242E0	0.20
1999	7.466E0	7.466E0	1.697E0	0.23
2000	7.071E0	7.071E0	1.756E0	0.25

YEAR	----- PERCENTILES -----						MAX
	MIN	10	25	MEDIAN	75	90	
1983	1.309E0	1.751E0	1.996E0	2.288E0	2.629E0	3.056E0	4.607E0
1984	1.020E0	1.370E0	1.583E0	1.820E0	2.060E0	2.427E0	3.739E0
1985	1.790E0	2.422E0	2.657E0	3.001E0	3.341E0	3.878E0	5.385E0
1986	2.255E0	2.662E0	2.962E0	3.336E0	3.923E0	4.337E0	6.635E0
1987	2.629E0	3.500E0	3.915E0	4.594E0	5.230E0	6.076E0	9.190E0
1988	1.657E0	2.080E0	2.351E0	2.799E0	3.288E0	3.745E0	5.223E0
1989	2.150E0	2.972E0	3.387E0	3.940E0	4.531E0	5.049E0	8.634E0
1990	3.952E0	4.887E0	5.465E0	6.318E0	7.212E0	8.022E0	9.536E0
1991	8.586E0	9.907E0	1.100E1	1.241E1	1.380E1	1.551E1	2.078E1
1992	2.890E0	3.793E0	4.216E0	4.736E0	5.357E0	6.028E0	8.812E0
1993	5.249E0	6.402E0	7.181E0	8.171E0	9.311E0	1.025E1	1.483E1
1994	2.474E0	3.146E0	3.909E0	4.592E0	5.461E0	6.147E0	8.241E0
1995	4.074E0	5.341E0	5.969E0	6.642E0	7.890E0	8.951E0	1.144E1
1996	3.168E0	4.224E0	4.920E0	5.864E0	7.144E0	8.434E0	1.144E1
1997	2.523E0	3.395E0	3.850E0	4.508E0	5.276E0	6.088E0	7.524E0
1998	3.667E0	4.835E0	5.395E0	6.264E0	6.981E0	7.775E0	1.062E1
1999	3.369E0	5.453E0	6.423E0	7.213E0	8.576E0	9.705E0	1.373E1
2000	3.695E0	4.877E0	5.804E0	6.939E0	8.245E0	9.574E0	1.272E1

YEAR	BIAS ESTIMATE	BIAS STD ERROR	PERCENT BIAS	NLLS EST CORRECTED FOR BIAS	C.V FOR CORRECTED ESTIMATE
1983	ý6.239Eý16	3.669Eý2	0.00	2.348E0	0.22
1984	ý5.607Eý16	2.967Eý2	0.00	1.863E0	0.23
1985	ý7.327Eý16	4.245Eý2	0.00	3.055E0	0.20
1986	ý6.661Eý17	5.045Eý2	0.00	3.466E0	0.21
1987	1.055Eý15	7.683Eý2	0.00	4.699E0	0.23

1988	y1.099Ey15	4.993Ey2	0.00	2.879E0	0.25
1989	y2.849Ey15	6.556Ey2	0.00	4.022E0	0.23
1990	1.390Ey15	8.334Ey2	0.00	6.367E0	0.19
1991	5.906Ey15	1.593Ey1	0.00	1.260E1	0.18
1992	1.219Ey15	6.730Ey2	0.00	4.864E0	0.20
1993	y7.372Ey16	1.097Ey1	0.00	8.275E0	0.19
1994	3.428Ey15	8.006Ey2	0.00	4.699E0	0.24
1995	y1.474Ey15	1.000Ey1	0.00	6.966E0	0.20
1996	2.682Ey15	1.135Ey1	0.00	6.117E0	0.26
1997	2.442Ey16	7.265Ey2	0.00	4.647E0	0.22
1998	1.923Ey15	8.780Ey2	0.00	6.311E0	0.20
1999	y7.061Ey16	1.200Ey1	0.00	7.466E0	0.23
2000	3.921Ey15	1.242Ey1	0.00	7.071E0	0.25

APPENDIX C: YIELD AND SSB PER RECRUIT ANALYSIS
Growth Scenario 1 (K=0.75 and Lmax=234.7)

The NEFC Yield and Stock Size per Recruit Program - PDBYPRC
 PC Ver.1.2 [Method of Thompson and Bell (1934)] 1-Jan-1992

Run Date: 6- 1-1999; Time: 10:05:07.72
 DELAWARE BAY BLUE CRAB YIELD PER RECRUIT

Proportion of F before spawning: .5000
 Proportion of M before spawning: .5000
 Natural Mortality is Constant at: .80
 Initial age is: 0; Last age is: 3
 Last age is a TRUE Age;
 Original age-specific PRs, Mats, and Mean Wts from file:
 ==> CRAB1.DAT

Age-specific Input data for Yield per Recruit Analysis

Age	Fish Mort Pattern	Nat Mort Pattern	Proportion Mature	Average Weights Catch Stock	
1	.4200	1.0000	.1000	.021	.024
2	.9000	1.0000	.9000	.116	.107
3	1.0000	1.0000	1.0000	.263	.219
4	1.0000	1.0000	1.0000	.361	.288

Summary of Yield per Recruit Analysis for:
 DELAWARE BAY BLUE CRAB YIELD PER RECRUIT

Slope of the Yield/Recruit Curve at F=0.00: -->	.1089
F level at slope=1/10 of the above slope (F0.1): ----->	.638
Yield/Recruit corresponding to F0.1: ----->	.0286
F level to produce Maximum Yield/Recruit (Fmax): ----->	1.021
Yield/Recruit corresponding to Fmax: ----->	.0302
F level at 20 % of Max Spawning Potential (F20): ----->	1.164
SSB/Recruit corresponding to F20: ----->	.0175

1

Listing of Yield per Recruit Results for:
 DELAWARE BAY BLUE CRAB YIELD PER RECRUIT

	FMORT	TOTCTHN	TOTCTHW	TOTSTKN	TOTSTKW	SPNSTKN	SPNSTKW	% MSP
	.00	.00000	.00000	1.8009	.1538	.5867	.0874	100.00
	.10	.07539	.00930	1.7321	.1394	.5176	.0740	84.71
	.20	.13855	.01601	1.6719	.1271	.4592	.0631	72.18
	.30	.19207	.02080	1.6192	.1166	.4095	.0540	61.86
	.40	.23794	.02418	1.5726	.1075	.3670	.0466	53.30
	.50	.27767	.02653	1.5313	.0997	.3304	.0403	46.17
	.60	.31244	.02813	1.4944	.0930	.2988	.0351	40.20
FO.1	.64	.32459	.02858	1.4814	.0906	.2878	.0334	38.18
	.70	.34316	.02916	1.4614	.0870	.2712	.0307	35.16
	.80	.37053	.02979	1.4317	.0819	.2471	.0270	30.90
	.90	.39512	.03012	1.4048	.0773	.2260	.0238	27.28
	1.00	.41737	.03023	1.3803	.0732	.2073	.0211	24.18
Fmax	1.02	.42187	.03023	1.3754	.0724	.2036	.0206	23.57
	1.10	.43764	.03019	1.3580	.0696	.1907	.0188	21.51
F20%	1.16	.44969	.03010	1.3448	.0676	.1811	.0175	20.00
	1.20	.45622	.03003	1.3376	.0664	.1760	.0168	19.20
	1.30	.47333	.02979	1.3189	.0636	.1628	.0150	17.20
	1.40	.48917	.02950	1.3016	.0610	.1511	.0135	15.46
	1.50	.50391	.02917	1.2856	.0586	.1404	.0122	13.94
	1.60	.51765	.02882	1.2708	.0565	.1309	.0110	12.60
	1.70	.53053	.02845	1.2570	.0545	.1222	.0100	11.42
	1.80	.54263	.02808	1.2441	.0527	.1144	.0091	10.37
	1.90	.55404	.02770	1.2321	.0511	.1072	.0082	9.44
	2.00	.56481	.02733	1.2209	.0496	.1007	.0075	8.62

Growth Scenario 1 (K=0.62 and Lmax=200.6)

The NEFC Yield and Stock Size per Recruit Program - PDBYPRC
PC Ver.1.2 [Method of Thompson and Bell (1934)] 1-Jan-1992

Run Date: 6- 1-1999; Time: 10:15:28.33

DELAWARE BAY BLUE CRAB YIELD PER RECRUIT

Proportion of F before spawning: .5000
Proportion of M before spawning: .5000
Natural Mortality is Constant at: .80
Initial age is: 0; Last age is: 3
Last age is a TRUE Age;
Original age-specific PRs, Mats, and Mean Wts from file:
==> CRAB2.DAT

Age-specific Input data for Yield per Recruit Analysis

Age	Fish Mort Pattern	Nat Mort Pattern	Proportion Mature	Average Weights Catch Stock	
1	.4200	1.0000	.1000	.021	.024
2	.9000	1.0000	.9000	.073	.072
3	1.0000	1.0000	1.0000	.162	.144
4	1.0000	1.0000	1.0000	.228	.193

Summary of Yield per Recruit Analysis for:
DELAWARE BAY BLUE CRAB YIELD PER RECRUIT

Slope of the Yield/Recruit Curve at F=0.00: --> .0704
F level at slope=1/10 of the above slope (F0.1): -----> .693
Yield/Recruit corresponding to F0.1: -----> .0196
F level to produce Maximum Yield/Recruit (Fmax): -----> 1.258
Yield/Recruit corresponding to Fmax: -----> .0211
F level at 20 % of Max Spawning Potential (F20): -----> 1.192
SSB/Recruit corresponding to F20: -----> .0117

1

Listing of Yield per Recruit Results for:
DELAWARE BAY BLUE CRAB YIELD PER RECRUIT

	FMORT	TOTCTHN	TOTCTHW	TOTSTKN	TOTSTKW	SPNSTKN	SPNSTKW	% MSP
	.00	.00000	.00000	1.8009	.1105	.5867	.0588	100.00
	.10	.07539	.00604	1.7321	.1009	.5176	.0499	84.86
	.20	.13855	.01045	1.6719	.0927	.4592	.0426	72.44
	.30	.19207	.01365	1.6192	.0858	.4095	.0365	62.20
	.40	.23794	.01597	1.5726	.0797	.3670	.0316	53.72
	.50	.27767	.01764	1.5313	.0746	.3304	.0274	46.64
	.60	.31244	.01883	1.4944	.0700	.2988	.0239	40.72
F0.1	.69	.34114	.01962	1.4636	.0664	.2730	.0212	36.04
	.70	.34316	.01966	1.4614	.0661	.2712	.0210	35.72
	.80	.37053	.02024	1.4317	.0627	.2471	.0185	31.48
	.90	.39512	.02062	1.4048	.0596	.2260	.0164	27.88
	1.00	.41737	.02086	1.3803	.0569	.2073	.0146	24.79
	1.10	.43764	.02099	1.3580	.0545	.1907	.0130	22.13
F20%	1.19	.45479	.02105	1.3392	.0526	.1771	.0117	20.00
	1.20	.45622	.02105	1.3376	.0524	.1760	.0116	19.83
Fmax	1.26	.46635	.02106	1.3265	.0513	.1682	.0109	18.63
	1.30	.47333	.02106	1.3189	.0505	.1628	.0105	17.83
	1.40	.48917	.02102	1.3016	.0487	.1511	.0095	16.09
	1.50	.50391	.02095	1.2856	.0472	.1404	.0086	14.56
	1.60	.51765	.02087	1.2708	.0458	.1309	.0078	13.21
	1.70	.53053	.02077	1.2570	.0445	.1222	.0071	12.02
	1.80	.54263	.02066	1.2441	.0433	.1144	.0064	10.97
	1.90	.55404	.02055	1.2321	.0422	.1072	.0059	10.04
	2.00	.56481	.02043	1.2209	.0412	.1007	.0054	9.20

Growth Scenario 1 (K=0.93 and Lmax=200.3)

The NEFC Yield and Stock Size per Recruit Program - PDBYPRC
PC Ver.1.2 [Method of Thompson and Bell (1934)] 1-Jan-1992

Run Date: 6- 1-1999; Time: 10:17:08.35

DELAWARE BAY BLUE CRAB YIELD PER RECRUIT

Proportion of F before spawning: .5000
Proportion of M before spawning: .5000
Natural Mortality is Constant at: .80
Initial age is: 0; Last age is: 3
Last age is a TRUE Age;
Original age-specific PRs, Mats, and Mean Wts from file:
==> CRAB3.DAT

Age-specific Input data for Yield per Recruit Analysis

Age	Fish Mort Pattern	Nat Mort Pattern	Proportion Mature	Average Weights	
				Catch	Stock
1	.4200	1.0000	.1000	.021	.024
2	.9000	1.0000	.9000	.123	.113
3	1.0000	1.0000	1.0000	.229	.194
4	1.0000	1.0000	1.0000	.282	.232

Summary of Yield per Recruit Analysis for:
DELAWARE BAY BLUE CRAB YIELD PER RECRUIT

Slope of the Yield/Recruit Curve at F=0.00: -->	.0998
F level at slope=1/10 of the above slope (F0.1): ----->	.693
Yield/Recruit corresponding to F0.1: ----->	.0282
F level to produce Maximum Yield/Recruit (Fmax): ----->	1.128
Yield/Recruit corresponding to Fmax: ----->	.0300
F level at 20 % of Max Spawning Potential (F20): ----->	1.233
SSB/Recruit corresponding to F20: ----->	.0162

1

Listing of Yield per Recruit Results for:
DELAWARE BAY BLUE CRAB YIELD PER RECRUIT

	FMORT	TOTCTHN	TOTCTHW	TOTSTKN	TOTSTKW	SPNSTKN	SPNSTKW	% MSP
	.00	.00000	.00000	1.8009	.1451	.5867	.0812	100.00
	.10	.07539	.00861	1.7321	.1325	.5176	.0694	85.39
	.20	.13855	.01494	1.6719	.1217	.4592	.0596	73.33
	.30	.19207	.01957	1.6192	.1124	.4095	.0514	63.32
	.40	.23794	.02294	1.5726	.1043	.3670	.0446	54.95
	.50	.27767	.02537	1.5313	.0973	.3304	.0389	47.93
	.60	.31244	.02709	1.4944	.0912	.2988	.0341	42.01
F0.1	.69	.34114	.02822	1.4636	.0861	.2730	.0303	37.30
	.70	.34316	.02829	1.4614	.0858	.2712	.0300	36.98
	.80	.37053	.02908	1.4317	.0810	.2471	.0266	32.69
	.90	.39512	.02958	1.4048	.0768	.2260	.0236	29.01
	1.00	.41737	.02985	1.3803	.0730	.2073	.0210	25.84
	1.10	.43764	.02995	1.3580	.0697	.1907	.0188	23.10
Fmax	1.13	.44293	.02995	1.3522	.0688	.1865	.0182	22.41
	1.20	.45622	.02993	1.3376	.0666	.1760	.0168	20.71
F20%	1.23	.46198	.02990	1.3313	.0657	.1715	.0162	20.00
	1.30	.47333	.02981	1.3189	.0639	.1628	.0151	18.63
	1.40	.48917	.02962	1.3016	.0614	.1511	.0136	16.80
	1.50	.50391	.02939	1.2856	.0592	.1404	.0123	15.20
	1.60	.51765	.02911	1.2708	.0571	.1309	.0112	13.77
	1.70	.53053	.02881	1.2570	.0552	.1222	.0102	12.52
	1.80	.54263	.02850	1.2441	.0535	.1144	.0093	11.40
	1.90	.55404	.02817	1.2321	.0519	.1072	.0084	10.40
	2.00	.56481	.02783	1.2209	.0504	.1007	.0077	9.50

ATTACHMENT #2

**Project No. 1: REPRODUCTIVE BIOLOGY OF WEAKFISH IN THE
DELAWARE BAY.**

Reproductive Biology of Weakfish in the Delaware Bay

Janet Nye, University of Delaware Graduate Student

Introduction

Estimates of maturity and fecundity are important life history characteristics needed to manage stocks. Maturity and fecundity are not static characteristics and have been shown to vary considerably from year to year in many fish species including weakfish (Lowerre-Barbieri et. al. 1996). These factors are considered plastic and may change as the size of the stock changes (Helser and Almeida 1997). In heavily exploited stocks, growth increases with reduced competition for food. With greater nutritional condition, fish may mature much earlier and be able to contribute to the exploited stock (Stearns and Crandall 1984). However, this decrease in age and size at maturity may compromise the reproductive success of the stock as smaller fish may release fewer eggs. These eggs may also be smaller eggs and produce smaller larvae that are more susceptible to predation and starvation (Knutsen and Tilseth 1985).

A study in the Chesapeake Bay estimated fecundity and growth characteristics of weakfish (Lowerre-Barbieri 1996), but information is needed on these parameters in the Delaware Bay. Although there is significant gene flow between weakfish in estuarine systems of the mid-Atlantic coast (Graves et. al. 1992), there may be variations in life history characteristics between individual estuaries. The only study of weakfish reproduction in the Delaware Bay was conducted in 1988 (Taylor and Villoso 1994). Currently the weakfish stock is at a higher abundance than previous studies so reproductive characteristics such as size/age at maturity, individual fecundity, and spawning frequency may be different. Weakfish are an important resource in the Delaware Bay and in their range along the Atlantic Coast. Recent estimates of maturity, fecundity, and spawning frequency in both a spatial and temporal context are important to any management effort.

Methods

Weakfish were collected in 1999 and 2000 in the Delaware Bay on 16 and 30 foot DNREC DFW trawl surveys. Approximately 50 fish from each twenty-minute tow were taken, kept on ice, and taken to the lab for processing. Of these fish, the first 25 females or as many females as were present were lengthed (TL) to the nearest mm and weighed (TW) to the nearest 0.1 g. Ovaries were taken, weighed to the nearest 0.1 g, and preserved in 10% neutrally buffered formalin. Gonadosomatic Index (GSI) and Fulton's Condition factor (K) were calculated with these data. Sagittal otoliths were taken and used to age each fish.

To supplement samples with larger individuals, weakfish were collected in gill nets in 1999 and 2000. Nets were set for 45-90 minutes in the evening from approximately 1600 to 1800. Time of kill was noted for each individual. Commercial gillnet samples also supplemented the samples with larger individuals in both sampling seasons.

Ovaries were prepared to estimate spawning frequency and batch fecundity. A 5mm section of each ovary was taken from the center of the left ovary, dehydrated, and embedded in paraffin wax. These embedded samples were sectioned at 5 μ m, mounted on slides, and stained with Harris' Hematoxylin and Eosin-Y. Histological characters such as post-ovulatory follicles (POFs), developmental stage of oocytes, and atresia will be examined microscopically to determine spawning frequency as detailed by Hunter and Macewitz (1985). Microscopic analysis will also determine which samples contain advanced yolked oocytes, and no new POFs, and thus, are suitable to use for batch fecundity.

Results and Discussion

In 1999 and 2000, approximately 655 samples were collected by trawl, gillnet, and hook and line (Table 2). In addition, samples from Long Island Sound, CT; Pamlico Sound, NC; and Chesapeake Bay, MD were collected and processed in the same manner. These samples will be used to compare length-fecundity relationships in different estuaries.

In both years, GSI of fish collected by trawl showed the same general trend. Average GSI was low in April when spawning and collection began; it increased in May and peaked in June (Figure 1). By July, there were still females in spawning condition, but most fish were regressing or spent. Although gonad weight was on average slightly higher in 2000, GSI estimates were lower because average total weight was much higher than 1999 females.

Condition factor did not follow the same trend in both years, but was low at the end of each spawning season (Figure 2). Spawning requires a high amount of energy, which may come from either feeding, or energy reserves in the female. Reduced nutritional condition may affect the number and size of eggs produced at the end of the spawning season.

In 1999, analysis of GSI by date shows a dramatic decrease in condition factor on the same date as the peak GSI on 1 June (Figure 3). In 2000, there is no such dramatic relationship, but a peak in GSI is associated with a low condition factor on 28 June (Figure 4).

Logistic regression of the proportion of mature females in each 10mm length class for 2000 revealed the length at 50% maturity (or mean size at maturity) was 212 mm (Figure 5). The length at 100% maturity was 425 mm, but no immature fish were found above 310 mm.

All of the 1999 samples and half of the 2000 samples have been processed for histological analysis. Preliminary analysis of 1999 histological slides revealed some immature females and many maturing females that had not spawned at the beginning of the season (Figure 6). Females collected later in the season had post-ovulatory follicles (POFs), atresia, and several stages of oocyte development in each ovary indicating multiple spawning (Figure 7).

Those mature females with POFs follicles were described. POFs younger than 24 hours old have distinct granulose cells, are larger, and appear more organized. POFs older than 24 hours are thin, have fewer folds and the granulose cells are not large and distinct. Older POFs are smaller as they are collapsing and being reabsorbed.

Estimates of spawning frequency and batch fecundity have not been completed, but all of the histological slides have been prepared for these procedures. Thus, annual fecundity, which is calculated with batch fecundity and spawning frequency, has not been completed. Egg size will be done at the same as batch fecundity analysis. Complete age data is not yet available to analyze age at maturity, but all these parameters will be completed by the next grant cycle.

Table 1. Weakfish ovary samples collected to date. Numbers in parentheses represent Age 2 and 3 fish collected in another study.

Location	1999	2000
Delaware Bay, DE	325	330
Chesapeake Bay	(142)	99
Pamlico Sound, NC	(181)	118
Long Island Sound	(31)	22

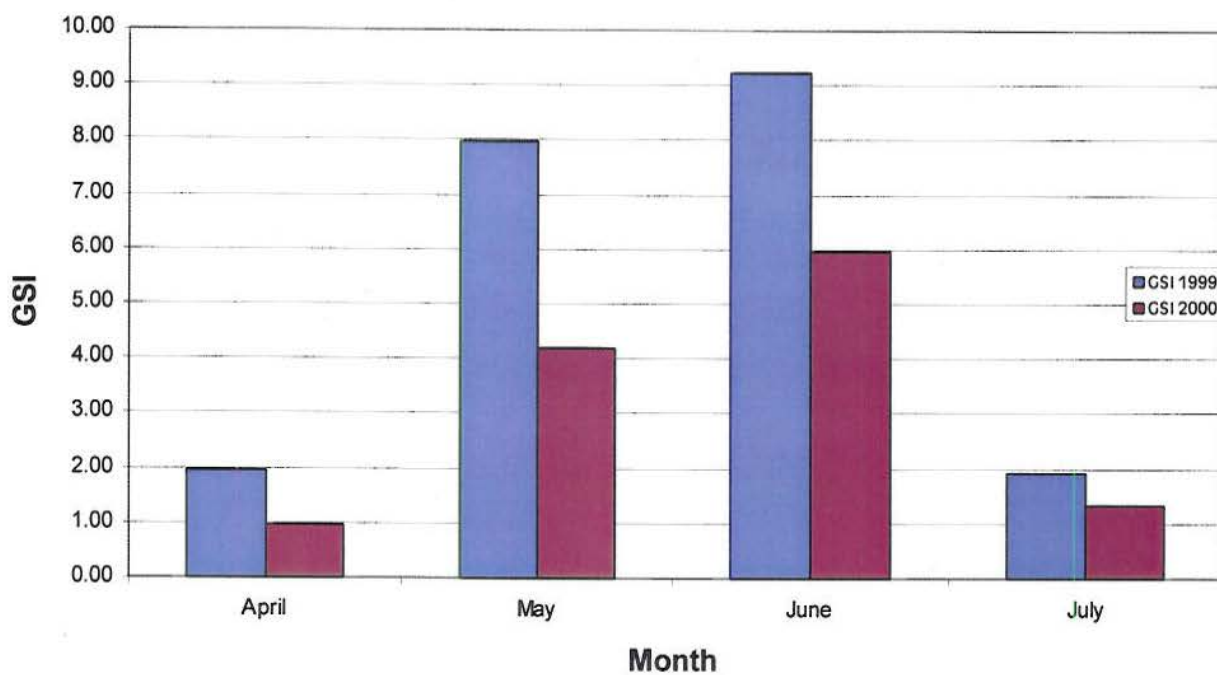


Figure 1: Average Monthly GSI for all females caught in 20 foot DNREC trawl

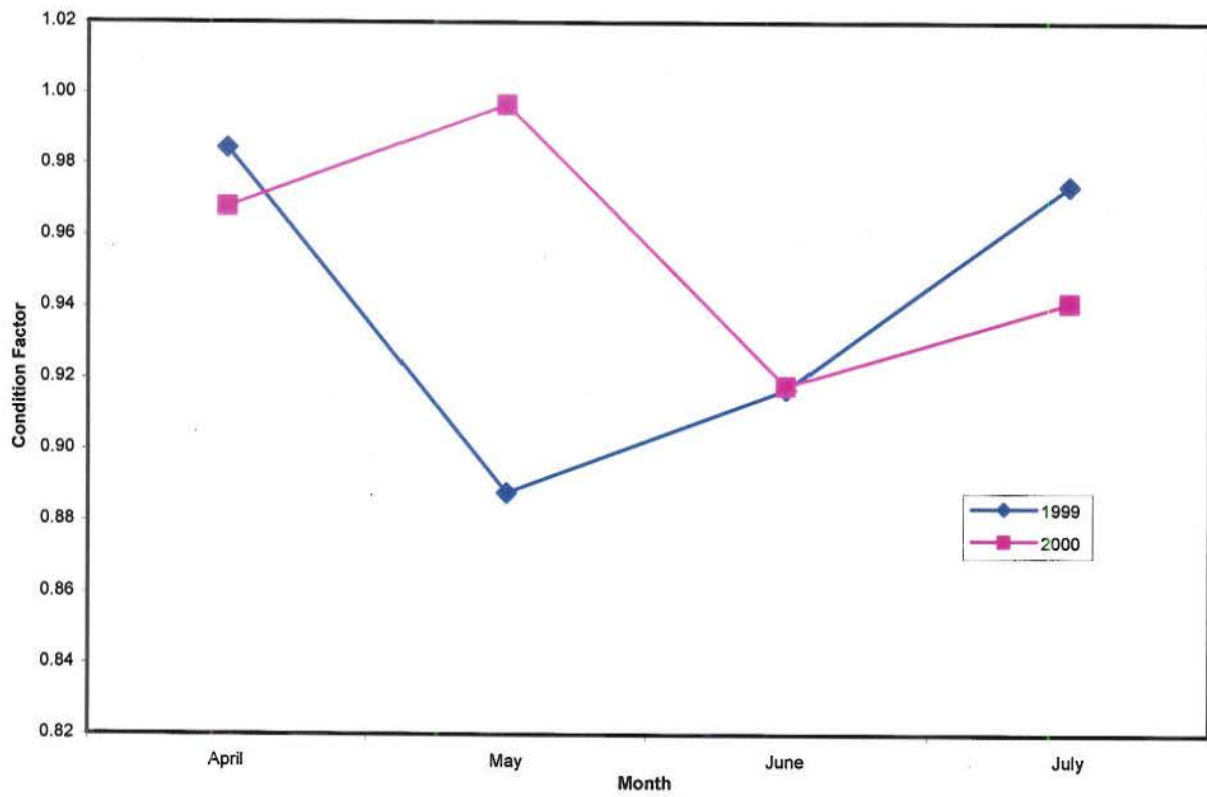


Figure 2: Average Monthly Condition Factor for all females caught in 20 foot DNREC trawl survey in 1999 and 2000

Figure 3: 1999 GSI and Condition Factor

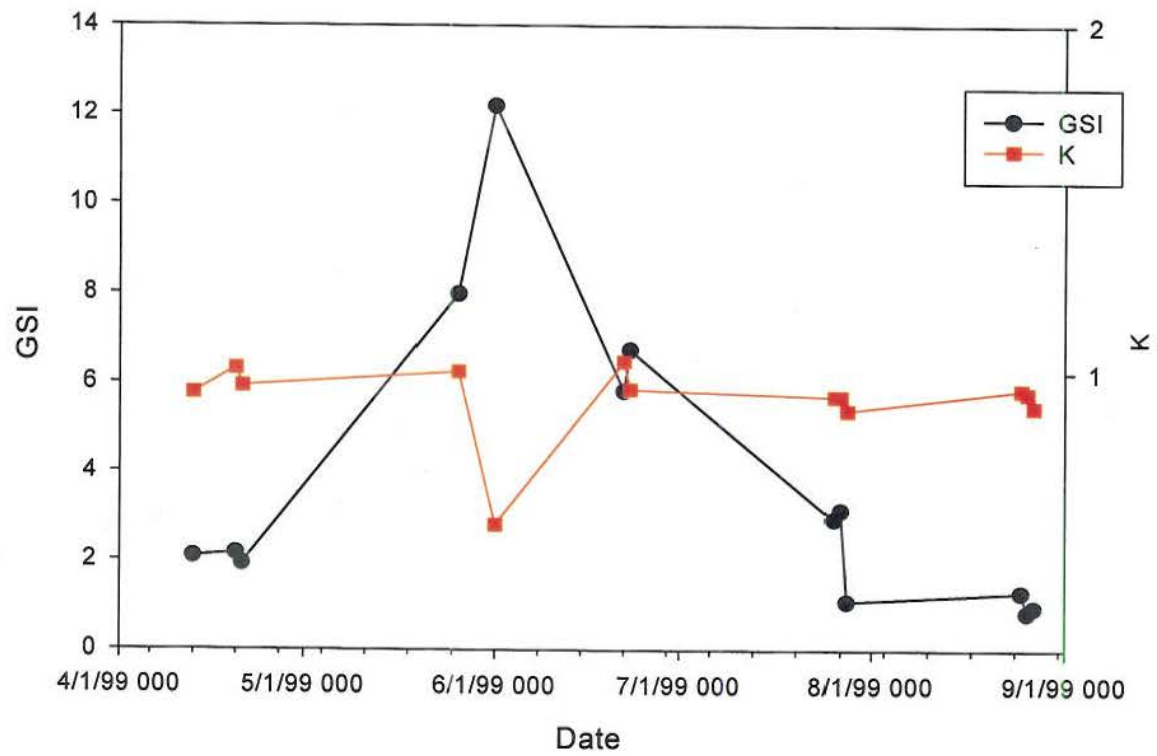
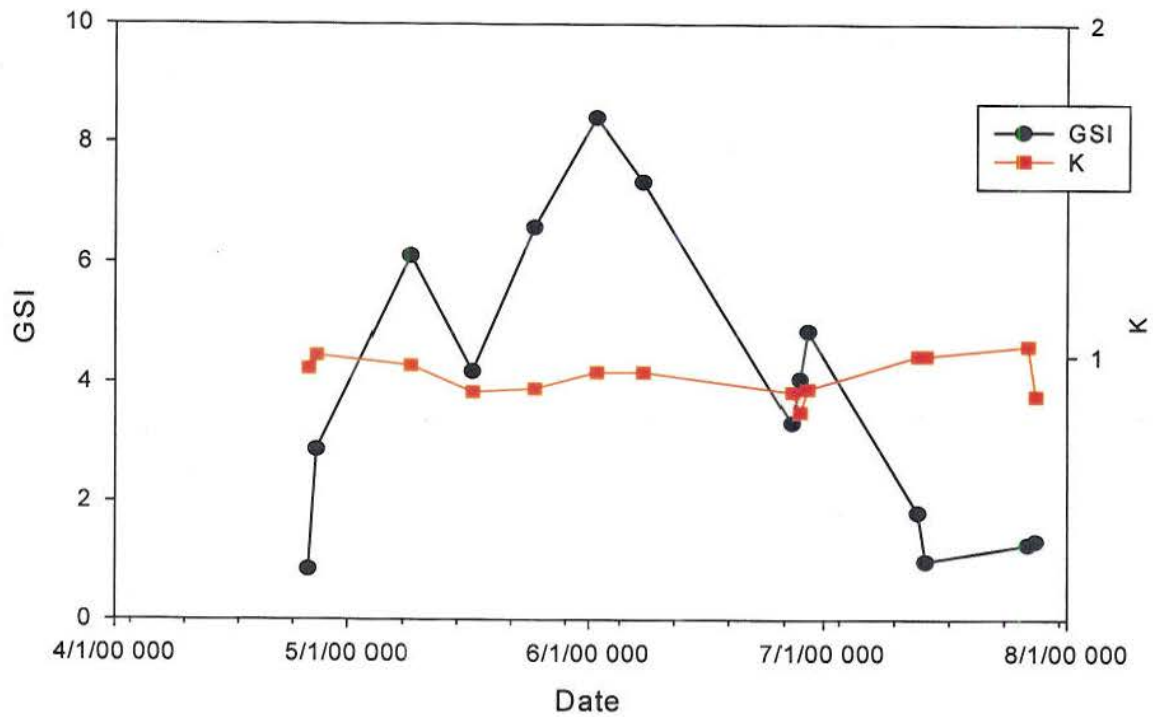


Figure 4: 2000 GSI and Condition Factor



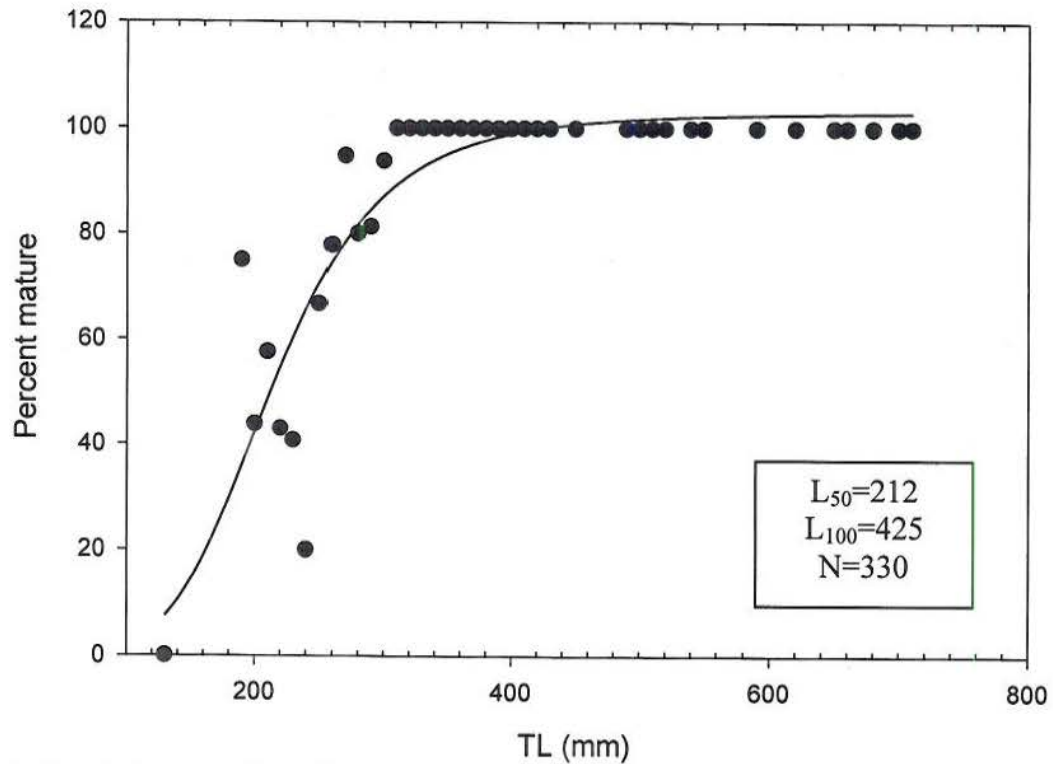


Figure 5: Logistic regression of proportion of mature females in each 10 mm length class for 2000.

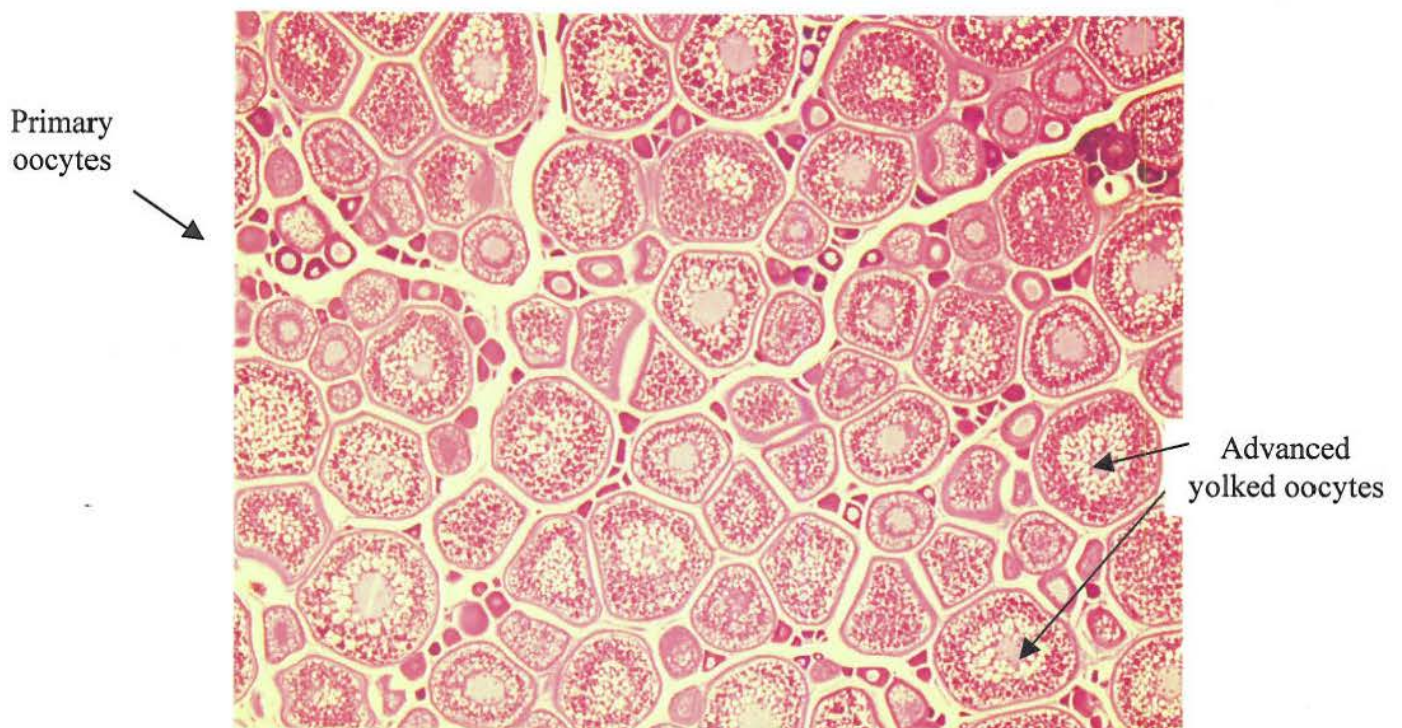


Figure 6: Mature female caught in May with many stage of early oocyte development, but no post-ovulatory follicles or evidence of spawning (40x)

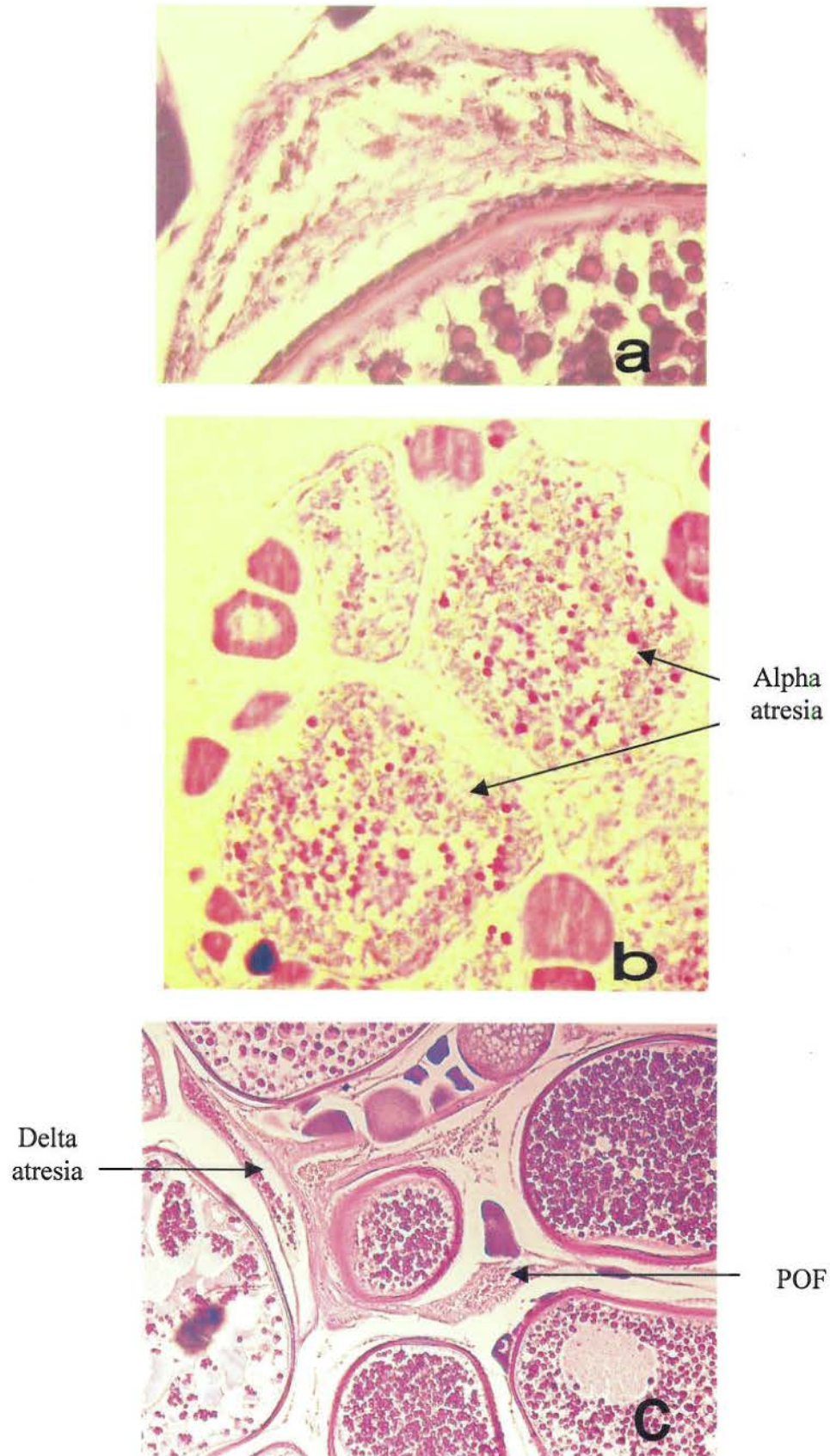


Figure 7: a) POF in spawning fish (400x), b) Alpha atresia of yolked oocytes (100x), c) delta atresia of oocyte with POF (100x). Delta atresia is characterized by a dark-yellow, granular appearance.

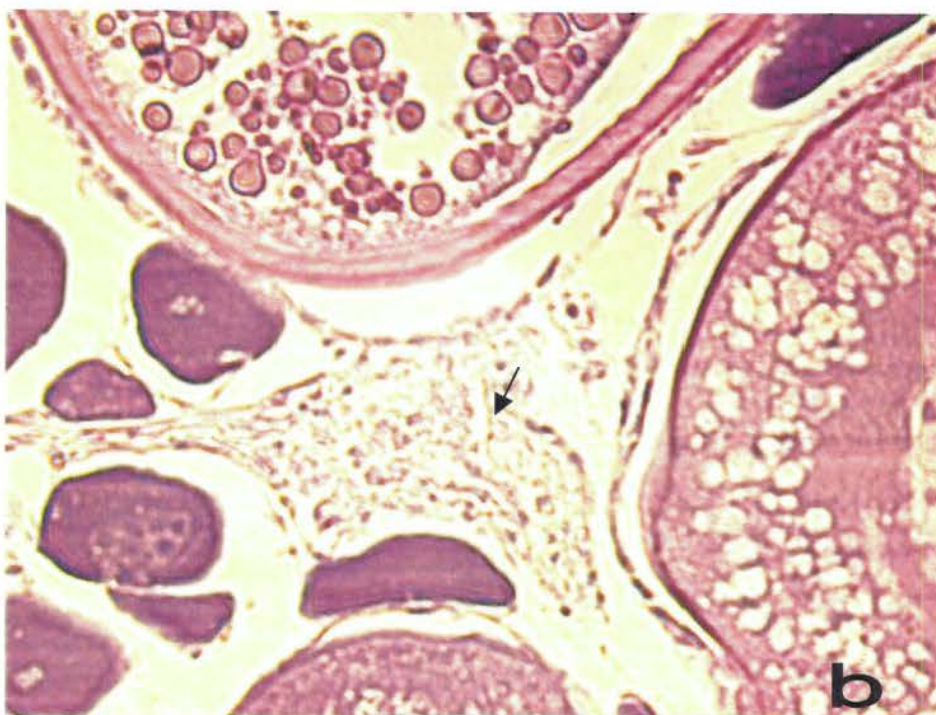
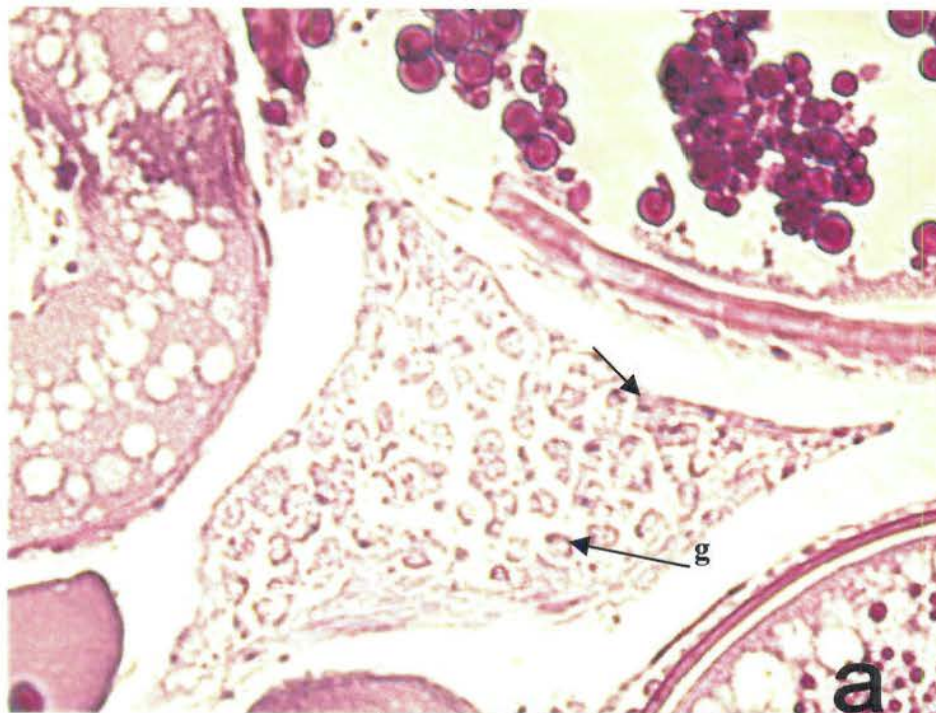


Figure 8: Degenerating post-ovulatory follicles (POFs) in weakfish. g=granulosa epithelial cell layer, t=thecal connective layer

a) POF less than 24 hours old

b) POF greater than 24 hours old

ATTACHMENT #3

**Project No. 1: EFFECT OF FOUR BYCATCH REDUCTION DEVICES
ON DIAMONDBACK TERRAPIN CAPTURE AND BLUE
CRAB HARVEST IN THE DELAWARE RIVER
ESTUARY.**

DIAMONDBACK TERRAPIN BYCATCH REDUCTION

**Effect of Four Bycatch Reduction Devices on Diamondback
Terrapin (*Malaclemys terrapin*) Capture and Blue Crab
(*Callinectes sapidus*) Harvest in the Delaware Estuary**

Keywords: Bycatch Reduction Device, *Malaclemys*, *Callinectes*, Delaware Bay,
TED, turtle exclusion device

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Abstract

Diamondback terrapins, *Malaclemys terrapin*, face declining populations throughout their expansive range from by-catch mortality in commercial and recreational crab pots. Conservation efforts in recent years have focused on the use of bycatch reduction devices (BRDs) installed in commercial style crab pots, but no standard configuration of BRD is presently in use. We conducted a four year study between 1997-2000 to investigate the impact of four BRDs on diamondback terrapin capture and its effect on blue crab, *Callinectes sapidus*, catch and average size. A total of 52 sets consisting of five replicate blue crab pots for each BRD treatment and controls was deployed at random in 10 tidal tributaries and inland bays within the Delaware Estuary. The BRD sizes tested were: 5.0 x 10.0, 5.0 x 12.0, 4.5 x 12.0, and 3.8 x 12.0 cm. In 1997-1998 when we tested the 5.0 x 10 cm BRD, a total of 137 diamondback terrapins and 996 legal sized blue crabs (≥ 127 mm) was caught. We observed a statistically significant reduction ($p < 0.01$) in terrapin catches (59%) in pots fitted with the 5 x 10 BRD vs. controls, with no statistical difference in blue crab catches. In 1999-2000, we captured a total of 235 terrapins and 2526 legal size blue crabs. The 5.0 x 12.0 cm BRD did not show a statistically significant reduction in overall terrapin catches (-12%) nor was there a significant loss of legal sized blue crab catches. Only a nominal loss (12%) of legal sized blue crab catches was observed in pots fitted with the 4.5 x 12.0 cm BRDs while we observed a significant ($p < 0.01$) reduction in diamondback terrapin captures (38% male and 96% female). No terrapins were captured in the smallest BRD (3.8 x 12.0 cm), however, losses of legal sized blue crab catches were substantial (26%). We therefore recommend the use of the 4.5 x 12.0 cm BRD for use in recreational crab pots as a conservation measure as this would effectively protect all sub-adult and reproductive females with minimal loss of legal blue crabs. We also stress the importance of the use of BRDs in concert with other conservation measures such as efforts directed at monitoring the effects of BRD implementation on bycatch mortality and preservation of nesting.

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Introduction

The diamondback terrapin (*Malaclemys terrapin*) is an indigenous inhabitant of brackish wetlands ranging from southern Massachusetts to Mexico (Daiber 1982). There are seven recognized subspecies throughout its range with three subspecies reported along the Atlantic coast (Palmer 1988). Male and female terrapins exhibit sexual dimorphism where males are smaller with narrower heads and longer, thicker tails. Straight-line carapace lengths in adult males range from 10-14 cm and 15-23 cm in adult females (Conant 1975). Sexual maturity occurs between 4-7 years in males and 8-13 years in females (Roosenburg 1990). Nesting terrapins prefer flat areas in high dunes and have a mean clutch size of 10 eggs with a range of 4-18 eggs (Daiber 1982). Life span is unknown due to difficulty in aging older terrapins but is believed to be as long as 50 years (Roosenburg 1990).

Throughout its narrow but expansive range terrapins face numerous perturbations including environmental and human induced habitat loss, predation, mortality on roads, and by-catch mortality in commercial and recreational crab pots. Although population status is unknown in Delaware, the species is believed to be declining throughout their coastal range (Siegal and Gibbons 1995). By-catch mortality has led to severe declines and, in extreme cases, complete extirpation of some local populations can occur in as few as 3-4 years (Roosenburg et al. 1997). Species such as diamondback terrapins are at greater risk because they have low fecundity, slow growth rates and late maturation. Additionally, Delaware regulations list the diamondback terrapin as a game species

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allowing a daily limit of four terrapins with harvest dates of September 1 – November 15. The timing of this season reduces the possibility of harvesting reproductive females.

At the same time the blue crab (*Callinectes sapidus*) is Delaware's number one commercial species in terms of license sales, pounds landed and revenue (Whitmore and Cole 1997). Widespread recreational crabbing occurs along the coast in tidal tributaries and coastal bays by both residents and vacationers. However, surveys conducted by Delaware Division of Fish and Wildlife assessing recreational crabbing in the Delaware estuary (Cole et al. 1997) accounted for <1% of the total pounds landed statewide. These surveys, however, did not evaluate the recreational harvest in two important inland bays, Indian River and Rehoboth Bays. Although a quantitative survey was not conducted in this study, qualitative assessment indicates these bays are more intensively utilized than tidal tributaries by recreational crabbers using commercial style crab pots thereby subjecting terrapins to a greater risk of capture. Therefore, terrapin bycatch is potentially significant in these inland bays.

Bycatch reduction has been studied in other estuarine systems in neighboring states including Maryland, New Jersey and North Carolina using bycatch reduction devices (BRDs). BRDs are simple wire or plastic devices (usually rectangular) fitted into the funnel of commercial style crab pots providing a physical impediment to turtles desiring to enter the pot to reach bait used to attract blue crabs. Research has shown that installation of bycatch reduction devices can reduce the capture and subsequent drowning of terrapins (Grant 1997; Roosenburg, in press; Wood 1997). Configurations of BRDs

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tested by other researchers (Wood 1997, Roosenburg, in press, Grant 1997) includes: 4 x 8, 4 x 10, 4.5 x 10, 4.5 x 12, 5 x 10, 5 x 15 and 5 x 18 cm. Maryland and New Jersey have adopted regulations mandating the use of BRDs measuring 4.5 x 12cm (1.75 x 4.75") and 5 x 15 cm (2 x 6"), respectively, in certain waters. However, there is no standard configuration of BRDs due to potential morphological variations among turtle populations in different geographic areas as well as political considerations in different states. To this end, we conducted a four year study from 1997-2000 on the effectiveness of four BRD configurations used in blue crab traps to reduce diamondback terrapin bycatch mortality and their effect on blue crab harvest.

Materials and Methods

Sampling and Data Collection

Geographically the study area consisted of eight tidal tributaries located throughout the state and two coastal bays in southern Delaware (Figure 1). Spatial coverage included brackish portions of tidal and coastal bay tributaries as well as open water habitats in Rehoboth Bay. Tributary lengths ranged from approximately 2 to 10 miles from their mouth at Delaware Bay to their upstream terminus. Rehoboth and Indian River Bays are 9,957 and 9,994 acres, respectively.

In 1997-98, 26 sets were made consisting of 10 individual traps per set with 5 controls (no BRDs) and 5 traps with a 5 x 10 cm BRD. In 1999-2000, we made 26 sets of 25 individual traps consisting of 5 controls and 20 traps with BRDs of four configurations. Thus, each BRD and control consisted of 5 replications per set. Our

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data showed that a higher percentage of both blue crabs and terrapins were restricted from entering crab pots due to BRD height rather than width. We therefore incrementally expanded BRD height in 1999 by 0.64 cm (0.25"). The following BRD configurations used were: 3.2 x 12.0 cm (1.25 x 4.75"), 3.8 x 12.0 cm (1.5 x 4.75"), 4.5 x 12.0 cm (1.75 x 4.75"), and 5.0 x 12.0 cm (2.0 x 4.75"). We selected two of these configurations based on studies conducted in New Jersey (Wood, Personal communication) and Maryland (Roosenburg, Personal communication) (i.e., 5 x 10 cm used in 1997-98 and 4.5 x 12.0 cm used in 1999) as well as commercial availability. However, when we examined the results of the crab catch in pots fitted with the 3.2 x 12.0 cm BRD, virtually all legal size crabs were restricted from entering the pot. Therefore this BRD was eliminated from the analysis and future study because it is not a viable option for use in recreational crab pots.

We used commercial crab pots of identical design for all samples. They were made of coated vinyl, hexagon mesh wire measuring 61 x 61 cm² (24 x 24 inches square) with an entrance funnel located at the base of each side. Pots were weighted with 1.6 cm (5/8") rebar and demarcated with the Division's address on a 28 cm (11") white PVC sponge float, attached to 7.6 meters (25') of 1 cm (3/8") polypropylene rope. Each BRD was measured for accuracy before installing them into the narrowest portion of the funnel. Pots were baited with equal amounts of menhaden (*Bevorrtia tyrannus*) which is used by commercial crabbers in this region. We fished pots for a 24-hour period and routinely checked pots twice daily in high terrapin density areas to minimize drowning

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of terrapins.

We measured, sexed and recorded each crab and turtle captured by pot type. Only carapace width measurements (distance between the tips of the lateral spines of the cephalothorax) were taken on blue crabs while straight-line carapace length and width were recorded on terrapins in 1997. In addition to length and width measurements, we also measured terrapin depth during 1998 through 2000 field seasons. Both species were measured to the nearest 1-mm. Limited length and depth measurements were taken on blue crabs because a large sample of measurements in three dimensions was available from our earlier studies. We used measuring boards demarcated in millimeters to measure crab width and terrapin length and width and vernier calipers to measure small terrapin depth. Depth measurements of larger terrapins were measured with a small tree caliper from the center of the plastron to the highest point on the carapace. Sex was determined by examining the position of the vent relative to the margin of the carapace (Palmar 1988). Measuring instruments were checked for accuracy prior to use.

Statistical Analysis

The statistical analysis consisted of two separate but related components. The first was to evaluate the effect of BRD on reduction of terrapin catch and blue crab harvest in blue crab traps. To evaluate catch data we used a log-linear model analysis (Agresti 1990) on a three-way contingency table consisting of BRD, CRAB TYPE (CT), and SEASON. Crab type was categorized on the basis of commercial grading of blue

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crab harvest and consisted of number 1 (males $\Rightarrow$ 140 mm), number 2 (127 mm $\leq$ males $<$ 140 mm), and number 3 (mature females). Season classes were defined as spring (May-June), summer (July-August), and fall (September-October). The log-linear model has a structure analogous to the three-way factorial ANOVA and can be written as:

$$\log f_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + \alpha\beta_{ij} + \alpha\gamma_{ik} + \beta\gamma_{jk} + \alpha\beta\gamma_{ijk}$$

The log-linear model was then followed up by a correspondence analysis (Greenacre 1984; Greenacre and Hastie 1987) as a technique of model interpretation and graphically displaying results in the form of biplots. For these analyses, we used PROC CATMOD and PROC CORRESP in SAS, respectively (SAS Inst. 1989).

The second analysis was to investigate whether the use of BRDs resulted in different average sizes of terrapin turtles and blue crabs in traps. For blue crabs, we used a three-way ANOVA (PROC GLM, SAS Inst. 1989) with BRD, CRAB TYPE and SEASON as explanatory variables. We used individual traps as the experimental unit, and therefore calculated the average blue crab carapace width per trap as the dependent variable in the GLM. Each dependent observation, however, was weighted by the number of individual blue crab carapace widths. The GLM was applied to terrapin carapace length and only BRD and SEX were used as explanatory variables. Here, because so few turtles were caught within the different factor levels, we used the individual terrapin as the experimental unit and was thus used as the dependent variable.

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Finally, we used analysis of covariance to explore different allometric growth patterns between depth-length and sex. All statistical hypotheses were tested at $\alpha=0.05$.

Results

Terrapin Captures

During the 1997-1998 field season, a total of 137 terrapins was caught with 40 in the 5 x 10 cm BRD and 97 in crab pots with no BRD (Table 1). This represents a significant reduction of 59% ($X^2 = 23.7, p < 0.001$) in total terrapins between crab traps fitted with the 5 x 10 cm BRD vs. the control traps. A Chi-square analysis of numbers of terrapins caught by BRD and SEX showed a significant interaction between BRDxSEX ($X^2 = 5.8, p < 0.02$). This effect can be seen in table 1 where despite the fact that male (54%) and female (46%) terrapins were present in all traps with a nearly a 1:1 ratio, there was a 76% reduction ($X^2 = 24.1, p < 0.001$) in female terrapins captured in traps fitted with the 5 x 10 cm BRD, whereas a 39% male terrapin reduction ($X^2 = 4.4, p < 0.04$) was realized in traps with the BRD.

Similarly, we found significant reductions in terrapin catches during the 1999-2000 field season when we tested three additional BRDs. Chi-square analysis of the 1999-2000 data cross-classified in the BRDxSEX contingency table also showed a significant interaction between BRDxSEX ($X^2 = 41.1, p < 0.001$). For male terrapins, there was a 33% catch increase in traps fitted with the 5.0 x 12.0 cm BRD, which was not statistically significant ($X^2 = 2.5, p > 0.1$), a 38% catch reduction in 4.5 x 12.0 cm

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traps ($X^2 = 5.0, p < 0.03$), and a 100% catch reduction in male terrapins in traps fitted with a 3.8 x 12.0 cm BRD (Table 2). In contrast, greater reductions in female terrapin catches were realized across all BRDs; 61% in 5.0 x 12.0 cm BRD traps ($X^2 = 13.5, p < 0.001$), 96% catch reduction in traps fitted with the 4.5 x 12.0 cm BRD ($X^2 = 45.3, p < 0.001$) and a 100% catch reduction in 3.8 x 12.0 cm traps. Based on total terrapin captures in 1999-2000, we observed a male dominated sex ratio of 69% with 31% females, as compared with the previous two years (males 54% vs. females 46%).

Analysis of variance of terrapin carapace lengths showed a significant interaction between BRDxSEX ($p < 0.001$) for the 1997-2000 field seasons. Figure 2 illustrates changes in terrapin length for SEX and BRD for all years combined. Mean carapace lengths for male terrapins (110.6 mm - 117.3 mm) were essentially identical across all BRD sizes where they were captured (i.e., controls and BRD sizes 5 x 10 cm, 5.0 x 12.0 cm, and 4.5 x 12.0 cm; no captures in 3.8 x 12.0 cm BRD) for both field seasons (Figure 2). In contrast, mean carapace lengths declined for female terrapins captured in traps fitted with BRDs (i.e., 5 x 10 cm, 5.0 x 12.0 cm and 4.5 x 12 cm; no captures in 3.8 x 12.0 cm BRD) relative to the controls (Figure 2). Mean length in control pots in 1997 - 2000 was 139.4 mm and declined to 108.8 mm and 98.0 mm in the 5 x 10 cm and 5 x 12 cm BRDs, respectively. Thus, for female terrapins we observed a 22-30% reduction in the mean carapace length corresponding to a 61-96% reduction in catches in traps fitted with BRDs. For male terrapins, however, the mean lengths remained essentially identical across controls and BRDs even though we observed significant catch

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reductions in the 4.5 x 12 and 3.8 x 12 cm BRDs and a 33% catch increase in the 5 x 12 cm BRD. Differences in catch reduction and means sizes between male and female terrapins may in part be explained by sex-specific allometric growth patterns (Figure 3). Analysis of covariance showed a significant LENGTHxSEX interaction ($p < 0.01$). In general, female terrapins grow to larger sizes and attain a greater average body depth for a given length than do male terrapins (Figure 3). Therefore, depth is a greater limiting factor than width for entrance of terrapins into traps; substantiated by greater reductions in female terrapin catches in traps equipped with BRDs.

Blue Crab Captures

Because control traps and traps fitted with BRDs were fished with equal effort among years during the two different periods of this study, we discuss blue crab captures in terms of actual catch rates. Results of the log-linear model analysis did not show any significant BRD main or interaction effects ($p > 0.05$) for the 1997-1998 period comparing control vs. 5 x 10 cm BRD (Table 3). Thus, even though there was a 39% to 76% (overall 59%) reduction in male and female terrapin catches, respectively, no blue crabs of any crab type were excluded from entering the 5 x 10 cm BRD (Table 4). In contrast, using the 1999-2000 data the log-linear analysis showed both a main BRD effect ($p < 0.001$) and an interaction between BRDxCT ($p < 0.05$) (Table 3). The significant BRDxCT interaction is illustrated in Figure 4 with its associated contingency table (Table 5) showing the results of the correspondence analysis. Most of the variation

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in blue crab catch rates is found in dimension 1 (74%) from the correspondence analysis and shows the relationship of blue crab catches and its association between BRD size and CT (crab type) (Figure 4). This plot depicts that most of the significance of the X^2 was associated with the 3.8 x 12.0 cm BRD type.

In traps fitted with the 5.0 x 12.0 cm BRD, there was no substantial change in total blue crab catch rates (Table 5) even though we observed on average a 12% reduction in terrapin catches. It should be noted that this BRD provides no significant protection to male terrapins. Traps with the 4.5 x 12.0 cm BRD showed an overall 12.3% ($X^2 = 5.511, p < 0.05$) reduction in blue crab catch rates, with the greatest loss seen in crab type 2 (-17.0%) followed by crab type 1 (-5.9%). The only statistically significant blue crab catch reduction for the 4.5 x 12 cm BRD was for crab type 2 ($X^2 = 5.573, p < 0.05$). However, we observed a 38% reduction and a 96% reduction in male and female terrapin catch, respectively. For traps fitted with the smallest BRD (3.8 x 12.0 cm), we observed a 100% reduction in both sexes of terrapin catches, but total blue crab catch rates were reduced by 25.9% (Table 5). The greatest reduction of blue crab catch rates occurred in crab type 1 (-38.4%), followed by crab type 3 (30.6%) and then crab type 2 (-17.3%). All crab types for the 3.8 x 12 cm BRD showed statistically significant blue crab catch reductions (i.e., crab type 1, $X^2 = 16.860, p < 0.001$; crab type 2, $X^2 = 5.769, p < 0.05$; crab type 3, $X^2 = 8.860, p < 0.05$). We should note that the significance of the BRDxCT interaction was almost exclusively associated with the catch of number 1 crabs in the smallest BRD equipped pots.

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We found that none of the traps fitted with any of the BRDs affected mean blue crab carapace widths among any crab types. This is illustrated in Table 6 that shows the ANOVA results for the 1997-1998 and 1999-2000 periods. Here, there were no significant higher order interaction effects with BRD, but there was a significant main BRD effect for the 1999 - 2000 period. Mean blue crab sizes narrowly ranged between 147.6 mm and 145.0 mm and 132.4 mm to 132.2 mm for crab type 1 and 2, respectively, across all traps with BRDs and controls (Figure 5). The most variation in mean crab size occurred in crab type 3 (mature females), which accounted for the significant main effect. Despite this statistical difference in mean size of mature females, sizes ranged only from 133.8 mm to 137.7 mm. This effect of bycatch reduction device on crab size is important because implementation of a particular BRD we tested will have little consequence on the commercial market grading of blue crabs.

Discussion

Similar studies in the Mid-Atlantic region by Grant (1997) in North Carolina, Roosenburg and Green (In Press) in Chesapeake Bay, and Wood (1997) in New Jersey have shown that BRDs can effectively reduce diamondback terrapin captures without adverse effect on blue crab harvest. The optimal BRD size, however, will probably vary due to latitudinal variation in terrapin size (Carr 1952) throughout their range. For instance, Wood's (1997) study, which concentrated primarily in estuaries on the Atlantic coast, found equal reductions in the number of terrapins caught in crab traps fitted with

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both 5 x 10 cm and 4.5 x 12 cm BRDs. In contrast, our study on the western side of the Delaware Bay showed a 61% reduction in terrapins in the 4.5 x 12 cm BRDs over traps fitted with the 5 x 12 cm BRD. These results were more similar to those of Roosenburg and Green (In Press) in Chesapeake Bay who showed that traps fitted with the 5 x 12 cm BRD caught nearly three times as many terrapins than 4.5 x 12 cm BRDs.

Our finding document that the 4.5 x 12 cm BRD is the most optimal size configuration in the Delaware estuary for reducing terrapin capture in blue crab pots while minimizing impacts on blue crab harvest. This is based on our findings that the 4.5 x 12 cm BRD was 96% and 38% effective at reducing female and male terrapin catches, respectively, with an overall 12% reduction in legal sized blue crab harvest and only a 6% decrease in the most desirable number 1 crabs. While the 3.8 x 12 cm BRD was shown to be 100 percent effective at reducing both male and female terrapin catches, the subsequent loss of legal sized blue crabs (26%) would probably make it unacceptable. Wood (1997) and Roosenburg and Green (In Press) who used similarly sized BRDs also showed that the small height restriction (3.8-4.0 cm) limited the catch of larger number 1 and mature female blue crabs.

It has been suggested that terrapin drowning in blue crab pots may be the greatest threat to diamondback terrapins throughout its range (Seigel and Gibbons 1995). In tidal tributaries and inland bays where terrapins and blue crabbing co-occur, local terrapin populations may suffer substantial population declines as Roosenburg et al. (1997) found in the Patuxent River. Despite the aforementioned study, little comprehensive

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data exists on the population status of diamondback terrapins throughout its range (Seigel and Gibbons 1995). At present, we have no information on the status of diamondback terrapin populations in the Delaware Bay estuary. Thus, the impact of blue crab traps on terrapin bycatch mortality and its effect on population levels is largely unquantifiable at this time. However, in areas of low to moderate recreational crabbing activity (Cole et al. 1997) terrapin catches appeared to be higher than areas with greater crabbing intensity. We initiated a mark recapture study in 1999 to evaluate local terrapin population abundance, document loss due to entrapment in crab pots in the recreational fishery and potentially monitor the effect of the use of BRDs in ameliorating this source of mortality.

The use of BRDs to prevent incidental kills of other marine animals has been implemented in many U.S. fisheries. For instance, the National Research Council (1992) identified fishery bycatch as the most significant source of mortality for all five species of sea turtles in the United States, and regulations requiring the use of turtle excluder devices (TEDs) in shrimp trawl fisheries were issued in 1987 (Renaud et al. 1991). Perra (1992) sites many other examples where technological gear modifications, area closures and altering fishing practices have been shown to be effective at reducing bycatch of non-target species. The purpose of the BRD is to protect reproducing individuals in the population, particularly in species such as the diamondback terrapin that are long lived, late maturing and have low fecundity (Roosenburg 1990). Protection afforded to reproductively active females may be even more critical to sustain and

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conserve terrapin populations because they require longer time to reach maturity (Roosenburg 1990). While Delaware has taken management action to protect reproductive females from commercial harvest by seasonal adjustments, it is likely that this is not enough to offset the additional mortality due to drowning in traps. Thus, the most effective tool to reduce drowning of terrapins in crab pots is through the implementation of BRDs in the tidal tributaries and lower bays.

Regional variation in terrapin morphology may be an important consideration when evaluating the optimal BRD to reduce bycatch by sex. Neither Wood (1997) nor Roosenburg and Green (In Press) studied terrapin entrapment reductions by sex. In our study the 4.5 x 12 cm BRD had a 66% effectiveness in reducing overall terrapin bycatch compared to the 5 x 12 cm BRD (12%). Moreover, the capture rate of females in the 4.5 x 12 cm BRD was 96% compared to only 61% in the 5 x 12 cm BRD relative to the control. Although the 5 x 12 cm BRD significantly reduced female terrapin capture, it affords limited protection to male terrapins. The differential catch reductions by sex in BRDs are probably a function of the different carapace depth-length relationships between the sexes. Other studies have shown that female terrapins attain greater sizes than males (Hurd et al. 1979; Wood 1997). However, it is important to note that for a given straight-line carapace length the expected depth of female terrapins is greater than that of males, which we found from the analysis of covariance in this study. This has important implication in choosing the most optimal BRD because as was found here and noted in Roosenburg and Green's (In Press) study, terrapin depth is the determining

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body dimension for preventing entrapment in blue crab traps.

Studies such as this and others should and have served as the scientific basis for legislating proactive management measures to protect and conserve terrapin populations. Presently, the State of New Jersey has implemented the use of 5.0 x 15 cm BRDs in commercial style crab pots fished in waters less than 4 meters in depth or in any man-made lagoon, while Maryland has legislated the use of 4.5 x 12 cm BRDs on recreationally fished pots. In concert with Maryland, we recommend the 4.5 x 12 cm BRD for use in recreationally fished crab pots in tidal tributaries and lower inland Bays in Delaware. Other diamondback terrapin conservation efforts could be implemented to augment BRD regulations such as protection of nesting habitats. Studies should be conducted to evaluate the quantity and quality of terrapin nesting habitat in the Delaware Bay Estuary. Future research efforts should also be directed at monitoring the effects of BRD requirements on terrapin bycatch mortality and local population abundance.

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Table 1. Contingency table of terrapin catches by Bycatch reduction device (BRD) and terrapin sex for 1997-1998. Also shown are percent reductions in terrapin catch by BRD.

Terrapin Sex	Bycatch Reduction Device (BRD) ¹			Reduction (%) ²
	Control	5 x 10 cm	Total	
M	46	28	74	39%
F	51	12	63	76%
Total	97	40	137	59%

¹ BRD: Control = No BRD, Treatment = 5 x 10 cm.

² Reduction = (Control-BRD/Control)x100%.

Table 2. Contingency table of terrapin catches by Bycatch reduction device (BRD) and terrapin sex for 1999-2000 period. Also shown are percent reductions in terrapin catch by BRD.

Terrapin Sex	Bycatch Reduction Device (BRD) ¹ (% Reduction) ²				Total
	Control	5 x 12 cm	4.5 x 12 cm	3.8 x 12 cm	
M	55	73 (+33%)	34 (-38%)	0 (-100%)	162
F	51	20 (-61%)	2 (-96%)	0 (-100%)	73
Total	106	93 (-12%)	36 (-66%)	0 (-100%)	235

¹ BRD: Control = No BRD, Treatment = 5 x 12 cm, 4.5 x 12 cm, 3.8 x 12 cm.

² Reduction = (Control-BRD/Control)x100%.

Table 3. Maximum-likelihood analysis of variance table for the effect of bycatch reduction device (BRD), crab type (CT), and season on number of blue crabs caught in crab pots for 1997-1998 and 1999-2000 sampling seasons.

1997-1998			
Source	DF	χ^2	$P > \chi^2$
BRD ¹	1	0.94	0.3313
CT ²	2	188.42	0.0001
SEASON ³	1	14.49	0.0001
BRD*CT	2	2.47	0.2913
BRD*SEASON	1	0.00	0.9803
CT*SEASON	2	11.61	0.0030
Model Deviates	2	0.18	0.9158
1999-2000			
Source	DF	χ^2	$P > \chi^2$
BRD ¹	3	30.68	0.0001
CT ²	2	238.21	0.0001
SEASON ³	1	97.70	0.0001
BRD*CT	6	12.86	0.0453
BRD*SEASON	3	2.45	0.4849
CT*SEASON	2	3.27	0.1948
Model Deviates	6	13.23	0.0396

¹ BRD: Control = No BRD; 1997-1998 Treatment = 5 x 10 cm BRD; 1999-2000 Treatment = 5 x 12 cm, 4.5 x 12 cm, and 3.8 x 12 cm.

² CT: Number 1 (males ≥ 140 mm), Number 2 (127mm $\leq$ males < 140 mm), Number 3 (mature females).

³ Season: Spring (May-June), Summer (July-August), Fall (September-October).

Table 4. Contingency table of crab catches by Bycatch reduction device (BRD) and crab type (CT) for 1997-1998.

Crab Type (CT) ²	Bycatch Reduction Device (BRD) ¹		Total	% Change
	Control	5 x 10 cm		
1	240	251	491	+ 4.4%
2	252	253	505	+ 0.4%
Total	492	504	996	+ 2.4%

¹ BRD: Control = No BRD, Treatment = 5 x 10 cm.

² CT: Number 1 (males ≥ 140 mm), Number 2 (127mm $\leq$ males < 140 mm).

Table 5. Contingency table of crab catches by Bycatch reduction device (BRD) and crab type (CT) for 1997-1998 and 1999-2000 period.

Crab Type (CT) ²	Bycatch Reduction Device (BRD) ¹ (% Change)				Total
	Control	5 x 12 cm	4.5 x 12 cm	3.8 x 12 cm	
1	170	185 (+ 8.8%)	152 (- 10.6%)	106 (- 37.6%)	613
2	301	311 (+ 3.3%)	247 (- 17.9%)	253 (- 15.9%)	1112
3	159	135 (-15.1%)	146 (- 8.2%)	111 (- 30.2%)	551
Total	630	631 (+ 0.2%)	545 (- 13.5%)	470 (- 25.4%)	2276

¹ BRD: Control = No BRD, Treatment = 5 x 12 cm, 4.5 x 12 cm, 3.8 x 12 cm.

² CT: Number 1 (males ≥ 140 mm), Number 2 (127mm $\leq$ males < 140 mm), Number 3 (mature females).

Table 6. General linear model analysis of variance table for the effect of bycatch reduction device (BRD), crab type (CT), and season on size of blue crabs caught in crab pots for 1997-1998 and 1999-2000 field seasons.

1997-1998				
Source	DF	MS	F	$P > F$
BRD ¹	1	1.2464	0.39	0.5330
CT ²	1	2807.0969	888.03	0.0001
SEASON ³	2	11.0839	3.51	0.0379
BRD*CT	1	0.9687	0.31	0.5824
BRD*SEASON	2	0.9334	0.30	0.7457
CT*SEASON	2	0.9815	0.31	0.7345
BRD*CT*SEASON	2	1.9706	0.62	0.5404
ERROR	48	3.1610		
1999-2000				
Source	DF	MS	F	$P > F$
BRD ¹	3	663.330	9.29	0.0001
CT ²	2	40738.940	570.85	0.0001
SEASON ³	2	930.152	13.03	0.0001
BRD*CT	6	130.156	1.82	0.0952
BRD*SEASON	6	23.163	0.32	0.9237
CT*SEASON	4	1256.420	17.61	0.0001
BRD*CT*SEASON	12	27.588	0.39	0.9675
ERROR	270	71.365		

¹ BRD: Control = No BRD, 1997-1998 Treatment = 5 x 10 cm BRD; 1999-2000 Treatment = 5 x 12 cm, 4.5 x 12 cm, and 3.8 x 12 cm.

² CT: Number 1 (males ≥ 140 mm), Number 2 (127mm $\leq$ males < 140 mm),

³ Season: Spring (May-June), Summer (July-August), Fall (September-October).

Figure Legends:

Figure 1. River and inland bay sampling locations in the Delaware River estuary for diamondback terrapins and blue crabs during 1997-2000.

Figure 2. Comparison of mean carapace lengths of diamondback terrapins caught in blue crab traps fitted with three different bycatch reduction devices and controls by sex. Shown are 95% confidence intervals.

Figure 3. Relationship between carapace depth and carapace length for male and female diamondback terrapins in the Delaware River Estuary sampled during 1997-2000.

Figure 4. Graphical display of scores from first two dimensions of a correspondence analysis applied to bycatch reduction device (BRD) and crab type (CT) contingency table of blue crab catches.

Figure 5. Comparison of mean carapace widths for number 1, number 2, and number 3 blue crabs caught in traps fitted with four different bycatch reduction devices and controls. Shown are 95% confidence intervals.

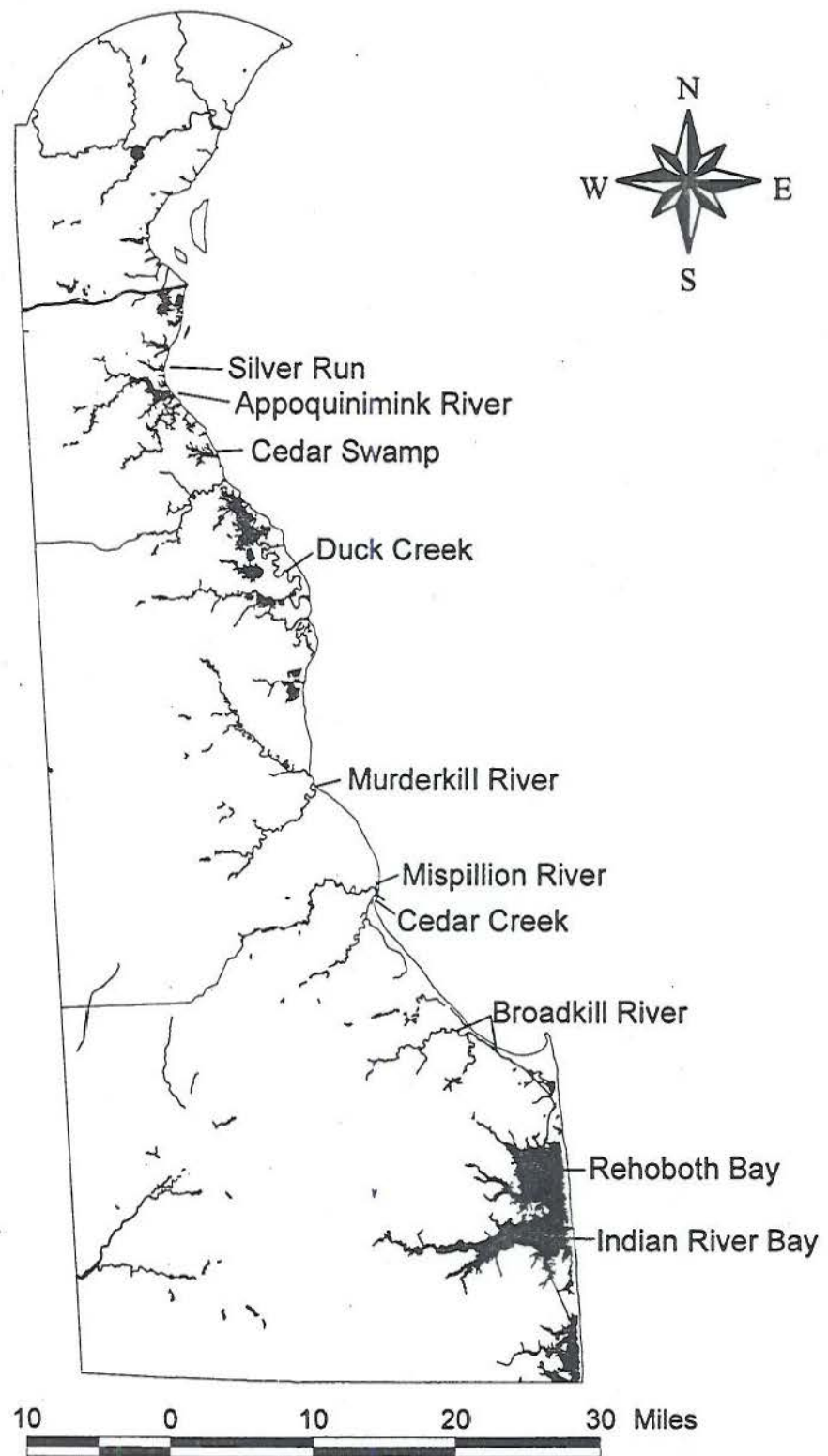
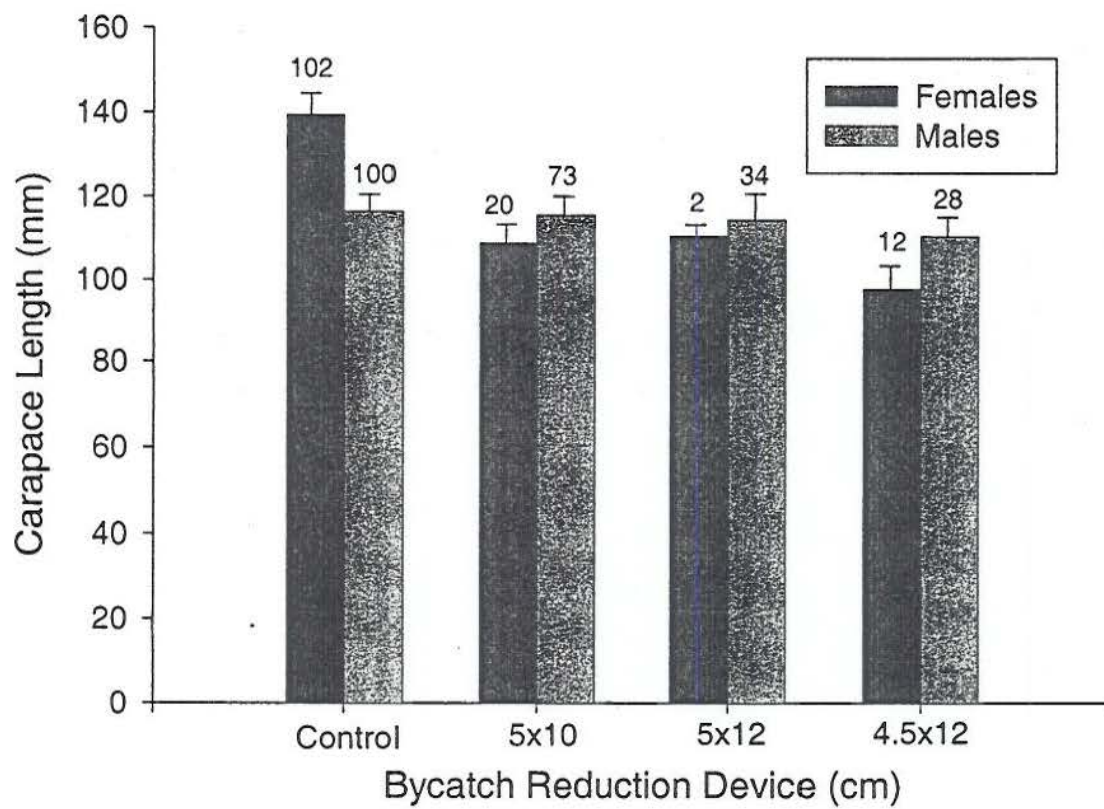
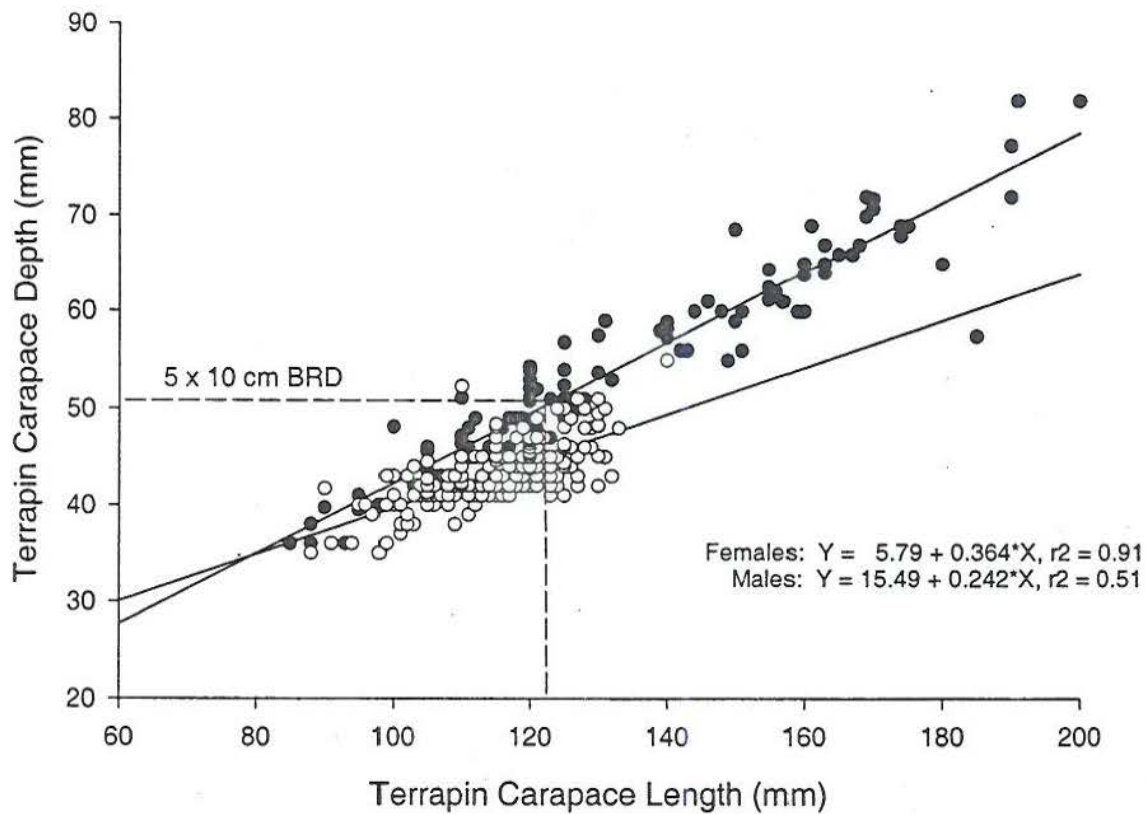


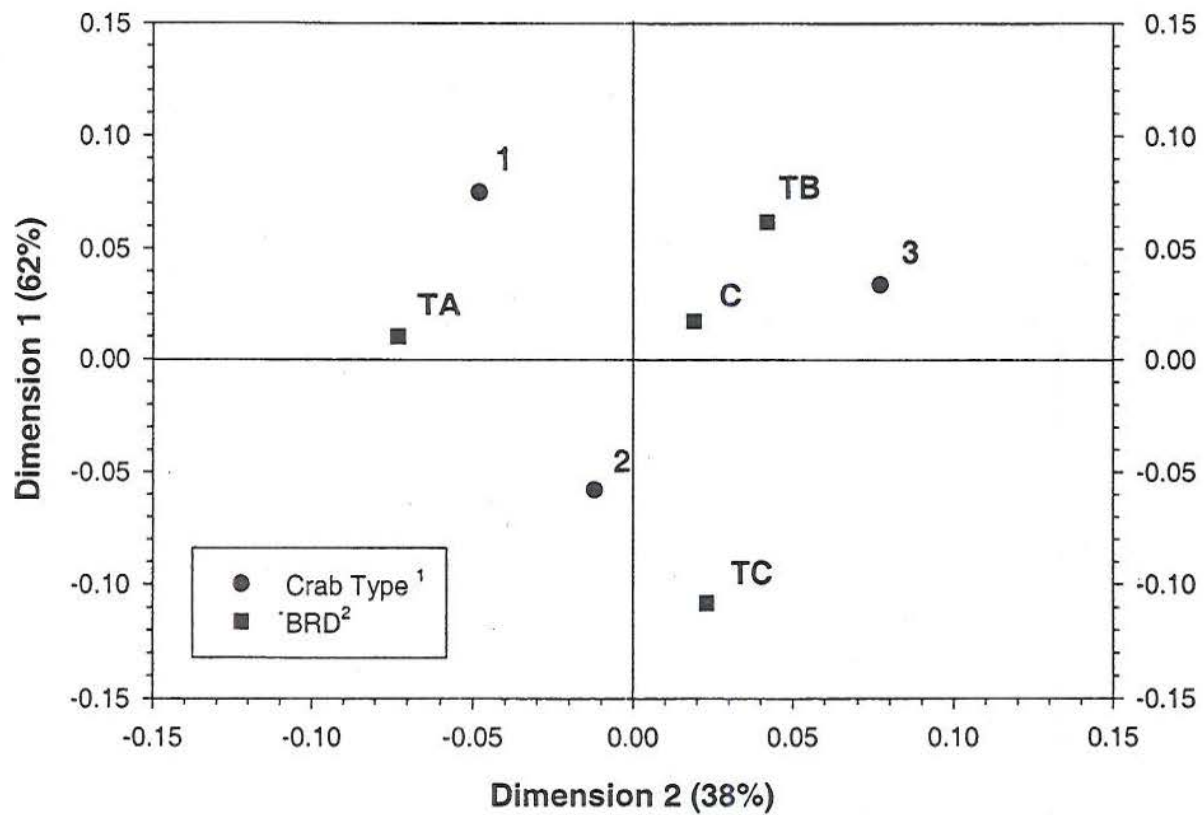
Figure 1. Statewide river and bay sampling locations for diamondback terrapins and blue crabs during 1997 - 1999.



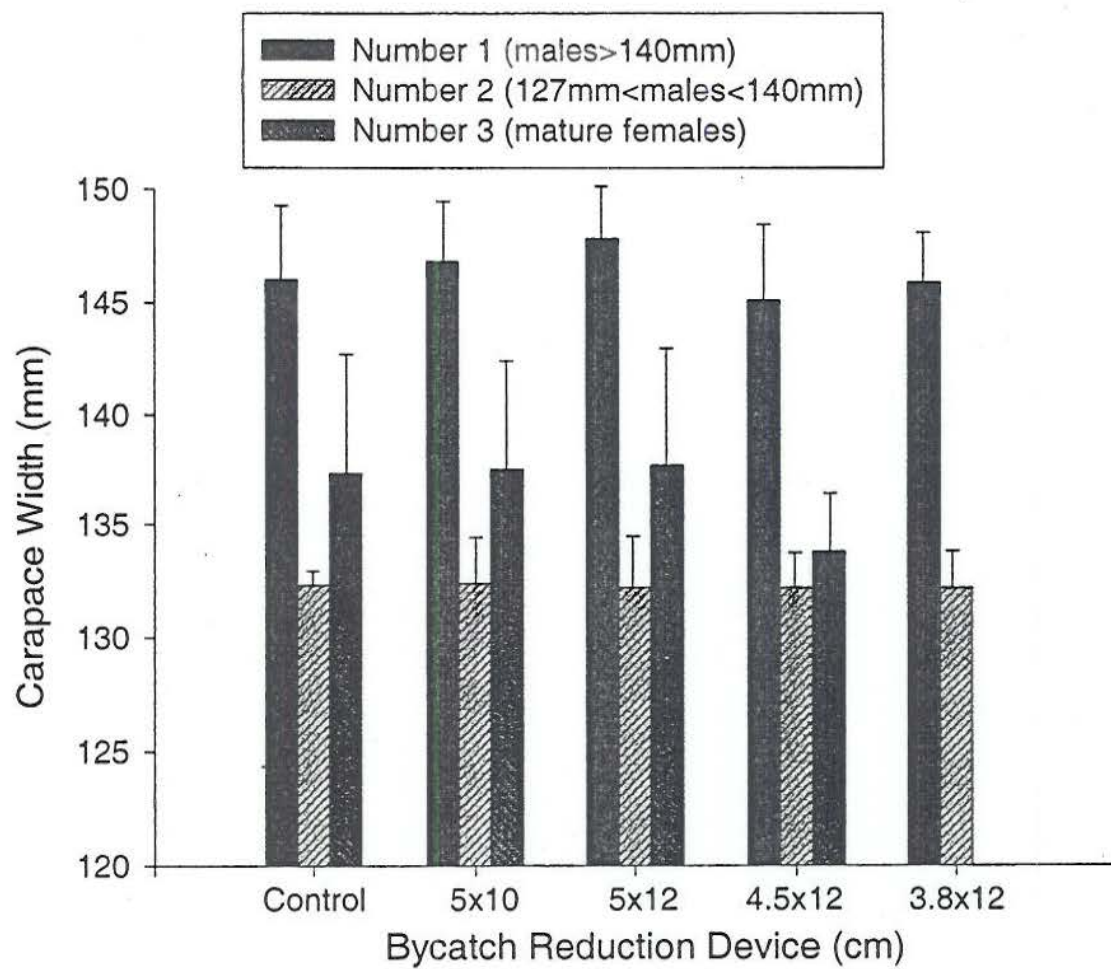
Relationship Between Carapace Depth-Length for Male and Female
Diamondback Terrapins in the Delaware Estuary



Correspondence Analysis of BRD vs. Crab Type (1999 - 2000)



- ¹Crab Type: 1 = male blue crabs ≥ 140 mm
 2 = 127 mm $\leq$ male blue crabs < 140 mm
 3 = mature females
- ²BRD: TA = 5 x 12 cm; TB = 4.5 x 12 cm; TC = 3.8 x 12 cm.



**Delaware Fish and Wildlife
Enforcement
Sept. 1, 1999 to August 31, 2000
Fisheries Management Plan Report**

Objectives:

To maximize enforcement efforts regarding state fishing laws and regulations and supplement daily patrol activities funded through Delaware's General Fund with Fisheries Management Plan grant money.

Approach:

Enforcement agents will be authorized extra-duty overtime hours to increase enforcement of fishing laws and regulations with additional patrol hours intended to detect and apprehend violators and increase the enforcement presence. During the grant period enforcement agents patrolled Delaware's coastal areas for violations. Patrols were conducted by vessel, vehicle and foot patrols. Both recreational anglers and commercial watermen were targeted by patrols. Patrol time was set up to maximize contacts with operations targeting high use areas. Checkpoints were conducted at public boat ramp facilities and on local fishing piers. Waterborne patrols worked high density areas near Roosevelt Inlet, Indian River Inlet, Delaware River, C & D Canal, Port Mahon, Cedar Creek, Bowers Beach, Collins Beach and the Nanticoke River. In addition to checkpoints at boat ramps, commercial docks and commercial seafood dealers, agents conducted covert patrols.

Results:

Total Overtime Funds Used: **\$26,864.91** Total Man-hours extra patrol: **863.25 hrs.**

Elvers	Patrol Hours:	143.25	Salaries paid:	\$4,186.44
Rockfish	Patrol Hours:	261.50	Salaries paid:	\$7,378.27
Horseshoe Crabs	Patrol Hours:	104.50	Salaries paid:	\$3,149.53
Finfish	Patrol Hours:	137.00	Salaries paid:	\$3,933.46
Shellfish	Patrol Hours:	134.00	Salaries paid:	\$5,636.78
Gill Nets	Patrol Hours:	83.00	Salaries paid:	\$2,580.43

Vessel Checks – Agents conducted approximately 4,093 vessel checks.

Violations -

During the period September 1, 1999 to August 31, 2000 the enforcement section issued the following summons for fisheries violations:

Violation Type	Charges
Commercial Reporting Violation	1
Commercial Equipment Marking Violation	1
Summer Flounder Creel	1
Summer Flounder Season	1
Summer Flounder Size	114
Method of Take Violation	14
Misc. Gill Net Violation	4
Gill Net in Prohibited Area	1
No Tidal Fishing Equipment Permit	1
No Commercial Foodfish License	1
Striped Bass Marketing Violation	17
Striped Bass Prohibited Area	1
Striped Bass Season	1
Striped Bass Size	12
Striped Bass Untagged	6
Tautog Size	4
Weakfish Creel	1
Weakfish Season	1
Weakfish Size	66
Blue Crab Season Violation	1
Blue Crab Size	160
Blue Crab Commercial Vessel Marking	1
Blue Crab Pot Attendance	10
Blue Crab Commercial Pot Limit	4
Blue Crab Recreational Pot Limit	17
Blue Crab Pot Marking Violation	5
Horseshoe Crab Method of Take	2

Enforcement Highlights for the period –

September –

Only a few operations were conducted and they were concentrated near the Indian River Inlet area for angler checks of recreational anglers fishing for Striped Bass.

January –

Operations consisted of patrols of the Lower Bays areas for nets and recreational Striped Bass Anglers. One operation was a surveillance of Bayside Seafood as a result of reports they were buying small fish. Seafood delivery trucks were stopped and fish sizes checked. No violation were observed.

February –

One elver patrol was conducted by SCpl. Howell and Rutherford who checked spillways in Kent and Sussex Co. at night for signs of activity. No violations found and only signs of activity near Red Mill Spillway Lewes DE.

March –

Several operations conducted. Two dedicated patrols of coastal lower Bays for illegal net activity. One patrol of the Nanticoke River for netting activity. Concentrated effort in Kent Co. on Commercial watermen during spring Rockfish season. March 25th SCpl. Rutherford and Howell were checking commercial watermen for tagging violations. One waterman found with six untagged rockfish and also using tags that were assigned to another waterman. March 28th Sussex Co. agents set up an operation

where commercial netters were watched from the coast and a second team of agents made stops at port where netters returned. No violations were found.

April –

Between April 1st and April 27th seven operations were conducted in Kent Co. with teams of agents conducting checkpoints and major ports. Commercial netters were boarded and Rockfish tags checked. April 19th Scpl Rutherford and Howell found one waterman at Cedar Creek with 51 untagged Rockfish and in possession of tags assigned to another.

April 17th New Castle Co. agents patrolled the closed Rockfish spawning area in plain clothes fishing with other anglers. Two arrests were made for keeping Rockfish.

May-

Several patrols were conducted of coastal areas to determine numbers of Horseshoe Crabs present and to watch for illegal harvesting.

June –

June 10th Boat block setup at Cedar Creek Public Ramp to check recreational anglers. 60 vessels checked with 10 violations for undersize Summer Flounder and undersize Weakfish.

June 17th Scpl. Trimmer conducted a night patrol in the Lower Delaware bay area as a result of a complaint involving the use of electric lights to draw fish. Observed several boats using lights but no violations.

July –

July 1st Boat block setup at Cedar Creek Public Ramp to check recreational anglers – 65 vessels checked 9 violations for Summer Flounder size and Weakfish size.

July 7th Sgt. Hennessey and Cpl. Messeck conducted a boat block at Port Mahon public ramp and found one vessel with 27 undersize Weakfish and one undersize Rockfish. 16 vessels checked.

July 7th Scpl. Rutherford and Howell conducted an operation to count the number of commercial crab pots being fished by some of the watermen. The two watermen targeted from complaints were found not to be in violation. While returning to port, the agents observed what was marked as a gill net but on inspection they found an illegal longline. The owner of the longline was found and charged.

July 11th All Kent CO. agents conducted an operation at the Commercial docks in the town of Liepsic where most of the commercial crabbing vessels dock. Each crabber was stopped when he returned from tending his pots and his # 2 blue crabs were checked for size. 15 crabbers were checked with no size violations found.

July 15th two teams of Kent Co. agents conducted boat blocks at Bowers Beach Public Ramp and Port Mahon Public Ramp. 20 recreational vessels were checked with 4 violations of fish sizes found.

August –

One patrol of Delaware Bay beachfront anglers was conducted by Ragt. Ptak and Scpl. Howell. Four violations found – one undersize Rockfish, one overlimit Rockfish, and two undersize Blue Crabs.

PROJECT NO. 3: HORSESHOE CRAB FISHERY MANAGEMENT PLAN

Introduction:

The horseshoe crab (*Limulus polyphemus*) is an important resource along the East Coast of the United States, particularly in the Mid-Atlantic region. The crabs have international significance as their eggs are a primary food source for several species of shorebirds, migrating from South America to their Arctic breeding grounds. The crabs are also an important food source for several species of juvenile finfish and the federally threatened Atlantic loggerhead turtle. Horseshoe crabs are commercially harvested in large quantities for use as bait in the American eel (*Anguilla rostrata*) and whelk (*Busycon spp.*) pot fisheries. The crabs are also harvested for use by the biomedical industry in the production of *Limulus* Amoebocyte Lysate (LAL). LAL is the worldwide standard used to detect human pathogens in patients, injectible drugs and all intravenous devices.

The Atlantic States Marine Fisheries Commission (ASMFC) completed an Interstate Fishery Management Plan (FMP) for Horseshoe Crabs in December of 1998. This FMP mandated a comprehensive monitoring plan to be implemented throughout the Atlantic coast and identified priority research needs to adequately manage this resource. Among these needs were statistically robust fishery-independent surveys to monitor trends in horseshoe crab abundance and the characterization of the commercial harvest to enable managers to monitor changes in the fishery and to establish / evaluate harvest restrictions.

In an effort to design statistically robust egg and spawner surveys, a workshop was convened by the Horseshoe Crab Technical Committee January 11 and 12, 1999. The Workshop participants (Technical Committee members and horseshoe crab researchers) agreed on a basic framework for the surveys. In the spring of 1999, with the unprecedented cooperation of numerous state and federal agencies, private companies, conservation groups and concerned individuals, pilot horseshoe crab spawning and egg count studies were implemented by the states of DE and NJ as required under the FMP.

It should also be noted that under the FMP the state of Maryland was required to implement a similar spawning survey. Although Maryland was (and is) surveying horseshoe crab spawning activity in the Chesapeake Bay, the survey's primary goal was identifying spawning locations and determining spawning periodicity as it relates to the lunar/tidal cycle. Recognizing that more work was necessary before an adequate long-term spawning survey could be designed to monitor changes in the Chesapeake Bay population, the particular importance of the Delaware Bay to migrating shorebirds, and the need for volunteers to sample the Delaware Bay horseshoe crab spawning population, the state of Maryland proposed continuing with its survey in the current form and sending staff and volunteers to participate in the Delaware Bay spawning survey. The Horseshoe Crab Technical Committee and Management Board agreed with this approach.

In addition to the egg and spawning survey requirement, the FMP also mandates that each state characterize a portion of its commercial horseshoe crab landings. Many states along the Atlantic Coast have not collected commercial horseshoe crab landings data. The Horseshoe Crab Technical Committee emphasized the need to characterize landings by gender and size. Although Delaware has collected horseshoe crab landings data through mandatory logbook reports since 1990, and characterized a portion of the catch in 1999, continued characterization is necessary to monitor changes in the fishery's performance and meet compliance with the FMP.

Objectives:

To support the State's implementation of the ASMFC Interstate Fishery Management Plan for the Horseshoe Crab by:

1. conducting horseshoe crab spawning surveys;
2. conducting horseshoe crab egg surveys; and
3. characterizing commercial horseshoe crab landings.

Expected Benefits:

SPAWNING SURVEY

The Delaware Bay spawning survey is currently the only directed survey that monitors horseshoe crab abundance. It is one of the best tools available for assessing trends in the Delaware Bay spawning population. The Horseshoe Crab Stock Assessment Subcommittee has established a framework for a quantitative stock assessment and identified several data needs (Anon. 2000). Among these needs is a coastwide benthic horseshoe survey. A pilot benthic survey is scheduled for the Fall of 2001. Until the data necessary for a quantitative stock assessment is available (minimally 5 - 10 years away), the Delaware Bay spawning survey is expected to serve as an interim method to assess changes in the population (Anon. 2000).

EGG SURVEYS

The presence of large numbers of migrating shorebirds on Delaware Bay beaches is due to a superabundance of horseshoe crab eggs (ASMFC 1998). A superabundance of eggs would require crab numbers in excess of those required to sustain the horseshoe crab population. Although egg sampling is not a component identified in the horseshoe crab stock assessment framework, a coordinated egg sampling effort may allow managers in the Delaware Bay to determine the level of crabs necessary to maintain this phenomenon. Egg surveys could similarly be used in concert with shorebird weight gain data to determine the optimal quantity of eggs needed to better ensure reproductive success. It should be noted that shorebird weight gain data is being collected annually in Delaware and New Jersey through the participation of an international shorebird team. It is important that egg surveys adequately monitor the egg resources. It is anticipated that sampling under this grant will further our understanding of factors influencing egg distribution and allow for an appropriately designed survey in the near future. Further work will undoubtedly be needed before a coordinated long-term egg sampling program can be fully implemented.

COMMERCIAL LANDINGS

The Horseshoe Crab FMP requires that non-*de minimis* states characterize a portion of its horseshoe crab landings by prosomal width and sex to maintain compliance with the FMP. The characterization of the commercial catch will provide managers with gender-specific conversion factors that can be used to more accurately describe landings data. In addition, size-frequency data, with other ancillary information, may yield clues about the age structure of the catch.

Approach:

SPAWNING SURVEY

Researchers (including the ASMFC Horseshoe Crab Technical Committee Chair and Co-Chair, and members of the Horseshoe Crab Stock Assessment Subcommittee), survey coordinators and volunteers involved in the 1999 Delaware Bay Horseshoe Crab Spawning Survey met on March 15, 2000 to discuss the results of the previous sampling effort and plan sampling for 2000. Adjustments were made to the 1999 spawning survey design based on the availability of man-power, power analysis conducted on the previous years data, and consideration for maintaining consistency in beaches sampled between 1990 and 1998.

Dr. David Smith with the United States Geological Survey's Biological Resources Division (USGS-BRD) provided a table estimating statistical power under various levels of sampling intensity (Table 1). It was agreed that the survey volunteer coordinators would make every effort to sample 12 beaches per state (NJ and DE). This would result in an estimated power of 0.75 ($\alpha = 0.20$) to detect a 25% decline in the population over 10 years. Recognizing the difficulty in training and scheduling the large number of volunteers necessary, however, the USFWS contracted for only 10 beaches.

The volunteer coordinators expressed concern over maintaining an existing time series (1990 - 98) using a random sampling design. Although it was argued that sampling methodology was significantly changed during the period 1990 - 1998 rendering annual comparisons invalid, it was the consensus of the group that a randomly selected

subset of beaches could be fixed without adversely affecting the current survey design. It was for this reason that a random subset of six beaches were fixed. Additional beaches are randomly selected each year. This decision to fix a subset of beaches facilitates volunteer participation, as a portion of the volunteers are beach residents, and allows inferences to be made in comparing the present spawning survey to spawning surveys conducted prior to 1999.

Sampling times were designed to coincide with peak spawning, which typically occurs around the new and full moons in May and June. Spawning peaks are affected by weather conditions (primarily high surf conditions), such that simply sampling on the lunar dates is not sufficient to adequately monitor horseshoe crab abundance. Smith and Pooler (1999) determined from the 1999 sampling that the most effective temporal sampling design (in terms of man-power and statistical variability) was sampling three days around the new and full moons in May and June (night of, two nights before and two nights after the lunar event). Two beaches, Woodland and Big Stone, were sampled by the Delaware Division of Fish and Wildlife. Other beaches in Delaware and New Jersey were sampled by staff from the USFWS, Limuli Labs, the University of Delaware, Delaware State University, NJ Division Fish, Game and Wildlife, MD DNR, several conservation groups and numerous independent volunteers.

Sampling was conducted on the highest of the daily tides, which typically occur during hours of darkness. Up to 1 km beach segments were sampled from known beach access sites. One hundred 1-m² quadrats were sampled from two, previously selected, random starting points at each beach. Sampling location along the beach was typically 500m north and south of the access point. The volunteer coordinators provided participants with details as to access and where to sample along the beach by the volunteer coordinators. Participants were asked to flip a coin to determine if sampling would start at the northern or southern location. Quadrat placement along the beach was determined by pacing or with a measured rope. Participants were instructed to place the provided 0.5-inch PVC quadrats at the front edge of the spawning horseshoe crab band (typically the high tide mark). Horseshoe crabs, at least half in a quadrat, were enumerated by gender and recorded on provided data sheets.

Data recorded at each beach included date, location, access site, participant names, participant contact information, starting location on the beach, time of arrival, survey start and end times, wave height, weather conditions, relative amount of ambient light (full moon, new moon, partial cloud cover, complete cloud cover, etc.) and random starting locations. Full instructions and data sheets are included in Appendix A.

EGG SURVEYS

Two types of egg sampling were conducted in 1999 - a rapid cluster assessment and a sediment core technique. Egg cluster sampling was conducted in 1999 after the May and June new and full moons. Samples were collected using a method developed by Weber (1998) for rapid assessment of egg cluster presence/absence. Beach sediment was sampled near the time of low tide for egg clusters to a depth of 20cm using 6-cm (5.2-cm id) PVC pipe. Three to 4 core samples were taken from a random starting point, at 2-m intervals, along a 9-m transect perpendicular to and extending from the high tide rack line at 100 randomly selected locations. Each core sample was sieved through 0.5-inch mesh screen to retain egg clusters. Presence/absence of egg clusters was noted.

Division staff collected eighty beach sediment core samples were collected from a 3m band the mid-beach face along a 100-meter segment of the Delaware beaches sampled for spawning in 1999. Sampling was conducted 1-3 days after the peak spawning events in May and June. Mid beach was determined by measuring the distance between the spring high tide line and low water beach break. The center 3m band was sampled at 40 predetermined random points. Sediment cores were collected using 6-cm (5.2-cm id) PVC pipe. Cores were collected from 0-5cm and 0-20cm at each sampling point. Samples collected from 0-5cm were used to monitor eggs available to shorebirds and samples from 0-20cm were used to monitor the eggs that contribute to the horseshoe crab stock. Sediment samples were placed in plastic bags and labeled to note the exact location of collection. Eggs were extracted and enumerated by Drs. Mark Botton (Fordham) and Robert Loveland (Rutgers).

The results of egg sampling in 1999 raised concerns that the egg sampling design was inadequate. Research conducted in 1999 failed to observe a predictive relationship between spawning horseshoe crabs and deposited eggs. One significant relationship occurred in New Jersey between deeply buried eggs (0-20cm) and spawning density in May. No significant relationships were observed between spawning and egg clusters (rapid assessment technique). It was possible that there were other relationships; however, several sources of sampling error could have concealed these relationships (variation in the proportion of the population sampled, spatial or

temporal mismatch of data collection and sampling variation). Other factors that may have contributed to the lack of a strong relationship include disturbance of eggs by wave action, variable fecundity and nesting behavior, or inadequate sampling design due to variable beach slope. Because the cost (in terms of money and manpower) of egg sampling was high, additional egg sampling was suspended in 2000 until the role of these variables could be investigated further.

Sampling in 2000 focused on testing if beach slope could have explained the lack of a relationship. Slope was selected because of the relative ease in testing this variable and the potential implications it could have on survey design. Although this portion of the project in Delaware involved less than one day of assisting USGS-BRD (the US Geological Survey - Biological Resources Division) personnel measure beach slopes, it was not necessary to reallocate funds from the egg survey to other elements of the project.

Delaware beach slopes and widths were measured at low tide by staff from the US Geological Survey - Biological Resources Division and the DE DFW using standard surveying equipment. New Jersey beach widths and slopes were measured by USGS-BRD personnel.

COMMERCIAL LANDINGS

Delaware's commercial horseshoe crab landings were sampled at the point of landing by Division personnel. Unlike finfish landings, horseshoe crab landings in Delaware are not sold to in-state dealers. Horseshoe crabs in Delaware are generally used by the harvester (as bait for eel and conch pots) or sold through out of state dealers. This complicated sampling since the catch must be measured at the point of landing. Only one public area is open to harvest in Delaware (about a mile long strip of extensively rip-rapped beach) and only on Tuesdays and Thursdays. Further, hand harvesting is conducted around the hours of high tide, as the crabs come ashore to spawn. These factors combine with the demands of other sampling programs to yield few intercepts.

Sampling of the dredge fishery is difficult because harvesters often fish for other species and only harvest horseshoe crabs when they receive an order for them or when the price of other species makes horseshoe crab harvesting lucrative. In 2000, large freezer stocks of horseshoe crabs and high blue crab prices severely dampened this fishery. Several attempts were made to intercept dredge vessels landing crabs, but either the dredger failed to fish or the crabs had already been off-loaded.

Division personnel were able to characterize a small portion of Delaware's hand harvest fishery. These crabs were measured for prosomal width, and the gender determined. Prosomal width measurements were made to the nearest half-cm.

Results:

SPAWNING SURVEY

Division personnel completed 15 surveys. Every sampling occasion was covered at Woodland Beach and Division personnel were used to cover Big Stone Beach on three sampling occasions. Woodland Beach is on the upper fringe of the crabs distribution. As such, densities are usually quite low relative to beaches lower in the bay, unless drought conditions bring the estuarine salt wedge further up the bay. Figure 1, for example illustrates the higher densities of crabs encountered lower down the bay at Big Stone Beach.

Horseshoe crab densities at Woodland Beach peaked on the new moon on 2 June 2000. A secondary peak occurred the previous month during the full moon on 18 May 2000 (Figure 1). The tremendous drop in spawner density recorded at Big Stone Beach on 20 May 2000 reflects the high wave activity on that date. Spawning has been shown to be adversely affected by high wave activity (Smith and Pooler 1999). On 20 May 2000, winds were from the east at 10-15 knots with waves activity greater than one foot. Wave action impedes spawning as it overturns the crabs as they come ashore to spawn and may interfere with the fertilization and egg laying processes.

All data collected by the Division was forwarded to Benji Swan of Limili Labs, Inc. for review and data entry. Once all beach survey sheets were entered into a spreadsheet, analysis was performed by the New Jersey Division of Fish Game and Wildlife with the assistance of staff with the USGS-BRD to produce state-specific and a comprehensive baywide indices of spawner abundance.

Results from the baywide survey (Smith et al. 2001) showed that spawning was generally higher in Delaware as compared to New Jersey, with peak spawning occurring in during the full moon in May (Table 2; Figure 2). The 2000 baywide index value was slightly higher than the 1999 value (Table 3). As stated in Smith et al. (2001), this does not support any broad conclusions about horseshoe crab population trends in the Delaware Bay.

EGG SURVEYS

Smith et al. (2000 (Appendix B)) did not find a clear relationship between horseshoe crab eggs and spawning activity. A large-scale egg sampling survey in 2000 was suspended until a better understanding of where best to sample along the beach profile can be established. Division personnel participated (with USGS-BRD personnel) in measuring beach slopes of all the Delaware beaches sampled in the spawning survey. This information was used to attempt to explain the discrepancies in the spawner - egg relationship.

Beach width and slope in New Jersey tended to be more narrow and steep than in Delaware. Using regression tree analysis Smith et al. (2000) found that beach width and time of sampling were important in explaining variation of surface eggs (0-5cm). Narrow beaches were associated with higher densities of surface eggs, while wider beaches were associated lower densities of surface eggs. Smith et al. (2000) found that spawning activity combined with beach width to explain some variation in eggs at 0-20cm (percent reduction in error was 43%). The regression tree model also indicated that beaches with high spawning activity were associated with high egg density. Among beaches with low spawning activity, egg density was lower on wide beaches and higher on narrow beaches.

COMMERCIAL LANDINGS

A total of 436 horseshoe crabs were measured by Division personnel for prosomal width and sexed from the hand harvest fishery in May. Of these, 435 were female and one was male. The average prosomal width of female horseshoe crabs was 26.2 cm (SD = 1.9) in 2000. This compares to an average of 26.5 cm (SD = 1.7) in 1999. The only male encountered in the 2000 was 22.0 cm. The average prosomal width of males sampled in 1999 (3 individuals) was 22.7cm (SD = 1.8).

The low number of males encountered was not surprising, since discussions with the harvesters revealed that they were collecting to supply bait for the American eel pot fishery. Female horseshoe crabs are almost exclusively used for eel bait in Delaware. Male crabs are more apt to be used by the conch pot fishery. Conch potters will often use two male crabs or a single female to bait a trap.

No horseshoe crabs were measured from the dredge fishery due to an inability to intercept harvesters. Several attempts were made, but either the vessel targeted did not fish, or the crabs had already been offloaded and shipped to out of state dealers.

Delaware's commercial horseshoe crab landings, based on mandatory logbook reports suggested permitted horseshoe crab dredge fishermen did not target horseshoe crabs as in years past (Table 4). Dredge harvesters accounted for about 18% of total landings. Historically this component of the fishery has accounted for about 40% of Delaware's annual horseshoe crab landings. The reduced take in 2000 was probably attributable to large quantities of horseshoe crabs in cold storage - a result of Virginia's record harvests in 1999, and the relatively high price of blue crabs - the preferred species of Delaware dredgers.

Literature Cited:

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- Weber, R.G. 1998. Further evaluation of a simple method for sampling horseshoe crab egg populations on Delaware Bay beaches. Report to the Delaware Department of Natural Resources and Environmental Control. Dover, DE.

Table 1. Sample size (beaches per state) for a survey of spawning horseshoe crabs and the resulting cost, CV, and power to detect exponential decline in spawning activity. In all cases, 3 nights were sampled in each of the 4 lunar periods in May and June, 100 quadrats were sampled per beach per night. Calculations were based on 25 accessible beaches per state, 7 day lunar periods, and 1 km long beaches. Unit of measurement for cost was person-nights or the number of participants required if each participant surveys only 1 night. Power was based on a 2-tailed t-test and the assumption that CV was a nonlinear function of spawning activity.

Source: Dr. David Smith, USGS-BRD

No. of beaches sampled per state	Cost (person- nights)	CV for baywide index	Power for $\alpha = 0.10$					Power for $\alpha = 0.20$						
			50%	33%	25%	50%	33%	25%	50%	33%	25%	50%	33%	25%
			decline over 5 years	decline over 5 years	decline over 5 years	decline over 10 years	decline over 10 years	decline over 10 years	decline over 5 years	decline over 5 years	decline over 5 years	decline over 10 years	decline over 10 years	decline over 10 years
5	360	0.22	0.39	0.22	0.17	0.73	0.41	0.27	0.59	0.38	0.30	0.85	0.57	0.43
6	432	0.20	0.44	0.24	0.18	0.79	0.46	0.31	0.64	0.41	0.32	0.90	0.63	0.46
7	504	0.18	0.50	0.27	0.20	0.86	0.53	0.35	0.70	0.45	0.34	0.94	0.69	0.51
8	576	0.16	0.57	0.32	0.22	0.92	0.61	0.41	0.77	0.50	0.38	0.97	0.76	0.57
9	648	0.15	0.62	0.34	0.23	0.95	0.66	0.44	0.81	0.53	0.40	0.98	0.80	0.61
10	720	0.14	0.67	0.37	0.25	0.97	0.71	0.49	0.85	0.57	0.42	0.99	0.84	0.65
11	792	0.13	0.72	0.41	0.28	0.98	0.76	0.53	0.88	0.61	0.45	1.00	0.88	0.70
12	864	0.12	0.77	0.45	0.30	0.99	0.82	0.59	0.92	0.66	0.49	1.00	0.91	0.75
13	936	0.11	0.83	0.51	0.34	1.00	0.87	0.65	0.95	0.71	0.53	1.00	0.95	0.80
14	1008	0.10	0.88	0.57	0.38	1.00	0.92	0.72	0.97	0.77	0.58	1.00	0.99	0.85
15	1080	0.09	0.93	0.64	0.43	1.00	0.96	0.80	0.99	0.83	0.64	1.00	0.99	0.90

Table 2. Index of spawning activity (ISA) computed for May and June 1999 and 2000. Index is shown separately for Delaware and New Jersey.

Year	State	ISA	90% Confidence Interval
1999	Delaware	1.0528	0.7933, 1.3971
1999	New Jersey	0.6076	0.4643, 0.7951
2000	Delaware	1.0137	0.7091, 1.4492
2000	New Jersey	0.6862	0.5521, 0.8530

Table 3. Index of spawning activity (ISA) for the Delaware Bay in 1999 and 2000. Standard error (SE) and 90% confidence intervals are also presented.

Year	ISA	SE	90% Confidence Interval
1999	0.8320	0.1039	0.6777, 1.0214
2000	0.8513	0.1196	0.6754, 1.0730

Table 4. Delaware's commercial horseshoe crab landings (in numbers of crabs) from mandatory logbook reports for 2000.

Mon	Males	Dredge Females	Total	Males	Shore Females	Total	Males	Total Females	Total
Jan	0	0	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	0	0	0
Mar	0	0	0	0	0	0	0	0	0
Apr	19,898	14,039	33,937	12	12	24	19,910	14,051	33,961
May	0	0	0	72,335	45,571	117,906	72,335	45,571	117,906
Jun	0	0	0	53,338	28,680	82,018	53,338	28,680	82,018
Jul	0	0	0	150	2,395	2,545	150	2,395	2,545
Aug	0	0	0	0	0	0	0	0	0
Sep	525	175	700	0	0	0	525	175	700
Oct	600	200	800	0	0	0	600	200	800
Nov	1,002	470	1,472	0	0	0	1,002	470	1,472
Dec	0	0	0	0	0	0	0	0	0
Tot	22,025	14,884	36,909	125,835	76,658	202,493	147,860	91,542	239,402
Pct	59.67	40.33	100	62.14	37.86	100	61.76	38.24	100

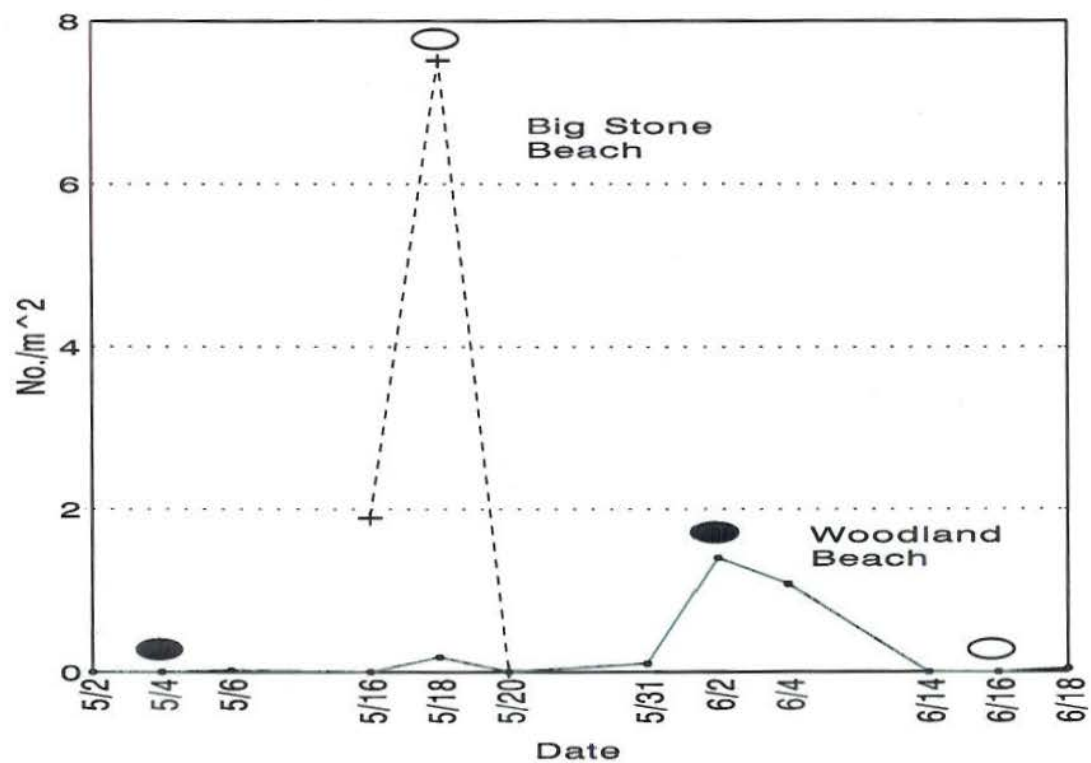


Figure 1. Horseshoe crab densities (number/M²) recorded during spawner survey at Woodland and Big Stone Beaches, DE during 2000. Open circles indicate full moon dates and darkened circles indicate new moon dates.

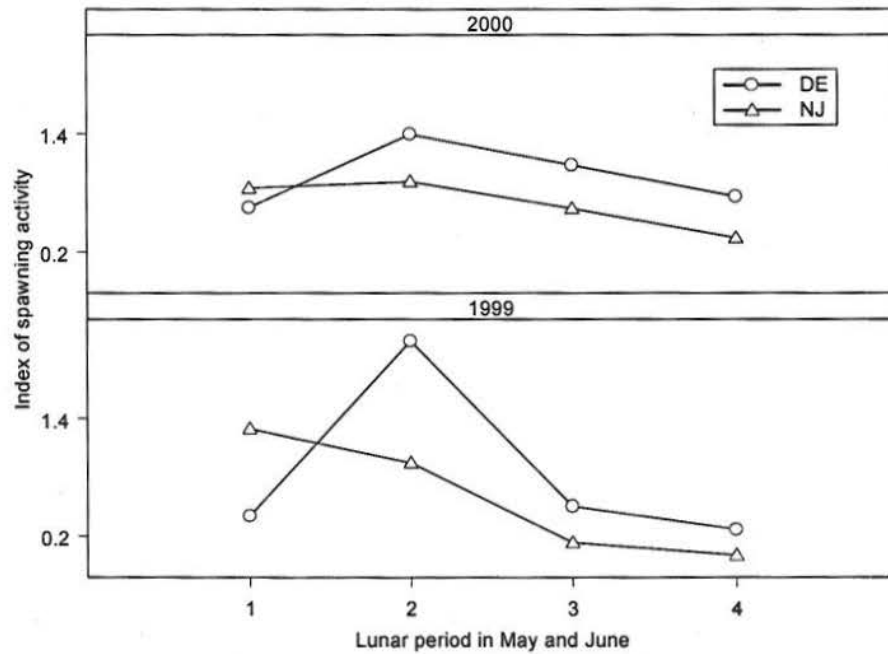


Figure 2. Index of spawning activity for Delaware Bay in each of the 4 lunar periods in May and June. The index is the no. of spawning females within 1 m of high tide line on beach index sites. Surveys were conducted within 3 days of the new or full moons, and these periods were termed 'lunar periods'. The index is shown separately for beaches in Delaware (DE) and New Jersey (NJ). (From Smith et al. 2000)

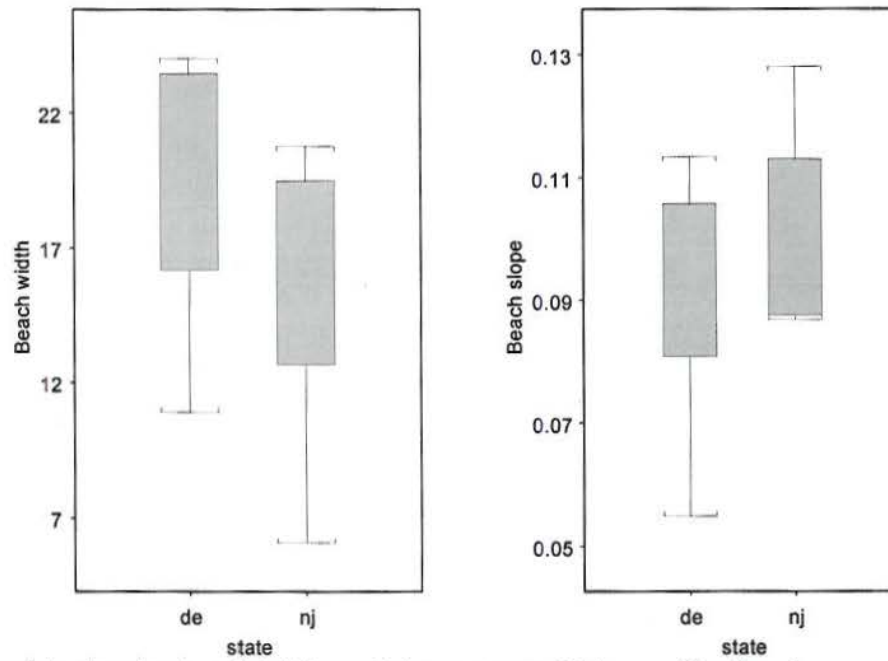


Figure 3. Box plots showing beach widths and slopes among Delaware Bay beaches sampled for eggs in 1999. (From Smith et al. 2000)

Appendix A.

SURVEYING SPAWNING HORSESHOE CRABS

CONTENTS:

1. These instruction sheets
2. Date of census and High Tide Times Tables
3. A 20 meter string for estimating pace length
4. Pacing trial form
5. Tally sheet for recording data.
6. Beach site sheet for recording volunteer and physical information (names of observers and recorders, amount of cloud cover, etc.)

The 1 m² quadrat used for sampling will be provided by survey coordinators. (Benjie Swan (609) 465-6552 or Bill Hall (302) 645-4253)

PREPARATION FOR THE SURVEY:

Determine your pace Follow these instructions ***before*** your first assigned time to survey and preferably on a beach since pace length is affected by the surface you are walking on. This should take 15 to 20 minutes to complete.

Note: Each person only has to determine their pace **ONCE** for the whole season.

- Lay the 20 m string out straight on the ground. You will use this to fill out the Pacing Trial Form.
- Count the number of paces it takes you to walk the length of the string using your normal stride. Remember that a pace equals two steps. Enter this number in the space next to TRIAL 1 on the Pacing Trial Form.
- Repeat this process twice more. Enter the second number next to TRIAL 2 and the third number next to TRIAL 3.
- These three numbers are A, B, and C on the Pacing Trial Form. Add A, B, and C, and divide this number by three to find D, your average number of paces per 20 meters.
- Divide D by 20 to find your average number of paces per meter (E on the form).

Note: The average number of paces per meter is probably different for each person, because it depends on your stride length. So, it is important you do this yourself and know these numbers before you arrive at the beach.

Clothing and accessories

- Wear appropriate clothing for weather and wet conditions at the water's edge. Consider using sunscreen during the day and insect repellent when needed. *If thunderstorms are in progress, do not go onto beach.*
 - Bring a headlamp or flashlight. Headlamps are preferred because they free up both hands.
 - Bring a clipboard or hard surface to write on. Also, bring a couple of pencils and a means to sharpen the pencils.
 - Work gloves may be useful if there are high densities of horseshoe crabs on the beach. You will have to lift animals up to count those underneath.
 - Shoes are a necessity. We recommend watershoes, old sneakers, or boots. *Do not go barefoot.*
 - An accurate wristwatch is needed for recording arrival time, as well as time survey is begun and finished.
-

SURVEY PROTOCOL

- At many beaches the endpoints of the survey area may be difficult to locate in the dark. You are strongly encouraged to visit your assigned beach during daylight hours before your scheduled survey time, to determine where these endpoints are.

Setup

- Arrive at the beach *at least* 30 minutes before high tide. Record the time you arrive in the space marked ARRIVAL AT SITE on the Beach Site Sheet.
- Fill out the beach site sheet as completely as possible. Addresses and Phone numbers of each survey team member are important in case we have questions about the data. Your address is also needed so we can send you a report of the survey findings for the season. Even if the weather prevents you from doing the survey, please fill out the Beach Site Sheet with all possible information and explain why the survey could not be completed.
- To survey horseshoe crabs, you will start at one end of a section of beach, walk to the other end, and along the way place quadrats to count crabs. Flip a coin to decide which end of the beach section you will start: if heads, start at the down-bay end; and if tails start at the up-bay end. Circle down-bay or up-bay on the Beach Site Sheet where it says STARTING LOCATION.
- Find the boundaries of the beach section by pacing from the beach access. The distance to pace depends on the beach you will be surveying. For example, if the beach access is at the midpoint of the beach section and the beach section is 1 km long, then you would pace 500 m from the access to the starting location you chose by flipping a coin. The survey coordinators, Benjie Swan and Bill Hall, will provide specific instructions for your particular beach.
- As you walk to the starting location find a stick (1 to 2 ft. long) that you can use to determine high tide. When you get to the starting location, stand the stick in the sand at the tide line. The tide line is the highest point on the beach that the water reaches. Move the stick up the beach as the water reaches higher on the beach. Begin the survey when the tide begins to recede and the water no longer reaches the stick. Record your starting time on the Beach Site Sheet where it says START OF SURVEY.

Placing the Quadrats

- You will be surveying in groups with at least two people. A survey protocol diagram which is printed on the back of the Beach Site Sheet illustrates the placement of quadrats described below.
 - The 'horseshoe crab line' you will follow is not a straight line, and may be above or below the water line.
 - If there is an obstruction or discontinuation in the beach section (bulkhead, large boulder, etc), pace up to the obstruction, walk to the other side of it, and then continue your pace count on the other side. Do not include the width of the obstruction in your pace count.
1. The quadrats on the Tally Sheet are numbered 1-100.
If the beach section is 1 km: Choose 2 random numbers from 0 to 19 (Use the random number sheet and instructions to select the random numbers) to locate the 1st and 2nd quadrats within the first 20 m stretch. Then pace 20 m from each random starting point to place the 3rd and 4th quadrats in the next consecutive 20 m stretch. Continue in this way until you have sampled 100 quadrats. (See survey protocol diagram on reverse of beach site sheet.)
If the beach is shorter than 1 km: Divide the length of the beach by 50 to find the distance between every other quadrat. For example, if the beach is 400 m, $400/50 = 8$. Within each 8 m stretch of beach you will place 2 quadrats. Choose 2 random numbers from 0 to 7 to locate the 1st and 2nd quadrats within the first 8 m. Then pace 8 meters from each random starting point and place the 3rd and 4th quadrats in the next consecutive 8 m stretch. Continue in this way until you have sampled 100 quadrat locations. (See survey protocol diagram on reverse of beach site sheet.)
 2. When you arrive at the quadrat location, place the quadrat at the toe of your foot on the last step. Place one side of the quadrat even with the line of horseshoe crabs and the opposite side towards the bay. Once the quadrat is in place, follow the instructions below under Counting Horseshoe Crabs.
 3. Once you are each done counting and all information is recorded, pick up the quadrat, and pace to the next quadrat. Begin pacing from the toe of your last step.

Note: If there are 2 observers, it may be easier to leapfrog, so that each observer starts at one of the random starting points and then paces to every other quadrat.

4. It is the observer's responsibility to make sure the recorder gets all tallies before pacing to the next quadrat.

Counting Horseshoe Crabs

- Once the quadrat is in place, do not move it until you are done counting.
- You will count all horseshoe crabs 'in the quadrat'. A horseshoe crab is considered 'in the quadrat' if more than half of its body is inside the quadrat.
- When animals are numerous, you may have to lift some up to assure you've counted all of those underneath. Heavy work gloves will be useful for this. Try to minimize disturbance to the spawning horseshoe crabs. Spawning females will be partially buried in the sand while laying eggs. *Do Not Lift Up A Partially Buried Horseshoe Crab.*
- Count the animals of each sex separately. If a horseshoe crab is not buried, the two most common ways to determine its sex are its size and position. Males are for the most part smaller and clasped or crowding on top of females. There also tends to be more males than females.
- Report your count of each sex to the recorder who will record the information under TOTAL. Report zero (0) when there are no horseshoe crabs. Do not try to move the quadrat from the preselected quadrat location just to include one or more nearby animals. Empty quadrats are just as important as those with horseshoe crabs because they will help reflect changes in the population.

Once you are done surveying

- Record the time in the space marked END OF SURVEY on the Beach Site Sheet.
- Send all of the following to the address below: (Note: PLEASE DO NOT FAX! WE NEED ORIGINALS!)
 - ✓ Completed Beach Survey Sheet,
 - ✓ Completed Tally Sheet
 - ✓ Completed Pacing Trial Form for each survey team member

*Benjie Lynn Swan
Limuli Laboratories
7 Bay Avenue, Dias Creek
Cape May Court House, NJ 08210
Phone No. (609) 465-6552
Fax no. (609) 465-0313*

RANDOM NUMBER TABLE

4	1	7	11	16	19	1	11	12	2	9	5	16	19	16	13	14	13	0	1
1	11	19	11	2	5	19	13	13	1	8	19	11	3	1	4	3	0	18	14
7	19	12	5	16	13	1	19	8	1	11	0	8	15	9	5	13	10	17	10
11	11	5	13	1	19	3	4	0	14	5	5	4	16	10	1	11	6	17	6
16	2	16	1	5	1	13	14	9	12	6	10	17	7	4	6	10	15	11	4
19	5	13	19	1	0	15	5	10	10	1	6	0	19	15	6	17	1	3	15
1	19	1	3	13	15	12	16	13	7	2	19	4	12	14	6	4	15	6	7
11	13	19	4	14	5	16	1	6	6	15	6	2	6	15	17	10	3	3	9
12	13	8	0	9	10	13	6	3	15	17	1	17	15	5	3	16	1	16	12
2	1	1	14	12	10	7	6	15	4	2	15	17	7	1	9	8	12	17	6
9	8	11	5	6	1	2	15	17	2	6	7	7	13	15	11	7	17	13	19
5	19	0	5	10	6	19	6	1	15	7	3	0	7	12	8	10	11	16	3
16	11	8	4	17	0	4	2	17	17	7	0	18	6	2	0	4	7	18	8
19	3	15	16	7	19	12	6	15	7	13	7	6	0	10	16	15	10	5	14
16	1	9	10	4	15	14	15	5	1	15	12	2	10	7	3	16	18	9	2
13	4	5	1	6	6	6	17	3	9	11	8	0	16	3	5	14	7	8	1
14	3	13	11	10	17	4	10	16	8	7	10	4	15	16	14	2	16	18	1
13	0	10	6	15	1	15	3	1	12	17	11	7	10	18	7	16	3	18	9
0	18	17	17	11	3	6	3	16	17	13	16	18	5	9	8	18	18	5	1
1	14	10	6	4	15	7	9	12	6	19	3	8	14	2	1	1	9	1	5

The above table of random numbers can be used to choose random starting points for quadrat sampling of spawning horseshoe crabs.

If the beach section is 1 km: Select any row or column of the table. The first number in the row, is your first random starting point. The next number is the second random starting point. If this number is equal to the first number, skip it and go to the next number in the row or column. Each night you will choose 2 random starting points to locate the first 2 quadrats. Then follow the directions under 'Placing the Quadrats' on the instruction sheet.

If the beach is shorter than 1 km: The distance between every other quadrat is the length of the beach divided by 50. If your beach is 400 m then the distance between every other quadrat is $400/50=8$ m. This means you only want to choose random numbers from 0 to 7 (or from 0 to 1 minus the distance between every other quadrat). Choose any row or column of the table. The first number in the row less than or equal to 7 is the first random starting point. The next number in the row or column less than or equal to 7 is the second random starting point. Each night you will choose 2 new random starting points to locate the first 2 quadrats. Then follow the directions under 'Placing the Quadrats' on the instruction sheet.

BEACH SITE SHEET

DATE _____

SURVEY TEAM NAMES AND CONTACT INFORMATION:

NAME

ADDRESS

PHONE NO.

1.	_____	_____	() -
2.	_____	_____	() -
3.	_____	_____	() -
4.	_____	_____	() -
5.	_____	_____	() -
6.	_____	_____	() -

SURVEY LOCATION (BEACH NAME AND DESCRIPTION OF ACCESS POINT):

TIME: ARRIVAL AT SITE _____ AM PM (CIRCLE ONE)
START OF SURVEY _____ AM PM (CIRCLE ONE)
END OF SURVEY _____ AM PM (CIRCLE ONE)

WEATHER CONDITIONS: _____

WAVE HEIGHT (CIRCLE ONE): LESS THAN 1 FT GREATER THAN 1 FT

RELATIVE AMOUNT OF NATURAL LIGHT (CIRCLE ALL THAT APPLY):

CLOUDY

PARTIAL CLOUDS

CLEAR

DAWN

FULL SUNLIGHT

PARTIAL SUNLIGHT

DUSK

MOONLIGHT

FULL DARKNESS

COMMENTS: _____

OTHER OBSERVATIONS AND COMMENTS: _____

STARTING LOCATION (CIRCLE ONE): HEADS TAILS
(SEE INSTRUCTION SHEET FOR EXPLANATION)

STARTING QUADRAT LOCATIONS: _____

TALLY SHEET

RECORDER _____ RANDOM STARTING LOCATIONS: _____

NO.	SEX	TOTAL	NO.	SEX	TOTAL	NO.	SEX	TOTAL	NO.	SEX	TOTAL	NO.	SEX	TOTAL	NO.	SEX	TOTAL
1	M		18	M		35	M		52	M		69	M		86	M	
	F			F			F			F			F			F	
2	M		19	M		36	M		53	M		70	M		87	M	
	F			F			F			F			F			F	
3	M		20	M		37	M		54	M		71	M		88	M	
	F			F			F			F			F			F	
4	M		21	M		38	M		55	M		72	M		89	M	
	F			F			F			F			F			F	
5	M		22	M		39	M		56	M		73	M		90	M	
	F			F			F			F			F			F	
6	M		23	M		40	M		57	M		74	M		91	M	
	F			F			F			F			F			F	
7	M		24	M		41	M		58	M		75	M		92	M	
	F			F			F			F			F			F	
8	M		25	M		42	M		59	M		76	M		93	M	
	F			F			F			F			F			F	
9	M		26	M		43	M		60	M		77	M		94	M	
	F			F			F			F			F			F	
10	M		27	M		44	M		61	M		78	M		95	M	
	F			F			F			F			F			F	
11	M		28	M		45	M		62	M		79	M		96	M	
	F			F			F			F			F			F	
12	M		29	M		46	M		63	M		80	M		97	M	
	F			F			F			F			F			F	
13	M		30	M		47	M		64	M		81	M		98	M	
	F			F			F			F			F			F	
14	M		31	M		48	M		65	M		82	M		99	M	
	F			F			F			F			F			F	
15	M		32	M		49	M		66	M		83	M		100	M	
	F			F			F			F			F			F	
16	M		33	M		50	M		67	M		84	M				
	F			F			F			F			F				
17	M		34	M		51	M		68	M		85	M				
	F			F			F			F			F				

RETURN TO:

Benjie Lynn Swan

Limuli Laboratories

7 Bay Avenue, Dias Creek

Cape May Court House, NJ 08120

Tel. (609) 465-6552 Fax (609) 465-0313

Appendix B.

Relationships Between Horseshoe Crab Spawning and Eggs in Delaware Bay

David R. Smith and Penelope S. Pooler
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Introduction

There is substantial interest in monitoring distribution and abundance of horseshoe crab (*Limulus polyphemus*) because of their keystone role in estuarine ecology along the mid-Atlantic coast, detection of contaminated intravenous products, and commercial harvest of whelk and eel (Berkson and Shuster 1999). Monitoring programs have been proposed to monitor spawning activity in Delaware Bay by counting spawning horseshoe crabs or their eggs (ASMFC 1998). Although densities of spawning horseshoe crabs and eggs are both a function of spawning activity, their selection as the target for a monitoring program depends on objectives. If population dynamics of horseshoe crabs were the primary objective, then spawning stock biomass and recruitment would be requirements for stock assessment (Shepherd 1977). Alternatively, if the food base for migrating shorebirds were the primary interest, then quantifying horseshoe crab eggs in habitats used by shorebirds would be required (Botton et al. 1994).

Because number of eggs is a function of the number of spawning horseshoe crabs, it is possible that one can be predicted from the other. Which raises the question, can surveying either spawners or eggs, and then predicting the other, provide data for both assessing horseshoe crab stock and quantifying shorebird food base? If so, then horseshoe crab monitoring needs could be met at much less cost. However, the answer depends on the strength of the relationship between spawners and eggs.

Long-term monitoring of horseshoe crabs is expensive so it is worthwhile to consider cost savings that could result from surveying either horseshoe crab spawners or eggs, but not both. A survey of spawning activity requires a large labor force distributed simultaneously throughout the Bay. For example, over 160 individuals participated in the 1999 spawning survey in Delaware Bay (Chap 1). Moreover, horseshoe crabs spawn in greatest numbers at the higher daily high tide, which often occurs at night or early morning. So volunteer participation may be

suppressed by the inconvenience of surveying at odd hours. In contrast, surveys of horseshoe crab eggs would involve fewer personnel and could be conducted at more convenient times. Eggs can be collected at whichever low tide is more convenient; and a crew of 3 to 5 can survey multiple beaches per day. So there is the potential for egg surveys to be considerably cheaper than surveys of spawning horseshoe crabs.

In this paper, we examine the relationship between indices of horseshoe crab spawners and eggs. We use observations from 16 beaches in Delaware Bay to explore that relationship and determine how it differs across geography, time within a spawning season, and beach characteristics. And finally, we discuss implications of our findings to horseshoe crab monitoring programs.

Methods

During May and June 1999, horseshoe crab spawners and eggs were counted at 16 beaches in Delaware Bay. The beaches were selected randomly as part of a survey of spawning activity, which we described in Chapter 1. In this chapter, we describe methods used to sample horseshoe crab and to relate spawners and eggs.

To sample horseshoe crab eggs, beach sediment was collected in 5 cm cores within a 3 m by 100 m strip of beach. Each strip was located at about the mid-beach height on the beach profile. Mid-beach height was found at the mid-point between the spring rack line and the point where the beach leveled. Within a strip, 40 locations were selected randomly for sediment collection. At each location a pair of core samples were taken: one to 5 cm deep and another to 20 cm deep. (Botton et al. (1992) found that most of horseshoe crab eggs are deposited 10 to 20 cm deep.) There was a slight variation among states as to how the core locations were selected. On New Jersey beaches, 2 random numbers were generated to determine coordinates for each location within the beach strip. On Delaware beaches, random selection was as follows: first 20 positions were selected at random along the 100 m strip parallel to the beach break, then at each of the 20 random positions 2 core locations were selected systematically with a random start along a line perpendicular to the beach break.

Beach sediment was processed under the direction of Drs. Loveland and Botton using standard procedures that they have applied over the last decade. Horseshoe crab eggs in 3 separate 80 ml subsamples from a core were counted, and then the counts were extrapolated to estimate the total count per core using estimates of core volume. Eggs were classified by stage (egg, marble, or trilobite) and viability (live or dead). We expressed the egg counts in terms of density or no. per 20 cm², which is the surface area of a core. Essentially, we summed counts across the depth dimension to reduce counts to an area basis rather than a volume basis. This was done because not all cores collected the same volume of sediment due to variation in depth of soft sediment.

We determined spawning activity in the vicinity of the strip where eggs were sampled. Although spawning was surveyed over a longer stretch (≤ 1 km) at each beach (Chap 1), we focused on spawning that occurred over a 200 m stretch of beach centered on the 100 m strip where eggs were sampled. Spawning activity was averaged across all survey days during the 15 days prior to eggs sampling, which occurred at 2 time periods: May 24th – 25th and June 14th – 15th.

In addition to sampling individual eggs, egg clusters were sampled across the entire span of beach where spawners were surveyed. This was done at 2 time periods: May 17th – 20th and June 1st – 3rd. Sediment from a core (5 cm diameter, 20 cm deep) was dropped through a 1.3 cm mesh and occurrence of at least 1 egg cluster was recorded. Cores were taken at 300 – 400 locations at each beach. Core were located as follows: first 100 positions were selected

systematically along the spring rack line, then at each of the 100 random positions core locations were selected systematically at 2 m intervals (with a random start) along a line perpendicular to the beach break. At the first sampling period (May 17th – 20th) cores were taken from 0 – 6 m from the spring rack line. At the second sampling period (June 1st – 3rd) cores were taken from 1 – 9 m from the spring rack line.

Relationships between spawning indices, egg density, and egg cluster occurrence were correlated and explored graphically. Because of the presence of outliers, Spearman rank correlations were used to gauge the strength of linear relationships. Regression tree analysis was used to explore the relationship between egg density and a variety of potential predictor variables including spawning activity, state (DE vs NJ), time of sampling (1st vs 2nd sampling period), % of spawning-survey days with waves > 0.33 m, beach azimuth, beach slope, and beach width. We applied regression tree analysis because it is a useful exploratory technique, is robust to nonlinear relationships between response and predictor variables, and incorporates interactions between predictor variables in an intuitive and transparent fashion (Anderson et al. 2000). Results from regression tree analysis can be interpreted similar to those of standard multiple regression. However, the tree-based method splits observations (beaches in this case) into groups with similar levels of the response variable (egg density). The splits are determined by explanatory variables. Thus, certain levels of the explanatory variables will be associated with certain levels of the response variable. For example, the regression tree might show that for certain habitat characteristics high spawning activity is associated with high egg density, but that association does not hold for other habitat.

Because preliminary analyses of 1999 data showed considerable variation in egg density that could not be explained by spawning activity alone, we revisited the 16 beaches in 2000 to measure beach characteristics that we thought might be affect the relationship between spawners and eggs. At each beach we recorded slope, width, height, and azimuth.

Results

Egg density, spawning activity, and beach characteristics

We found only 1 significant relationship between egg density and spawning activity (Table 1). Deeply buried eggs (0 to 20 cm deep) at the 1st period of sampling were related to previous spawning activity in New Jersey ($p = 0.002$). Deeply buried eggs at the 2nd period and shallow eggs (0 to 5 cm deep) at both periods were unrelated to previous spawning activity (Figs. 2-1 and 2-2).

Table 1. Spearman rank correlations and p-values in parentheses for spawning activity and egg density at 2 depths.

Time of egg sampling	Eggs 0 to 5 cm deep		Eggs 0 to 20 cm deep	
	Delaware	New Jersey	Delaware	New Jersey
May 25 -- 26	0.3571 (0.3851)	0.3333 (0.4198)	0.0476 (0.9108)	0.9048 (0.0020)
June 14 -- 15	-0.4762 (0.2329)	0.3214 (0.4821)	-0.2619 (0.5309)	0.3571 (0.4316)

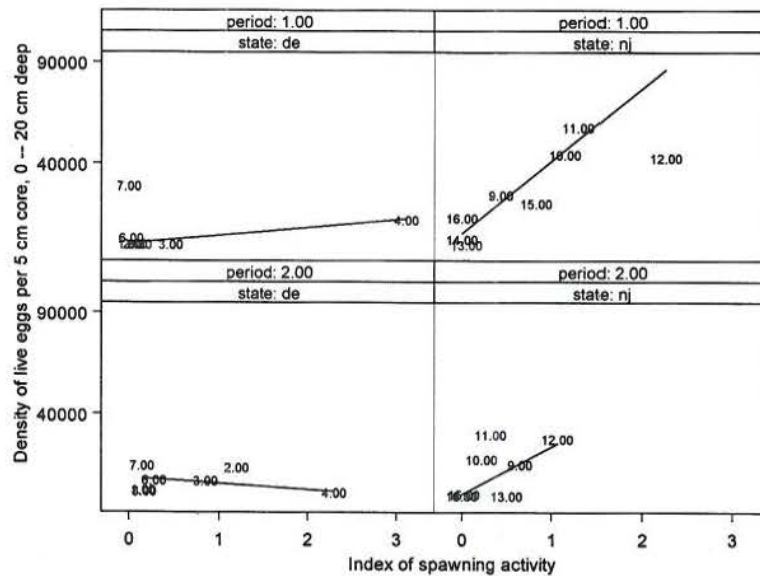


Figure 2 - 1. Relationship between eggs 0 to 20 cm deep and spawning activity on Delaware Bay beaches in Delaware and New Jersey at 2 time periods in 1999. For the first time period eggs were sampled May 24th – 26th, and spawning was surveyed during the May 10th – 23rd. For the second time period, eggs were sampled June 14th – 15th, and spawning was surveyed during May 31st – June 13th. Delaware beaches are labeled 1) Broadkill, 2) Big Stone, 3) Fowlers, 4) Kitts Hummock, 5) North Bowers, 6) Prime Hook, 7) Slaughter, and 8) Woodland. New Jersey beaches are labeled 9) Fortescue, 10) Highs, 11) Kimbles, 12) South Cape Shore Lab, 13) North Cape May, 14) Raybins, 15) Reeds, and 16) Sea Breeze.

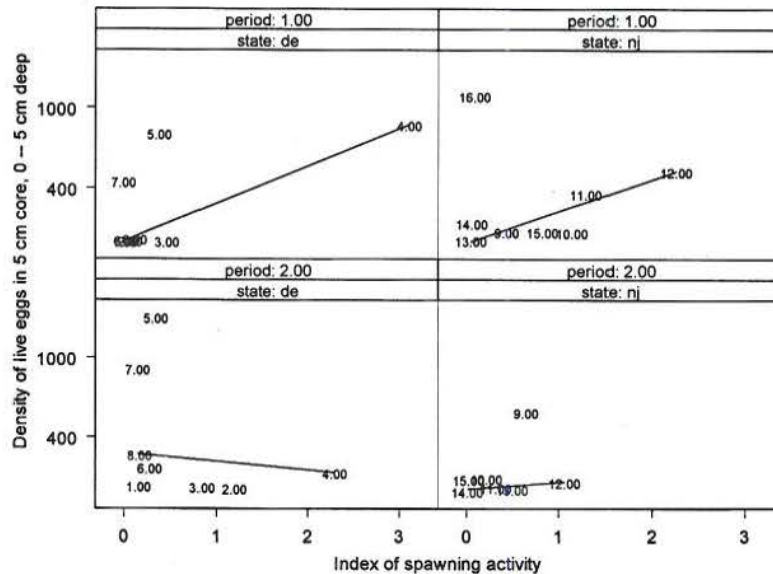


Figure 2 - 2. Relationship between eggs 0 to 5 cm deep and spawning activity on Delaware Bay beaches in Delaware and New Jersey at 2 time periods in 1999. For the first time period eggs were sampled May 24th – 26th, and spawning was surveyed during the May 10th – 23rd. For the second time period, eggs were sampled June 14th – 15th, and spawning was surveyed during May 31st – June 13th. Delaware beaches are labeled 1) Broadkill, 2) Big Stone, 3) Fowlers, 4) Kitts Hummock, 5) North Bowers, 6) Prime Hook, 7) Slaughter, and 8) Woodland. New Jersey beaches are labeled 9) Fortescue, 10) Highs, 11) Kimbles, 12) South Cape Shore Lab, 13) North Cape May, 14) Raybins, 15) Reeds, and 16) Sea Breeze.

Spawning activity combined with beach width to explain some variation in buried eggs (0 – 20 cm deep) according to results from a regression tree analysis (percent reduction in error was 43%, which is equivalent to R^2 statistic in linear regression). Other variables did not explain variation in eggs beyond what was explained by spawning activity and beach width. The regression tree model indicated that beaches with high spawning activity (index of spawning activity > 0.96) were associated with high egg density ($\bar{x}$ = 28960 per core, SD = 20648). Then among those beaches with less spawning activity (index of spawning activity < 0.96), egg density was lower ($\bar{x}$ = 4548 per core, SD = 6823) on wide beaches (width > 16.5 m) and higher ($\bar{x}$ = 18330 per core, SD = 10665) on narrow beaches (width < 16.5 m).

Beach width and time of sampling were found to be important in explaining variation of surface eggs (0 – 5 cm deep) according to results from a regression tree analysis (percent reduction in error was 45%). Narrow beaches (width < 16.5 m) were associated with higher density of surface eggs ($\bar{x}$ = 428 per core, SD = 381). Density of surface eggs was lower ($\bar{x}$ = 59 per core, SD = 74) on wider beaches (width > 16.5 m).

We found a tendency for New Jersey beaches to be more narrow and steep (Fig. 2-3). Thus, effects due to beach width and slope are confounded, at least in the extremes, by state.

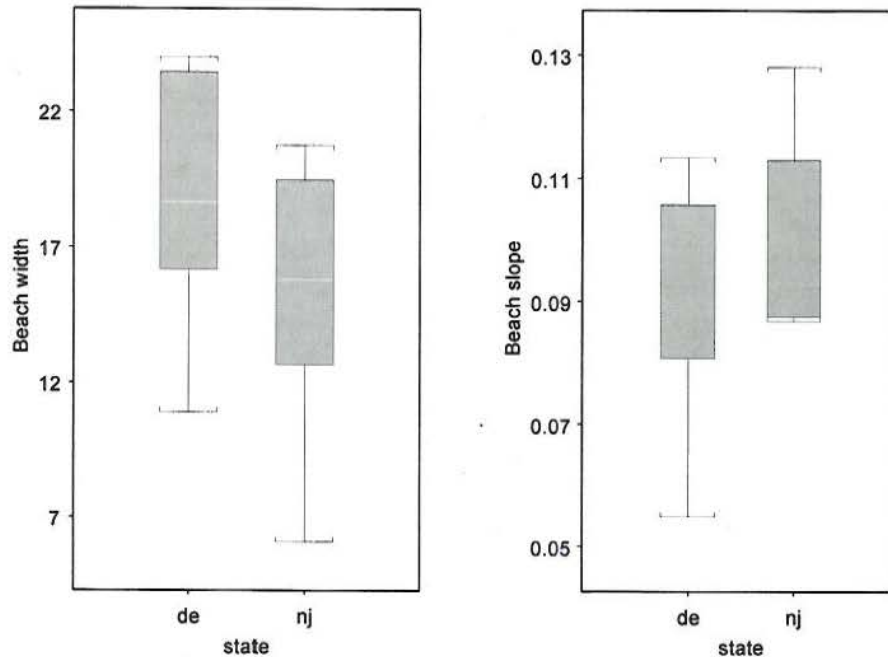


Figure 2 - 3. Box plots showing beach widths and slopes among Delaware Bay beaches sampled for eggs in 1999.

Egg clusters and egg density

Occurrence of egg clusters was associated with buried eggs (0 to 20 cm deep) on New Jersey beaches, but not on Delaware beaches (Table 2, Fig. 2-4).

Table 2. Spearman rank correlations and p-values for relationships between egg clusters and eggs 0 to 20 cm deep.

Time of egg sampling	Delaware	New Jersey
May 25 -- 26	0.3416 (0.4076)	0.7381 (0.0366)
June 14 -- 15	0.0120 (0.9775)	0.7748 (0.0408)

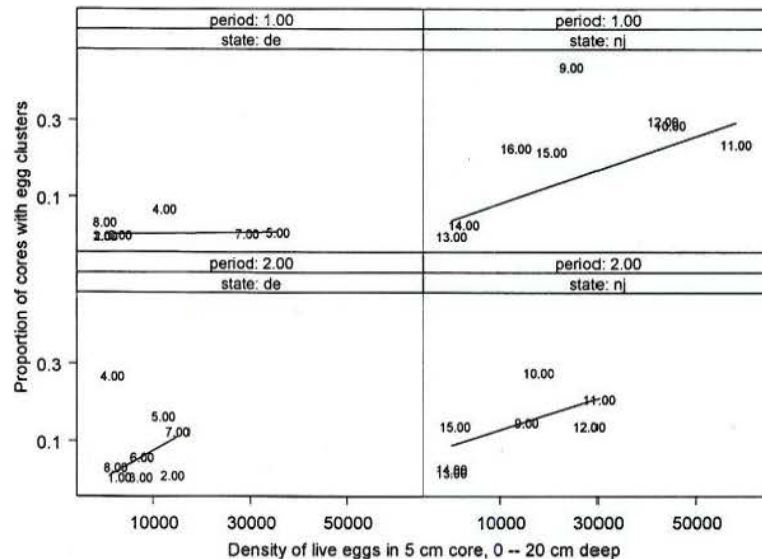


Figure 2 - 4. Relationship egg clusters and egg density on Delaware Bay beaches in Delaware and New Jersey at 2 time periods in 1999. For the first time period eggs were sampled May 24th – 26th, and spawning was surveyed during the May 10th – 23rd. For the second time period, eggs were sampled June 14th – 15th, and spawning was surveyed during May 31st – June 13th. Delaware beaches are labeled 1) Broadkill, 2) Big Stone, 3) Fowlers, 4) Kitts Hummock, 5) North Bowers, 6) Prime Hook, 7) Slaughter, and 8) Woodland. New Jersey beaches are labeled 9) Fortescue, 10) Highs, 11) Kimbles, 12) South Cape Shore Lab, 13) North Cape May, 14) Raybins, 15) Reeds, 16) Sea Breeze, and 17) Gandys.

Egg clusters and spawning activity

Similar to egg density, we found no strong relationships between occurrence of egg clusters and spawning activity (Table 3 and Fig. 2-5).

Table 3. Spearman rank correlations and p-values for relationships between egg clusters and spawning activity.

Time of egg sampling	Delaware	New Jersey
May 17 -- 20	0.3366 (0.4604)	0.5714 (0.1390)
June 1 -- 3	0.4671 (0.2433)	0.4144 (0.3553)

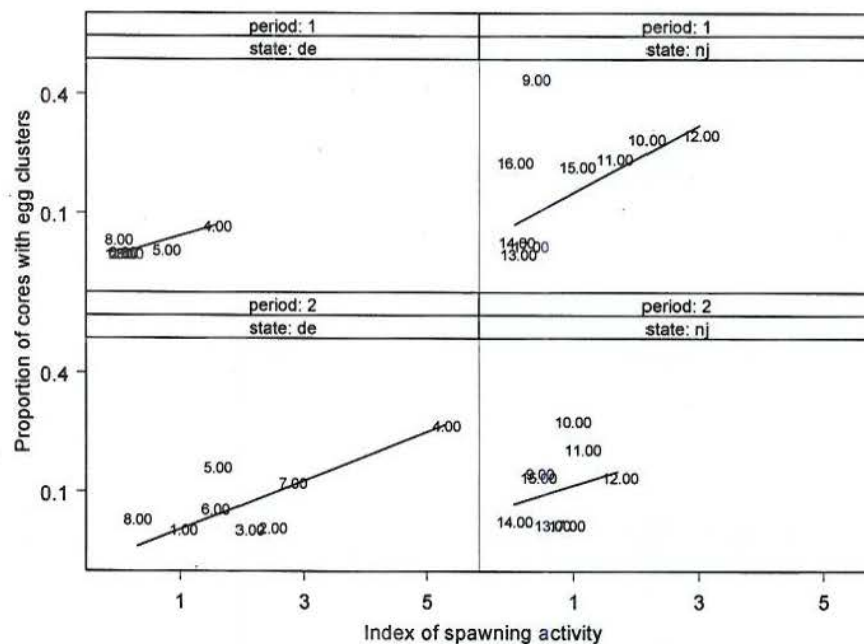


Figure 2 - 5. Relationships between egg clusters and spawning activity on Delaware Bay beaches in Delaware and New Jersey at 2 time periods in 1999. For the first time period egg clusters were sampled May 17th – 20th, and spawning was surveyed during the May 13th – 17th. For the second time period, egg clusters were sampled June 1st – 3rd, and spawning was surveyed during May 28th – June 1st. Delaware beaches are labeled 1) Broadkill, 2) Big Stone, 3) Fowlers, 4) Kitts Hummock, 5) North Bowers, 6) Prime Hook, 7) Slaughter, and 8) Woodland. New Jersey beaches are labeled 9) Fortescue, 10) Highs, 11) Kimbles, 12) South Cape Shore Lab, 13) North Cape May, 14) Raybins, 15) Reeds, and 16) Sea Breeze.

Table 4. Proportion of cores with egg clusters on 16 Delaware Bay beaches. Number of cores are in parentheses. The 1st period of sampling occurred May 17th – 20th and the 2nd period occurred June 1st – 3rd. Spatial extent of the sampling differed between the periods of sampling. Sampling was 0 – 6 m from the spring rack line during 1st period and 1 – 9 m during the 2nd period.

State	Beach	1 st period	2 nd period	Length of beach (m)
NJ	No. Cape May	.00 (310)	.02 (310)	1000
	So. Cape Shore Lab	.30 (300)	.14 (400)	1000
	Highs	.29 (300)	.28 (400)	500
	Kimbles	.24 (300)	.21 (400)	800
	Reeds	.22 (300)	.14 (400)	1000
	Raybins	.03 (350)	.03 (288)	200
	Fortesque	.44 (300)	.15 (388)	1000
	Gandys	.02 (282)	.09 (396)	400
	Sea Breeze	.23 (173)	NA	100
	Broadkill	.00 (295)	.008 (399)	1000
DE	Primehook	.003 (300)	.06 (400)	1000
	Fowler	.00 (300)	.008 (398)	1000
	Slaughter	.007 (300)	.126 (398)	1000
	Bowers	.01 (299)	.165 (400)	1000
	Big Stone	.00 (289)	.013 (391)	1000
	Kitts Hummock	.07 (300)	.27 (397)	1000

Spatial distribution of eggs

Occurrence of egg clusters across the beach profile showed geographic (DE vs NJ) and temporal (1st vs 2nd sampling period) differences in egg distribution (Fig. 2-6). During mid-May just after the peak spawning on New Jersey beaches (Fig. 1-2), distinct peaks in egg cluster occurrence were observed within 0 to 6 m from the spring rack line on 5 of 8 beaches. During the 2nd sampling period (early-June) on New Jersey beaches, egg cluster occurrence was more evenly distributed across 1 to 9 m of the beach profile. On Delaware beaches during the 1st sampling period, egg clusters occurred infrequently, which was consistent with low spawning activity in mid-May (Fig. 1-2). During the 2nd sampling period on Delaware beaches, maximum occurrence was between 7 to 9 m on 6 of 8 beaches. Average location of egg clusters was closer to the spring rack line on New Jersey beaches than on Delaware beaches ($p < 0.001$; Fig. 2-7).

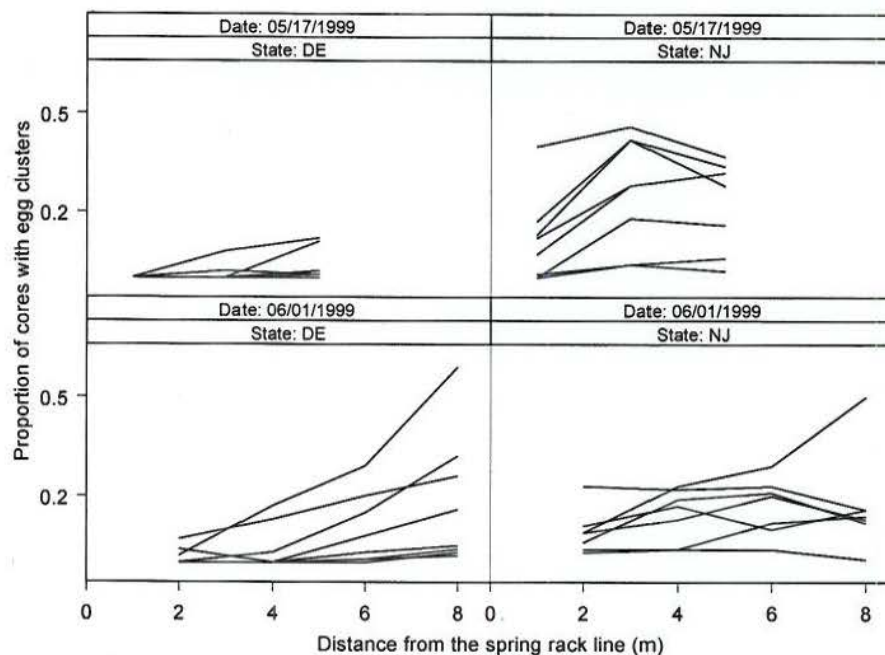


Figure 2 - 6. Occurrence of egg clusters across the beach profile on Delaware Bay beaches sampled for eggs in 1999. Plot shows proportion of cores with egg clusters at mid-point of 2 m intervals. During the first period of sampling (beginning 5/17/99), sediment cores were sampled across a distance of 0 to 6 m from the spring rack line. During the second period (beginning 6/1/99), cores were sampled 1 to 9 m from the spring rack line.

Results from a pilot study conducted by Dr. Richard Weber and David Carter (Delaware Department of Natural Resources) to examine distribution of eggs across the beach profile at 2 Delaware beaches (Ted Harvey and North Bowers) offer further evidence of large-scale variation in egg distribution. At each beach trenches (9 at North Bowers and 10 at Ted Harvey) were dug perpendicular to the beach break, and location and number of egg clusters were recorded. There was no difference in number of clusters per transect between the 2 beaches ($p = 0.74$). However, the position of the eggs relative to the nocturnal rack line and the spread of the eggs did differ ($p < 0.0001$ and $p = 0.0006$, respectively). On Ted Harvey eggs were closer to the nocturnal rack line and less spread out. The differences were meaningful. At Ted Harvey approximately 2/3 of the eggs were between 0.3 to 2.75 m from the nocturnal rack line. However, at North Bowers 2/3 of the eggs were between 1.5 to 4.5 m from the nocturnal rack line. These data also show that

results (egg densities) depend on where sampling occurs (Table 5). For example, if on Ted Harvey beach a 3 m strip was centered 1.5 m above the center of the egg distribution (offset = -1.5), then the strip would cover 49% of the eggs. In contrast, if on North Bowers beach a 3 m strip was centered 1.5 m below the center of the egg distribution (offset = 1.5), then the strip would cover 77% of the eggs. In each case the strip was misplaced by only 1.5 m however the net result is that 36% less eggs would have been available for sampling at Ted Harvey than at North Bowers. Use of a wider strip to sample eggs would be more robust. For example, a 6 m strip offset in either direction by 1.5 m would still cover >90% of the eggs at both beaches.

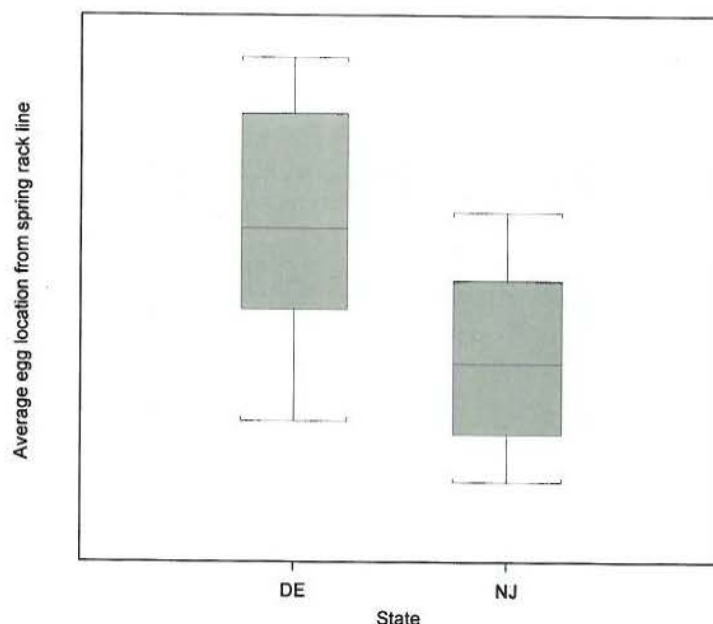


Figure 2 - 7. Box plots of the average location where egg clusters occurred among Delaware Bay beaches sampled in 1999. During the first period of sampling (beginning 5/17/99), sediment cores were sampled across a distance of 0 to 6 m from the spring rack line. During the second period (beginning 6/1/99), cores were sampled 1 to 9 m from the spring rack line.

Table 5. Percent of eggs that would be sampled in 3 m and 6 m strips at 2 Delaware beaches based on egg distribution data collected in May 2000. The % depends on the offset of the strip from central location of the eggs and strip width.

Offset from central location (m)	3 m strip		6 m strip	
	Ted Harvey	North Bowers	Ted Harvey	North Bowers
-1.8	39	23	90	86
-1.5	49	32	94	91
-1.2	58	46	98	95
-0.9	68	58	100	97
-0.6	77	66	100	97
-0.3	86	75	100	99
0.0	88	84	100	100
0.3	89	88	100	100
0.6	92	87	100	100
0.9	82	85	100	100
1.2	70	84	99	99

1.5	61	77	98	98
1.8	51	68	95	96

Discussion

We failed to observe predictive relationships between horseshoe crab spawners and their deposited eggs. There are 2 possible interpretations. First, sampling errors or confounding obscured underlying relationships. Second, the relationships were inherently weak.

The absence of strong relationships could be an artifact of sampling. Imagine tuning a radio, but static covers the radio station's signal. Similarly, there could have been underlying relationships between spawners and eggs, but sampling errors concealed the relationship. We can think of several sources of sampling error of potential importance: 1) variation in the proportion of the population subject to sampling, 2) spatial or temporal mismatch of data collection, and 3) sampling variation.

The comparison of spawners and eggs was based on estimates of relative, rather than absolute, density of spawners and eggs. These indices are biased measures of density because the proportion of the population that is subject to sampling is unknown, resulting in an underestimation of density (Seber 1982). It is inescapable that comparison of indices includes comparison of biases, and any variation in biases across beaches will add noise to or potentially confound the comparison. For example, counts of spawners are limited to 1 m from the high tide line. We think a high proportion of spawning occurs within 1 m of the high tide line. For example, Brockman (1990) observed that 94% of spawning occurred within 1 m of the high tide line. If that were true in general then 94% of spawners would be subject to sampling. However, we don't know how variable that proportion might be. It might be that the proportion of spawners within 1 m of the high tide line decreases as spawner density increases. Then as spawning increases, a higher proportion of spawners are "out of reach" of the sampling. This effect of increased bias with increased spawner density would tend to reduce the slope and diminish the appearance of the relationship between spawners and eggs.

There is also reason to suspect that the proportion of eggs subject to sampling within a 3 m strip could vary among beaches. On beaches with low to moderate levels of spawning, beach width was associated with egg density. Beach width was negatively related to slope ($r = -0.62$, $p = 0.0002$) and on narrow, steep beaches high tide lines are closer together than on wide, more level beaches. Thus, eggs may be distributed in a tighter pattern across the beach profile of narrow, steep beaches. And, the appearance that there were more eggs on narrow beaches could have been an artifact that was really due to the fact that we sampled a higher proportion of eggs on those beaches. This could explain why the relationships appeared stronger on New Jersey beaches, which tended to be more narrow and steep.

There is an issue about whether the spatial and temporal extent of egg sampling matched spatial and temporal extent of spawner sampling. In an attempt to match the spatial extents, we counted only spawners near the 3 m x 100 m egg-sampling strip. In doing so, we reduced the sample size used to compute the index of spawning activity, which increased the sampling variation of the index. This was unlikely to be a major factor because the observed relationships (or lack of relationships) were similar when counts of spawners over larger beach sections were used. Temporal extent for the spawners is also a source of error. Spawner counts were summarized over a 15 d periods relative to when egg sampling occurred. The period was limited to 15 d because eggs deposited earlier could have developed to a larval stage (Brockman 1990). Perhaps spawning was summarized over too many or too few days.

Imprecision of our estimates, due to sampling variation alone, could have obscured relationships. However, in Chaps 1 and 3 we evaluate precision and sample size and conclude that indices based on counts of spawners and eggs are precise given existing sample sizes.

There remains the potential that the lack of strong relationships between spawners and eggs is the true state of nature and not a sampling artifact. One possibility is that abiotic factors interact with density-dependent factors so that the egg/spawner relationship is strong only under certain conditions. Wave action could be mixing sediment and bringing eggs to the surface even where spawning was light. Thus, certain beaches may have high egg density near the surface even though spawning was relatively low. Four beaches did have high egg densities at 0 – 5 cm, but low or intermediate levels of spawning (Fig. 2-2). However, wave height (as measured by the % of survey nights with waves > 0.33 m) did not explain variation in egg densities in the regression tree analyses.

Finally, it could be that the egg/spawner relationship is inherently weak because of variable fecundity and nesting behavior. Presence of spawning female does not guarantee a fixed amount of eggs deposited in beach sediment. Brockman (1990) found nests at 80% of the locations where females paused 5 min or more; nests contained 1 – 15 clutches of eggs, and there were 50 – 7750 eggs per clutch. However, it is possible that density affects fecundity and nesting behavior so that females deposit fewer clutches when the beaches are crowded. However, this would cause a reduced slope in the egg/spawner relationship, it would not imply no relationship.

Implications for monitoring

The relationship between indices of spawning horseshoe crabs and their eggs are not predictive. Egg availability to shorebirds cannot be predicted accurately from the results of the spawning survey. If egg density is to be monitored then a baywide survey of horseshoe eggs must be designed.

Sampling of eggs needs to be reconsidered. Protocol to identify the center of egg distribution needs to be studied across a range of beach types. Sampling over a 3 m strip is unlikely to be robust to errors in locating the strip relative to egg distribution.

Further, research is needed to determine whether certain beach characteristics make it more like that eggs become available to shorebirds. Such information would be helpful in identifying shorebird habitat.

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