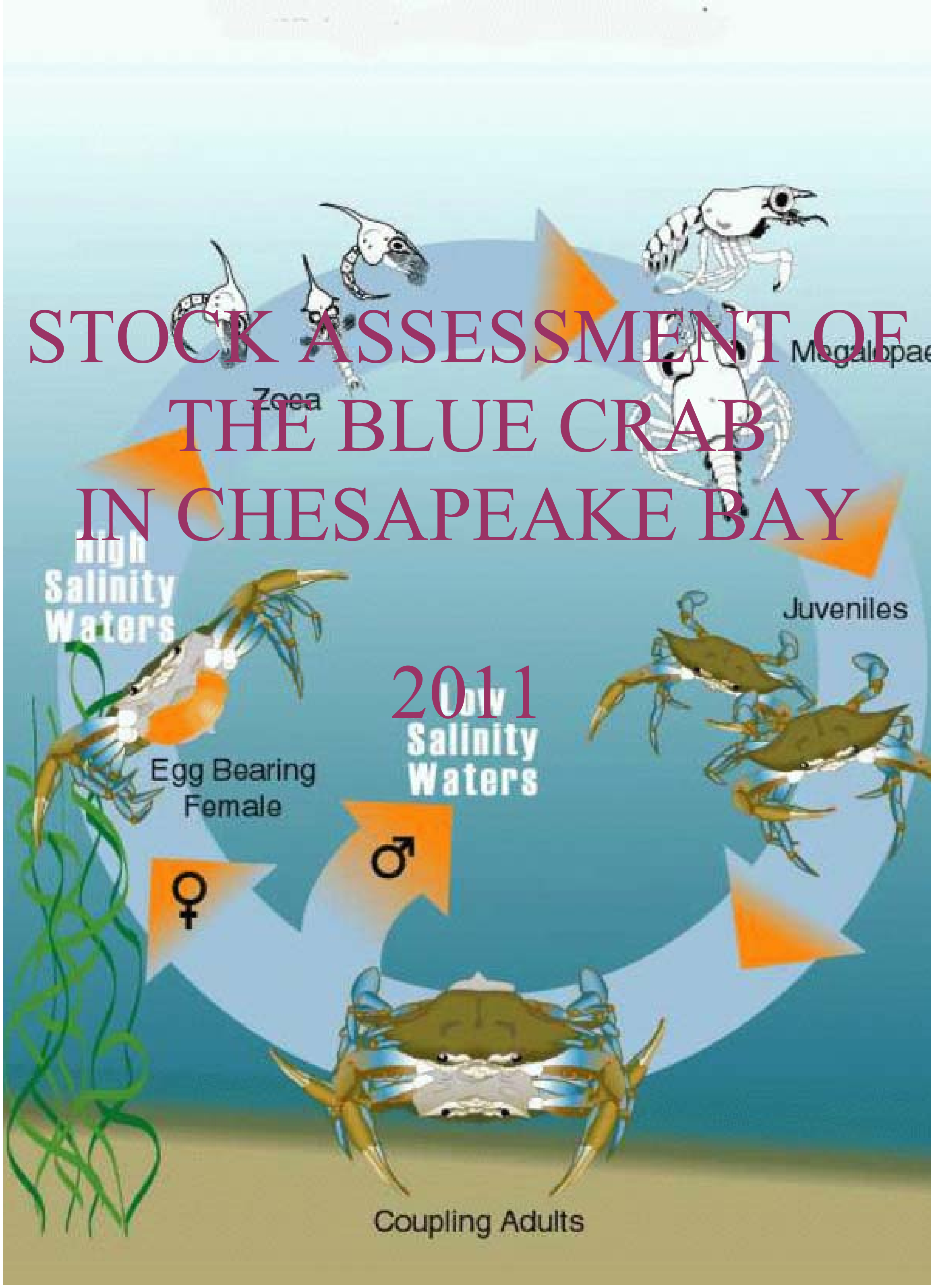
STOCK ASSESSMENT OF THE BLUE CRAB IN CHESAPEAKE BAY

2011



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Stock Assessment of Blue Crab in Chesapeake Bay
2011

Final Assessment Report

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Executive Summary

The blue crab (*Callinectes sapidus*) is an icon for the Chesapeake Bay region. The commercial fisheries for blue crab in the Bay remain one of the most valuable fishery sectors in the Bay. Ecologically, blue crab is an important component of the Chesapeake Bay ecosystem. Thus, sound management to ensure the sustainability of this resource is critical.

The first bay wide assessment for blue crab was completed by Rugolo et al. in 1997. It concluded that the stock was moderately to fully exploited and at average levels of abundance. Subsequent to this assessment concerns over the continuing status of blue crab were raised because of declines in abundance and harvests. In response to concerns from stakeholders, a Bi-State Blue Crab Advisory Committee was established in 1996. Work by this committee led to the establishment in 2001 of biomass and exploitation thresholds and an exploitation target reference point. The stock was assessed again in 2005 by Miller et al. This assessment analyzed fishery-dependent and fishery-independent data to assess the status of the blue crab population in the Chesapeake Bay. Population status was compared to reference points developed from an individual-based yield per recruit analysis which used the exploitation rates equivalent to maintaining 10% and 20% of the virgin spawning potential. The assessment recommended adoption of an exploitation fraction based management regime with an overfishing definition equivalent to $F_{10\%} = U_{threshold} = 53\%$ of all available crabs and a target exploitation rate of $F_{20\%} = U_{target} = 46\%$. Based on these reference points, the assessment concluded that exploitation rates in the fishery were too high. Since 2005, the status of the blue crab stock has been updated annually and its status determined relative to these reference points.

In 2009, we proposed and were funded to complete a thorough revision of the stock assessment for the blue crab in Chesapeake Bay. The following terms of reference were adopted to guide our assessment activities. We sought to (i) critically assess and where necessary revise the life history and vital rates of blue crab in the Chesapeake Bay that are relevant to an assessment of the stock, (ii) evaluate and recommend biological reference points for the Chesapeake Bay blue crab population. The potential for implementing sex-specific reference points should be evaluated. (iii) describe and quantify patterns in fishery-independent surveys. Analyses should include an evaluation of the impacts of environmental and abiotic factors on survey catches, to maximize the information content of resultant survey time series. (iv) describe and quantify patterns in catch, effort and survey-based estimates of exploitation by sector and region, including analyses that examine the impacts of reporting changes and trends in CPUE, (v) develop and implement assessment models for the Chesapeake blue crab fisheries. In particular, models that permit estimates of the trends and status of the crab population and fisheries on a sex-specific basis should be evaluated. (vi) examine density-dependent exploitation patterns derived from survey-based and model-based approaches, (vii) characterize scientific uncertainty with respect to assessment inputs and stock status and (viii) evaluate stock status with respect to reference points.

We developed and implemented a sex-specific catch, multiple survey model to develop integrated estimates of management reference points and stock status. This model represented the blue crab population in Chesapeake Bay of being composed of four stages: (i) age-0 male crabs, (ii) age-0 female crabs, (iii) age-1+ male crabs and (iv) age-1+ female crabs. Crabs in all stages were differentially vulnerable to the fisheries. Natural mortality was assumed to be stage and sex- independent and constant. We employed credible estimates of the rate of natural mortality such that $0.6 < M < 1.2$. Reproduction was modeled as a Ricker-type renewal process with stock productivity being dependent on the abundance of age-1+ females only, but population density-dependence was relative to the abundance of age-1+ crabs overall. Based on empirical evidence we assumed a sex-ratio at recruitment of 52% female. The model employed standardized time series of fishery independent abundance (1968-2009) and was fit to time series of total (1968-1993) and sex-specific catches (1994-2009) using a penalized log likelihood scheme. The model was able to replicate time series of total catch, sex-specific catch and sex-specific abundances for the baywide winter dredge survey, the Virginia trawl survey and the Maryland trawl survey. The model used the abundance of age-1+ crabs in the winter dredge survey as estimates of absolute abundance. Abundances in all other stages and surveys were considered as time series of relative abundances. The best fitting model indicated a coefficient of proportionality between the abundance of age-0 crabs in the winter dredge survey and total abundance of q_0=0.4. This estimate leads to considerable changes in the interpretation of reference points and trajectory of the stock.

In implementing the model, we developed female-specific exploitation rate and female-specific abundance reference points. We recommend that all exploitation-based reference points should be based on an estimate of the exploitation fraction of age-0+ female crabs – the exploitable stock. Further, we recommend that all abundance-based reference points should be expressed in terms of the abundance of age-1+ female crabs – an index of the spawning stock. We recommend the following management reference points

1) The overfishing limit in the Chesapeake Bay blue crab fishery should be defined as the exploitation rate of age-0+ crabs that coincides with maximum sustainable yield. The best estimate of U_{MSY} for age-0+ female crabs is U_{MSY}=0.34.
2) We consider blue crab as a data poor species. Following precedent from Restrepo et al., the New England Fishery Management Council and the Mid-Atlantic Fishery Management Council, we recommend a target exploitation rate be established equivalent to 0.75* U_{MSY}. Our best estimate of the target exploitation rate is $U_{0.75*U_{MSY}}$=0.255 age -0+ female crabs.
3) We recommend an overfished abundance threshold be established based on the estimate of 0.5*N_{MSY}. Our best estimate of the overfished definition is 70

million age-1+ female crabs. This is equivalent to a total population abundance of approximately 135 million age-1+ crabs if the pattern of exploitation is the same for males and females.

4) We recommend that a target abundance reference point be established equivalent to the equilibrium abundance expected if the target exploitation rate is achieved. Specifically, the target abundance should be defined as $N_{0.75*U_{MSY}}$. Our best estimate of the target abundance is 215 million age-1+ female crabs. This is a level of abundance that was observed in the population in the mid-1980s. The recommended target is equivalent to a total population abundance of approximately 415 million age-1+ crabs if the pattern of exploitation is the same for males and females.

We recommend that the management control rules defined above are implemented using empirical data from the winter dredge survey. Based on this approach, in 2009 the blue crab stock in the Chesapeake Bay was not overfished, nor was it experiencing overfishing. More specifically, the exploitation rate in 2009 (U_{2009} =0.24 age-0+ female crabs) was below the U_{target} = 0.255. Also, the blue crab population in 2009 was above the overfished definition of 70 million age-1+ females. The best estimate of the abundance in 2009 (N_{2009} = 174.3 million age-1+ female crabs) was lower than the target abundance. We note that the abundance of crabs in the winter dredge survey of 2009-2010 suggest that the population was above target abundance in 2010. Inspection of the stock trajectory indicated that the stock had experienced overfishing from 1998-2004 and was technically overfished from 2001-2003.

Effective conservation of the blue crab requires an understanding of the relationships between exploitation rate, catch, and population abundance. Our analyses of temporal patterns in abundance and exploitation indicated that they were approximately mirror images of each other, suggesting depensatory exploitation. Consequently, precautionary management measures will be required when the blue crab population is at low abundance to prevent population collapse.

Our analyses indicate that the stock responded favorably to management measures aimed at conserving female crabs. Management measures likely led to an increase in the abundance of age-1+ female crabs such that the recommended abundance target was exceeded for the first time since the early 1990s. We note that the female specific management measures appear to have changed the ratio of sex-specific exploitation rates in the population. Model results indicate that this will likely be associated with higher levels of sustainable harvests – with projected increases from 400 million crabs annually from 1994-2007, to almost 600 million crabs currently. However, the long-term response of the ratio in sex-specific exploitation rates is not known. We caution that if there continues to be a pattern favoring male-specific exploitation rates, management may have to consider increasing abundance targets.

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Terms of Reference

The 2011 stock assessment of blue crab in the Chesapeake Bay was funded by grants from the NOAA Chesapeake Bay Office, the Maryland Department of Natural Resources and the Virginia Marine Resources Commission. There were two components to the project: a benchmark stock assessment and research activities in support of the assessment and management. This report focuses on the assessment activities: the research results will be reported elsewhere.

The stock assessment has the following eight specific terms of reference.

TOR 1: Critically assess and where necessary revise the life history and vital rates of blue crab in the Chesapeake Bay that are relevant to an assessment of the stock.
TOR 2: Evaluate and recommend biological reference points for the Chesapeake Bay blue crab population. The potential for implementing sex-specific reference points should be evaluated.
TOR 3: Describe and quantify patterns in fishery-independent surveys. Analyses should include an evaluation of the impacts of environmental and abiotic factors on survey catches, to maximize the information content of resultant survey time series.
TOR 4: Describe and quantify patterns in catch, effort and survey-based estimates of exploitation by sector and region, including analyses that examine the impacts of reporting changes and trends in CPUE.
TOR 5: Develop and implement assessment models for the Chesapeake blue crab fisheries. In particular, models that permit estimates of the trends and status of the crab population and fisheries on a sex-specific basis should be evaluated.
TOR 6: Examine density-dependent exploitation patterns derived from survey-based and model-based approaches.
TOR 7: Characterize scientific uncertainty with respect to assessment inputs and stock status.
TOR 8: Evaluate stock status with respect to reference points.

1. Introduction

The biology, ecology and exploitation history of blue crab in the Chesapeake Bay was reviewed in depth by Kennedy and Cronin (2007). Here we provide general background information sufficient to evaluate the assessment. The blue crab (*Callinectes sapidus*) is one of fourteen swimming crab species in the genus *Callinectes* (Williams 2007). Nine of the fourteen swimming crabs, including the blue crab are endemic to the western Atlantic basin, mainly in tropical and subtropical areas. The distribution of the blue crab is much wider than those of conspecific species as it ranges from Uruguay to Massachusetts, with occasional records from Argentina to Nova Scotia (Williams 1974, Norse 1977). In addition to its endemic range, the species has become established as an exotic in the Mediterranean basin (Holthuis 1961, Banoub 1963).

Throughout its range, the blue crab is an important component of estuarine ecosystems (Hines 2007). Blue crabs are dominant and opportunistic benthic predators and scavengers (Eggleston et al. 1992, Hines 2007). Their diets may include a wide range of taxa including bivalves, crustaceans and fish (Hines et al. 1990, Mansour and Lipcius 1991). It is a dominant benthic predator and scavenger (Eggleston et al. 1992). Diets vary with crab size. Small crabs exploit thin-shelled bivalves and other invertebrates that are buried relatively shallowly in the sediments. Larger crabs can exploit thicker-shelled bivalves and cannibalism is not uncommon (Dittel et al. 1995, Hines and Ruiz 1995). Thus, crabs may be keystone predators in the estuary, *sensu* Paine (1966), possibly playing a dominant role in structuring benthic communities throughout its range.

In addition to its ecological importance, the blue crab supports important commercial and recreational fisheries throughout much of its range. Blue crab has been harvested since pre-colonial times. The commercial fishery started in earnest in the mid-nineteenth century (Cronin 1998, Kennedy et al. 2007). Commercial landings are regularly reported from coastal states from Texas to Connecticut[1]. In the last decade larger and more consistent landings have been reported from the more northerly states of New York, Connecticut and Rhode Island (K. McKowen, NY Department of Environmental Conservation, pers. comm.). In the 1950's, the Chesapeake Bay region represented almost 80% of the national landings. This figure has fallen steadily since then, so that based on the last 10 years (2000-2009), the Chesapeake Bay represents only 34% of the national landings. However, there is some evidence of an increase in importance of the Chesapeake region in the last two years ($\text{Average}_{2008\text{-}2009}$ = 42.2%)

Maryland, Virginia and the Potomac River Fisheries Commission are the management jurisdictions for blue crab in Chesapeake Bay. The management actions of the three jurisdictions are coordinated since all are signatories to the Chesapeake Bay

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[1] Data from NOAA's Fishery Statistics and Economics Division, available online at http://www.st.nmfs.noaa.gov/pls/webpls/FT_HELP.SPECIES

Blue Crab Fishery Management Plan (FMP -- Chesapeake Bay Program 1997). The FMP provides recommendations for the management of commercial and recreational fishing of blue crab in the Bay. Its goal is "to manage blue crabs in the Chesapeake Bay to conserve the bay wide stock, protect its ecological value, and optimize the long-term utilization of the resource." The blue crab FMP adheres to the principles proposed for Chesapeake Bay FMPs that were developed by the Chesapeake Bay Program in 1998, in which precautionary management and protection of critical habitats are highlighted. Regulations and management actions are complementary across the jurisdictions, but recognize age-specific and sex-specific differences in utilization of the estuary by blue crab, and historical fishing patterns.

More recently, blue crab has been selected as one of five key species at the heart of the Maryland Sea Grant Ecosystem-based Fisheries Management project. As a part of this initiative, a comprehensive briefing document was synthesized from available scientific information to identify the major biological, ecological and economic stressors acting on the blue crab and the fisheries it supports (EBFM Blue Crab Species Team 2010). The EBFM blue crab brief identified several indicators of population health including patterns of connectivity at local and regional scales, recruitment variability and mortality processes.

1.1. Assessment History

Studies of the dynamics of blue crab in the Chesapeake Bay began as early as the late 19th Century. Considerable efforts were made in subsequent years to understand the dynamics of the blue crab population in Chesapeake Bay. These initial studies documented growth, spawning periodicity and population variability (Hurt et al. 1979). However, it was not until 1997 that the first baywide assessment of blue crab in the Chesapeake was completed (Rugolo et al. 1997). This first comprehensive assessment was conducted under the auspices of the Chesapeake Bay Stock Assessment Committee (CBSAC). Rugolo et al. (1997) used index-based approaches and a simple production model in their assessment. They indicated that stock abundance had been high in the 1980s and had declined to more average abundances over the subsequent decade. The authors noted a decrease in catch-per-unit-effort (CPUE) in the blue crab fishery since 1945. But no consistent decreases were evident in survey-based CPUE or fishing mortality rates. Rugolo et al. attributed these counter-intuitive results to gear saturation effects as the amount of commercial gear proliferated from 1970-1995. The CBSAC stock assessment also reported that recruitments of young crabs were above average from 1970-1990. The stock was characterized as moderately to fully-utilized at the exploitation levels then occurring. Rugolo et al. recommended establishing and maintaining a fishing mortality rate reference point that ensured escapement of at least 10% of the virgin spawning potential. Although finding no cause for alarm, Rugolo et al. recommended no further increases in fishing effort or fishing mortality.

Following the Rugolo et al. (1997) assessment, Miller and Houde (1999) revisited the assessment of the blue crab fishery to develop threshold and target reference points. The Miller and Houde report is available online at http://hjort.cbl.umces.edu/crabs/doc/Final_targeting_report.pdf. Miller and Houde recommended a hierarchy of target levels, designated to address sustainability, efficiency, and recovery scenarios. Targets were derived from 1) reported catches and effort in the commercial fishery, 2) statistics from fishery-independent surveys, and 3) knowledge of the biology of blue crab. Targets recommended included population sizes, catches, and effort levels, as well as reference fishing mortality rates. They were intended to be conservative and risk-averse and promote a sustainable and economically viable fishery, while protecting the ecological value of the blue crab in Chesapeake Bay. In the hierarchy, the first targeting level was one that designated population abundances and fishing mortality rates to ensure sustainability of the resource. Miller and Houde recommended a long term potential yield of ~36,000 metric tonnes (MT ~ 80 million Lbs.) and fishing mortality rates of $F < 0.9$. A second target level equivalent to $F=0.6$ was recommended to ensure that the maximum reproductive potential per crab would be obtained over the long term. A recovery target was also recommended of $F <0.5$ to help build the stock in the case of recruitment overfishing. Some of the recommendations from the Miller and Houde assessment differed substantially from the earlier assessment as these authors interpreted the effects of a reporting change that occurred in Maryland in 1981 differently than had Rugolo et al. (1997). Fogarty and Miller (2004) demonstrated the impacts of reporting changes in the blue crab fisheries and argued that accounting for them would be important in future assessments.

In 1996, the Governors and Legislatures of Maryland and Virginia established the “Bi-State Blue Crab Advisory Committee” (BBCAC) to provide them with independent advice on the status and future trends of the blue crab fisheries. In 1998, BBCAC endorsed the findings of its technical work group that indicated that there were signs that the crab population was not in a healthy condition. Specifically BBCAC identified the following indicators of concern:

- Overall abundance for all age groups was down,
- Fishing mortality was increasing,
- Fishing effort was at near record levels,

- Spawning stock biomass was below the long-term average,
- The average size of crabs was decreasing,
- Fishery-independent surveys showed a decreasing percentage of legal size crabs,
- The reproductive potential of the population was of concern because of the reduced size of males and lack of mature females.

This consensus view motivated the development of a new management framework for the Chesapeake Bay blue crab fisheries (Miller 2001b). The framework recognized the need to distinguish between threshold and target reference points. The document is available online at http://hjort.cbl.umces.edu/crabs/docs/Charette_01.pdf. Specifically, the framework identified biomass- and exploitation-based threshold reference points that bounded a zone of sustainable exploitation (Fig. 1.1). Within this zone of sustainable exploitation, researchers recommended a target exploitation rate that sought to double the current spawning potential of the blue crab population (Fig. 1.1). In making these control rules functional, empirical evidence and elementary per recruit analyses were combined to determine values for the threshold and target reference points. The abundance threshold reference point was determined to be the lowest standardized abundance (Z-score) that had been observed in the average of three fishery-independent surveys. This was determined to be the value observed in 1968. The justification for this choice was that evidence was lacking to suggest that lower abundances could support a sustainable fishery. The fishing mortality rate threshold was determined from a standard spawning potential per recruit analysis. A value of $F_{10\%}$ (F=1.0) was chosen based on previous precedence and because the value indicated was greater than the majority of fishing mortality rates that had been observed previously. The target reference point was chosen as $F_{20\%}$ (F=0.7). This level was chosen as it was believed to be sufficiently far from the threshold reference points as to be detectably different, and because it would lead to an effective doubling of the spawning stock present in 2001.

Miller et al. (2005) produced the next full assessment of the blue crab stock and its fisheries in Chesapeake Bay. The full assessment is available online at http://hjort.cbl.umces.edu/crabs/Assessment05.html. These authors reviewed key life history parameters for blue crab. In particular, they reviewed direct and indirect estimates of the rate of natural mortality, M (Hewitt et al. 2007). Importantly, Miller et al. recommended abandoning the M = 0.375 value used by Rugolo et al. (1997) in favor of a revised M=0.9 estimate. This increased level of M was used throughout the assessment, although assessment results retaining the former lower estimate were presented for comparison purposes. The 2005 assessment used an individual-based yield per recruit model to estimate fishery reference points (Bunnell and Miller 2005).

The changes in M and in the methodological approach yielded new values for the target and threshold reference points, although the definitions of the reference points (i.e., 20% and 10% virgin spawning potential) were maintained. However, Miller et al. (2005) expressed these reference-points not in terms of instantaneous rates (e.g., F) but in terms of the target and threshold exploitation fractions (U) equivalent to the 20% and 10% spawning potential ratios. Specifically, Miller et al. (2005) calculated values of U_{target}=0.46 and $U_{threshold}$=0.53. Miller et al. (2005) maintained the definition of the overfished threshold as the abundance equivalent to the lowest abundance observed in the baywide winter dredge survey (Miller et al. 2001c), but expressed this value in terms of absolute abundance rather than as a standardized value. To assess the status of the blue crab stock against these reference points, Miller et al. (2005) used a catch-survey model (Collie and Sissenwine 1983), modified to include multiple fishery-independent surveys. Based on this new framework, Miller et al. (2005) concluded that the blue crab stock in 2005 was not overfished nor was it experiencing overfishing.

The Miller et al. (2005) assessment was reviewed by an international panel of independent experts. The review team concluded that the 2005 assessment represented the best science then available and therefore provided a sound basis for management (http://hjort.cbl.umces.edu/crabs/Assessment05.html). Subsequent to the acceptance of the assessment, the management jurisdictions implemented policies aimed at reducing exploitations fractions to the target level of U_{target}=0.46.

No major new integrated analyses have been conducted since the Miller et al. (2005) assessment. However, several modifications to the management framework have been made by CBSAC. Perhaps most significantly, stock status is now determined annually using a purely empirical approach. The abundance of crabs is estimated using the winter dredge survey (see Section 3.2.4) and the exploitation fraction is calculated as the harvest during the year divided by the observed winter dredge survey abundance at the beginning of the year. The catch survey model is not used in the annual determination of stock status. In 2008 an interim abundance target was established, equal to 200 million crabs (Chesapeake Bay Stock Assessment Committee 2008). This figure was based on analyses of the relationship between winter dredge-based estimates of abundance and harvest, and abundance and recruitment. Moreover, in 2008 CBSAC noted that management actions had yet to achieve the target exploitation rate and recommended adoption of management policies that focused on conserving female crabs.

2. Biology and Life History

2.1. Stock Structure

Population structure of blue crab within its range remains somewhat uncertain. In 1994, McMillen-Jackson et al. (1994) used a protein electrophoretic approach to quantify the genetic variability in samples collected from Texas to New York. This research indicated moderate genetic structuring, with spatial patchiness of several loci evident throughout the range. However, the findings also indicated that a high level of regional gene flow acted to diminish population structure. Recently, these researchers have revisited the question of population structure within the blue crab using multiple genetic markers and restriction length fragment polymorphism analysis of mitochondrial DNA (McMillen-Jackson and Bert 2004). The genetic results indicated no clear split between Gulf of Mexico stocks and Atlantic coast stocks. However, there was, within the Atlantic coast a cline of genetic diversity, with the New York samples exhibiting significantly lower diversity than more southerly stocks. The authors inferred from these patterns a latitudinal expansion from a sub-tropical center of diversity. Furthermore, the maintenance of a cline in diversity suggests that local gene flow may be low or restricted. Recently, Al Place and colleagues at the UMCES Institute of Marine and Environmental Technology have sequenced the mitochondrial genome of blue crab. These researchers documented genetic markers that distinguished among crabs in the Chesapeake Bay, but have yet to identify markers that can separate crabs among estuaries. Thus, definitive statements about the spatial scale of population structure are still lacking. Although there is no definitive evidence of genetic structuring indicative of separate populations, there is clear evidence of localized populations that experience limited gene flow between them. In summary, the genetic evidence suggests the existence of, at a minimum, a functionally separate Chesapeake Bay blue crab stock that experiences only limited exchange of individuals with neighboring stocks.

Studies of larval distributions provide further evidence for the presence of a “quasi-discrete” Chesapeake Bay stock (see Section 2.4). After being released, zoea move seaward, where they develop and return to enter estuaries as megalopae. While the precise details of the physical context and behavioral mechanisms employed by larvae to return to estuaries are not fully understood, what is known suggests that large scale exchanges of larvae are likely not typical. The prevailing oceanography of the regions suggests that only the Chesapeake Bay and more northerly populations (i.e., coastal bays and Delaware Bay) are sources of potential recruits to Chesapeake Bay. This suggests that population interchange is restricted. Furthermore, aspects of the physical environment and behavior of zoea suggests that the exchange is likely not a persistent feature of the dynamics of the different populations. Female crabs release zoea near the mouth of coastal Atlantic estuaries. Natunewicz and Epifanio (2001) found that zoea occur in distinct patches 0.5 – 2.5 km diameter in the vicinity of the mouth of Delaware Bay. Modeling studies by Garvine et al. (1997) indicated that some larvae return to Delaware Bay using upwelling-favorable wind events. However, these modeling studies also indicated that a not insignificant proportion of zoea are advected southward in a buoyancy driven coastal current. These larvae may represent potential recruits to the Chesapeake Bay population. Studies of recruitment in the Chesapeake Bay stock indicate a similar picture to that found for Delaware. Roman and Boicourt (1999), found patches of zoea associated with the Chesapeake Bay plume front. In a numerical analysis Johnson and Hess (1990) estimated that only 13% of released zoea remained in the Chesapeake Bay and that the remaining zoea (87%) are advected out to sea. Johnson and Hess (op. cit.) calculated that 29% of the zoeal production returns to the Chesapeake Bay. It is important to note that these figures do not include zoeal mortality, which is likely to be substantial, and thus represent an upper bound.

From this review, we conclude that there is sufficient evidence to support the assumption that the blue crab population in the Chesapeake Bay comprises a unit stock, at least for assessment purposes. This does not imply that there is no exchange with or subsidy from neighboring populations; rather it assumes that the dynamics of the Chesapeake Bay population are determined from internal considerations, and not from subsidies or exchanges with other populations. Subsidies and exchanges do likely occur with genetic and evolutionary implications– we are simply assuming that they are not significant to population dynamics. However, we note that such subsidies and exchanges are likely to be more important when the size of the Chesapeake Bay population is small.

2.2. Growth

Information on blue crab growth dynamics has expanded substantially since the last assessment (Miller et al. 2005). Three factors underlie this increase in knowledge: liposfuscin-based ageing (Ju et al. 2001), molt-process modeling (Brylawski and Miller 2006) and stock enhancement efforts (Zohar et al. 2008).

The physiology and energetics of growth in blue crab were summarized by Smith and Chang (2007). However, documenting the growth dynamics of blue crab and other crustaceans in the field is difficult because of the lack of structures for ageing. Lipofuscin, a complex lipo-protein builds up in post-mitotic tissues of all organisms as a result of intracellular reactions to protect cells from oxidative stresses. Ju et al. (1999) developed a biochemical assay to quantify the level of lipofuscin in blue crab eye stalks. By measuring the lipofuscin level in non-dividing tissues, such as nervous tissue, Ju and colleagues were able to estimate physiological age. Validation studies have been conducted that permit the absolute level of lipofuscin to be correlated with chronological age based on crabs raised in both the laboratory and in artificial ponds (Ju et al. 1999). Crabs raised in artificial ponds were held at ambient conditions, allowed to forage on naturally abundant prey and sampled on several occasions over 18 months. Information on the sizes of known age crabs from the ponds were fit to a von Bertalanffy growth function. Puckett et al. (2008) used the lipofuscin assay to age free-living crabs in the Chesapeake Bay. These authors concluded that the peeler-soft crab and the hard crab fisheries exploit crabs less than 18 months of age (Fig. 2.1).

Smith (1997) developed a discrete molt-process model for blue crab in the Chesapeake Bay. He used empirical relationships developed for crustaceans generally to develop a specific parameterization for blue crab. Using this approach, Smith estimated von Bertalanffy parameters that best described the growth trajectory generated. These model parameters yielded estimates of sizes at the onset of overwintering in the first, second and third years of 32.5, 107.5 and 147.6 mm carapace width (CW). Brylawski and Miller (2006) conducted laboratory experiments to directly estimate the parameters of Smith's molt process model. These authors incorporated their parameter estimates into a simulation model which demonstrated that observed variability in winter temperatures could vary the timing of recruitment to the fishery by up to 10%.

Recent research efforts to assess the feasibility of stock enhancement for blue crabs in Chesapeake Bay have generated new information on growth. Growth data are available from two components of this project (1) growth of early life stages during the development of aquaculture technologies and (2) growth of larger juveniles and adults from experimental field releases of hatchery-reared animals. Zmora et al. (2005) cultured juvenile crabs in a hatchery from captive spawning adults; zoea grew to 1st stage juveniles (C1) in approximately one month, and from C1 to C6-7 stage (~20 mm CW) in the subsequent month. Although, no quantitative estimates are given, Zmora et al. (2005) noted striking variability in growth rates among individuals in a single brood. Releases of hatchery-reared blue crab juveniles into shallow water habitats of the upper and lower Bays provided the opportunity to estimate growth rates of free-ranging animals under natural conditions (Davis et al. 2005, Hines et al. 2008). Similar to previous studies, growth was temperature-dependent with peak growth rates of 1.2 mm CW d^{-1} observed in July. A deterministic growth model based on field data predicts that juveniles recruiting in fall will enter the hard crab fishery during late summer to early fall of the following year. Growth rates of hatchery-reared animals appear to be representative of wild crabs; paired experimental releases of hatchery-reared and wild cohorts showed no difference in observed growth rates (Johnson et al. *In press*).

2.3. Reproduction

2.3.1. Molt to maturity

Blue crabs reproduce sexually, and males and females are sexually dimorphic and exhibit different growth forms. The reproductive physiology and anatomy are reviewed by Jivoff et al. (2007). Circumstantial evidence strongly suggests the presence of a terminal molt in female blue crab (Van Engel 1958, Abbe 1974). Limited physiological evidence suggests that the Y-organ does not degenerate as it does in other crabs that exhibit determinate growth, rather Smith and Chang (2007) speculate that in blue crab it is over production of MIH by the X-organ that enforces the terminal molt. As the Y-organ does not degenerate, female crabs maintain the physiological capacity to molt again under rare circumstances. Evidence for a terminal molt in males is less definitive than in females. There is some evidence for continued growth in males, particularly as most of the largest crabs collected are males. However, similarly to large females, large males form limb buds when they lose an appendage, and such males are often collected in the field suggesting that males molt infrequently at large sizes.

2.3.2. Age and size at maturity

Our limited ability to age blue crabs has precluded empirical development of maturity ogives for blue crab. However, recent evidence from attempts to develop large scale aquaculture of blue crabs at the Institute for Marine and Environmental Technology, indicate that females can mature within their first year under ideal conditions. In the field, given the annual temperature cycle and typical megalopal settlement dates in August and September, it is unlikely that crabs could mature within their first year. It is more likely that they mature in the autumn of the following year when they are 12-18 months of age. Those that do not mature at this time, likely delay maturity for a following year, and mature when they are 24-30 months old. Hester et al. (1982) reviewed information on age at maturity in Chesapeake Bay. Their review suggested two production schedules: those females originally hatched in May reach maturity in 15 months and spawn at 24 –27 months of age, and those crabs originally hatched in August reach maturity in 21 months and spawn at 24 months. More recently, Hines et al. (2003) suggest that although females in different parts of the bay may mature at the same time, they differ in the timing of larval release (see Section 2.4.3).

2.3.3. Mating and spawning periods and locations

Female blue crabs are only receptive during the period immediately following the post molt stage (see Section 2.3.1). Thus, all subsequent larval production results from sperm transferred by males during this single receptive period. Empirical evidence suggests intense competition among males for mating opportunities (Jivoff 1997, Kendall and Wolcott 1999). Males that mate frequently transfer less sperm which impacts the number of zoea released subsequently by mated females (Hines et al. 2003). Mating typically occurs from May – October (Hines et al. 2003). Mating pairs have been reported widely throughout the Chesapeake Bay system. Hines et al. (2003) found that 98% and 100% of mature females in the Rhode River and lower Bay held ejaculate stores, indicating a high level of mating success in the field.

Following mating, the behavior of inseminated females can differ depending on their mating location (Hines et al. 2003, Aguilar et al. 2005). Females inseminated in the upper Bay in the summer and fall will migrate southward towards the lower Bay in late fall, overwinter and release larvae in the summer of the following year. Current evidence suggests that none of the females inseminated in upper Bay sub-estuaries will produce broods during the same year as mating. Similar to females mating in the upper bay, most females inseminated in the lower Bay probably follow this same timing of brood production. However, unlike upper Bay females it is likely that some unknown fraction of females inseminated in the lower Bay can release larvae in the same season in which they were inseminated. Prior to hatching, ovigerous females migrate to the high salinity waters at the mouth of the Chesapeake Bay (Tankersley et al. 1998). Hatching occurs around nocturnal high tide and zoea are carried seaward on the ensuing ebb current.

2.3.4. Fecundity

Prager et al. (1990) conducted an extensive study of fecundity patterns in Chesapeake Bay blue crab. They found that fecundity level varied seasonally. Fecundity was low early in the season, peaked in mid-season and declined at the end of the season (Prager et al. 1990). They concluded that fecundity was an increasing linear function of female carapace width, given by Fecundity (millions) = -2.248 + 0.377 * CW (cm), R^2 = 0.24. The low R^2 value was partly due to a striking variability within a season, or may have arisen because of errors in estimation of carapace width. Data for Prager et al.’s study were collected during a time of relatively high abundance. There is a potential that density-dependent changes in fecundity may have occurred in this species. Recently, Wells (2009), re-examined the fecundity patterns in blue crab in the Chesapeake Bay. Wells quantified fecundity of female blue crab from 2002- 2006. She noted a significant decrease in the size of mature female blue crab from the 1980s to the present (2005). Wells also reported an absent or weak size-fecundity relationships. Significant linear regressions were reported for 2003-2005, but these only explained a small fraction of the variation in the data. No significant relationships were reported for 2002 or 2006. These results led Wells (2009) to conclude that fecundity of the Chesapeake Bay blue crab population has declined since the Prager et al. (1990) study.

There have been two important new studies since the last assessment quantifying the number of broods per season in blue crab. Dickinson et al. (2006) quantified brood production of mature female blue crab in estuarine waters in North Carolina. Dickinson and colleagues held individual females in minnow traps in the field, feeding them daily. For each crab, Dickinson and colleagues measured brood production and volume over 18 weeks. Their data indicate that an average sized crab (127 mm CW) that is mature at the beginning of the spawning season produces eight clutches within a full 25-wk spawning season. Additionally, Dickinson et al. report that although larger crabs produced larger clutches, they did so less frequently than smaller crabs such that the total reproductive output was almost invariant with crab size. Other authors have reported similar results for the North Carolina blue crab population (Darnell et al. 2009). Importantly, these authors evaluated the effective larval production as a function of the brood number. They reported a consistent decline in effective reproductive output such that the percentage of embryos that developed normally declined by up to 40% from the first to the fourth brood. Darnell et al. concluded that the majority of the reproductive output of individual females comes from a few initial broods.

2.4. Larvae

Epifanio (2007) reviewed the biology and ecology of larvae. Briefly, larvae are transported out of the Chesapeake Bay and onto the coastal shelf (Roman and Boicourt 1999). Miller (2001a) used a size-based approach to estimate the mortality rate of this life history stage. Miller estimated that the probability that an individual survives the entire zoeal and megalopal period was 1.19×10^{-6}. During their time at sea, zoea molt several times before molting to the last larval stage, the megalopa, which reinvade the Chesapeake Bay. Time series of abundances of zoea and megalopae are available from the Chesapeake Bay Program's monthly zooplankton monitoring program from 1979 – 1998. These data were analyzed by Lipcius and Stockhausen (2002). These authors report a decline in larval abundance by approximately an order of magnitude over the period of sampling.

2.5. Juveniles

The juvenile period is a critical life history stage for blue crabs (Lipcius et al. 2007). The importance of nursery habitats is widely reported (Etherington and Eggleston 2003, Etherington et al. 2003, Stockhausen and Lipcius 2003) – although recently the dominant paradigm of the critical role of sea grass as nursery habitat has been broadened to include a greater diversity of habitats. Van Montfrans et al. (pers. comm.) have documented predation of juvenile blue crab in sea grass beds by several fish including striped bass and red drum. Importantly, Etherington et al. found that mortality rates in sea grass habitats were equivalent to emigration rates, indicating that successful emigration to adult habitats is at least as critical a process as survival in the juvenile habitat.

2.6. Adults

A considerable amount is known about the feeding ecology (Mansour and Lipcius 1991, Hines 2007) and the response to environmental parameters (Bell et al. 2003b, a) of adult blue crab. Research has also focused on assessing their role in structuring estuarine ecosystems (Hines et al. 1990). However, with regard to this stock assessment, the only feature of adult biology that is relevant is lifespan.

2.7. Natural Mortality

Estimates for natural mortality in blue crab were thoroughly reviewed for the last assessment (Miller et al. 2005). Direct and indirect approaches were combined to estimate the most likely value of M for blue crab in the Chesapeake Bay. Full details are given in Hewitt et al. (2007) and are only summarized here. Indirect estimates were developed using empirical estimates involving estimates of von Bertalanffy K and CW_∞ parameters, ages at maturity and longevity as well as temperatures at different times during the season. Estimates of M based on these indirect measures ranged from 0.3 – 2.35. However, the distribution of values was centered around M=1.1 (Fig. 2.2). Hewitt et al. combined these indirect estimates with direct estimates from tagging studies (Lambert et al. 2006). Application of Brownie tag return models to three years of data (2002-2004) collected on returns of mature females. Tag-return based estimates of M varied from 0.42-0.87. Based on both the direct and indirect approaches, a value of M=0.9 was adopted as the most likely value for the rate of natural mortality. The previous Rugolo assessment had used a value of M=0.375 (Rugolo et al. 1997). Accordingly, Miller et al. (2005) used values of M=0.375, 0.6, 0.9 and 1.2 in all analyses. All values used in analyses were considered to be age-independent, sex-independent and constant.

Since November 2001, Lipcius et al. have continued their tag-recapture studies of mature, female blue crab. These data were used in the previous assessment to inform our estimate of M. Here, we update these data and provide additional estimates of M. From 2001-2010, 4,400 crabs were tagged and released. Between 219-985 crabs were tagged annually. Of these, 917 (20.8%) were returned. All but two were returned by commercial fishers. Information-theoretic model comparisons indicated that model with year-specific survival and tag-recovery rates best explained the data. The time series of annual survival rates of mature females is show in Fig. 2.3. Survival rates ranged from 0.09 in 2002 and 2003 to 0.28 in 2006. The mean annual survival rate of mature female crabs was 0.15 ± 0.01 (mean ± SE). A fuller summary of these results is provided in Assessment Working Paper 1.

If we assume that when tagged, females were 1.5 years old, the return of "known-age" females also provides a foundation of indirect estimation of M. Based on the pattern of returns, we used maximum ages of crabs of 5.5, 6 and 6.5 years to address uncertainty in the initial age at tagging. Using these values in Hoenig's model (1983) to predict M yields estimates of M = 0.79, 0.73 and 0.67 respectively. If we use instead a "rule of thumb" approach ($M= 4.22/T_{max}$ - Hewitt and Hoenig 2005), M estimates of M=0.7. 0.7 and 0.65 are obtained.

All estimates considered support the continued use of credible limits for M being $0.6<M<1.2$.

3. Fishery-independent Data

3.1. Size-at-age Convention

Despite difficulties with ageing blue crabs, previous assessments have used size composition data from fishery independent surveys to develop estimates of abundance of blue crabs that are age- 0, and age-1+ (Rugolo et al. 1997, Miller et al. 2005). Blue crabs are assigned an age cohort based on current knowledge of growth and timing of recruitment. The correct size cut-offs for a single cohort are certainly influenced by such factors as annual variations in growth rates, recruitment timing, and distribution. Considerable work has been undertaken to explore the consequences of alternative demarcations of size-at-age vectors (Chris Bonzek, VIMS pers. comm.). However, the size-based definitions of age-classes have not been rigorously and fully evaluated, in part because size information has been inconsistently recorded in some surveys. In this assessment, we used the spatial, temporal and size thresholds (Table 3.1) that have been adopted by CBSAC in producing its annual status of the stock report (Chesapeake Bay Stock Assessment Committee 2010). In support of the continued use of these size thresholds, figure 3.1 shows the size distribution in the winter dredge survey (see Section 3.2.4 below for details). We note the consistency of the bimodality of the size distribution for this survey

3.2. Fishery-independent Survey Time Series

A strong point of Chesapeake Bay blue crab assessments is the abundant fishery-independent data that are available. For this assessment, data were analyzed from three fishery-independent surveys that differ in duration and geographical coverage (Table 3.1). The VIMS trawl survey, conducted for the past 49 years, is the longest-standing fishery-independent survey for the region. It samples the southern portion of the Bay (Figure 3.2a). The MD trawl survey, which is restricted to eastern shore sites and tributaries in Maryland waters of the Bay, has been conducted for the last 28 years (Figure 3.2b). The winter dredge survey (WDS) has been conducted for 16 years and is the principal Baywide survey (Figure 3.2c). We analyzed the data from these three multi-year surveys.

However, these are not the only surveys available. For example, the US EPA Chesapeake Bay Program has been conducting zooplankton monitoring since 1985. This survey database includes records of blue crab megalopal abundance that were used by Lipcius and Stockhausen (2002) as a recruitment index. Other fishery-independent studies considered, but not used because they were either too short in duration or too regional, included the Calvert Cliffs pot survey - a fishery-independent survey conducted since 1968 at one mid-Bay location (Abbe and Stagg 1996), the Chesapeake Bay

Multispecies Monitoring and Assessment program which has been conducting baywide surveys from May-October since 2003, a trawl survey in the Rhode River (King et al. 2005) and a PEPCO survey were conducted in the Potomac River in support of power plant operations.

3.2.1. Statistical analyses.

Survey time series were provided by the collecting jurisdictions as counts using the size-age conventions above. Each jurisdiction also provided data pertaining to the time, location and environmental conditions for each survey tow.

A standard approach was adopted to analyze patterns in all survey time series. Count data derived from surveys typically possess statistical properties which must be accounted for during analyses: they often include a large number of observations when no animals were caught (zero-inflated), and the very fact that they are count data means they are unlikely to be normally distributed. Also the abundance of target animals in the survey can be affected by environmental variables in addition to reflecting underlying abundance. Ideally, all three properties should be addressed when developing indices of abundance from surveys.

Jensen et al. (2005) used a two stage approach to model blue crab abundance using survey data. In this approach, the first stage models the probability of occurrence and the second stage models abundance given occurrence. In their application, Jensen et al. used a generalized additive modeling framework because they were interested in describing the spatial pattern of distribution. For the current assessment, we adopted a generalized linear modeling (GLM) approach to develop standardized indices of abundance (Stefansson 1996). This approach addresses all three statistical properties of common to survey data. The first stage of the generalized linear model represents the presence/absence as a simple a Bernoulli-type absence/presence measurement. Within the GLM framework the effect of covariates of the probability of occurrence, including design factors, such as strata, month and continuous environmental variables, can be evaluated (Dobson and Barnett 2008). The second phase of the approach uses a lognormal or gamma distribution to model the distribution of positive tows. As with the first stage, a suite of design relevant or environmental covariates can be added as explanatory variables. We note that the variables used to improve the information captured in the first and second stages of the model need not be the same.

We conducted GLM analyses for each survey. Whenever possible sex-specific standardized survey indices were developed for age-0, age-1+ crabs. For all surveys, aggregate survey indices were also estimated for age-0 and age-1+ crabs. All GLM analyses were conducted within R using a modified from of the deltaGLM code developed by E. J. Dick at NOAA's Southwest Fisheries Science Center (version DeltaGLM-1-7-2-PBC). The program fits a GLM to each stage using the general formula

$$N = b_0 + Year + b_1 \cdot Month + b_2 \cdot Strata + b_3 \cdot Sal + b_4 \cdot Temp + b_5 \cdot Depth + \epsilon$$

Eq. 1.

The program uses a negative log likelihood fitting criteria using the glm function within R (R Core Development Team 2007). The best fitting model was determined using AIC. Not all surveys provided data for each design effect or environmental variable. The program assumed that the design variables were fixed factors, and the environmental variables and interactions were continuous. The program develops estimates of the standardized survey index for each year, standardized for all covariates. The program also produces estimates of the parameters governing each covariate (b_1-b_{10}) for both stages of the model estimation. We evaluated a series of nested models from the full model (all b's estimated) to the most simple model of just b0 and year effects for each stage. The model with the lowest AIC for each stage was selected. In this way, it was possible to have different models for each stage of the model. For each selected model fit, we generated year jackknifed estimates of the variance of the index. We also report the proportion of positive tows, and the distribution of catches.

For all fishery independent surveys used in the assessment model, we examined the correlation between abundance of age-0 crabs and abundance of age 1+ crabs both within the same year, and with a one year lag. We assumed that a strong correlation between age 0 crabs in year i and age one-plus crabs in year i+1 indicated that the survey is effectively tracking cohorts. Finally, to evaluate the performance of all surveys, we evaluated the correlation structure among all survey indices.

All analyses were conducted using the R statistical language. Sample code used for the Maryland DNR Trawl Survey is provided in Appendix I. The code for the other state surveys was broadly similar, although names of specific variables differed.

3.2.2. Virginia juvenile finfish and blue crab trawl

Since 1955, the Virginia Institute of Marine Sciences (VIMS) has conducted a trawl survey to monitor abundance trends in selected finfish and invertebrate species in the southern portion of Chesapeake Bay. Originally, the survey sampled only the York River, but it has expanded steadily. Currently, seven strata are recognized that cover an area from the mouth of the Bay to the VA/MD border, and up to the freshwater interfaces of the York, James and Rappahannock Rivers (Fig. 3.2). Samples are collected monthly from about 60 stations within the strata. Both fixed and random station assignments have been employed. All blue crabs collected in the VIMS survey are enumerated, sexed and measured. The trawl used in the survey has changed over the survey time series. The most important changes were the addition of a tickler chain and a net liner in 1973 and 1979, respectively. We employed published calibration factors to account for changes in gear types in our analysis (Hata 1997).

Previous assessments have primarily used population indices based on fall surveys (Rugolo et al. 1997, Miller and Houde 1999, Miller 2001b, Miller et al. 2005). Miller et al. (2005) evaluated indices from both the fall- and spring-based indices and found that they were generally coherent. These authors noted several benefits to using spring-derived surveys, particularly for age-0 crabs. In fall, age-0 crabs are constantly recruiting to the survey areas, and thus the cohort that the survey is indexing is changing from month to month. Similarly, age-1+ crabs are beginning to move toward preferred overwintering areas. Thus, for this stage too, the fall surveys are indexing a changing cohort from month to month. Based on these reasons, we adopted population indices based on spring surveys for this assessment.

To account for the expansion in the survey coverage since 1955, we focused analyses on samples from the three principal western short Virginia tributaries: the James, York and Rappahannock Rivers. We calculated geometric mean catch.tow^{-1} for each river system. The final survey index was the weighted mean of the three tributary indices, weighted by the area of each river sampled (Table 3.2). No index standardization analyses are presented for this survey.

Overall, the survey annual index for age-0 crabs was 12.92 ± 15.41 (mean ± SD) age-0 crabs.tow^{-1}. The time series for age-0 crabs is show in figure 3.3. The time series low was 0.67 age-0 crabs.tow^{-1} in 1968 and the time series maximum was 84.52 age-0 crabs.tow^{-1} in 1971.

Time series trends for age-1+ crabs are shown in figure 3.4. Overall, the survey annual index for age-1 crabs was 4.88 ± 3.89 (mean ± SD) age-0 crabs.tow^{-1}. The time series low was 1.03 age-1+ crabs.tow^{-1} in 2005 and the time series maximum was 20.9 age-1+ crabs.tow^{-1} in 1990.

As expected the survey indices showed a high degree of correlation (Fig. 3.5). The annual data for single sex-indices fall along the 1:1 line in the plot. When the single sex and the aggregate data are compared, these data for both male and female distribute around on the 1:2 line.

Regression of lagged age-0 abundance in year t on age-1+ abundance in year t+1 indicated that the VIMS trawl survey provides accurate information on the dynamics of the entire population (Fig. 3.6). The correlations between age-0 and lagged age-1 was high (r=0.77).

3.2.3. MD DNR Trawl Survey

Beginning in 1977, Maryland DNR instituted a trawl survey of Eastern Shore sites and tributaries. The survey was expanded in 1984 to include the Patuxent and Chester Rivers, and again in 2003 to include the Nanticoke, and Little Choptank Rivers as well as Fishing Bay. A sample of the current distribution of sampling stations is shown in Fig. 3.2. The survey is conducted from May - November. However, coverage is inconsistent temporally and spatially from year to year. Sites within each stratum are fixed and were selected based on patterns of commercial activity and habitat. The survey has used a consistent gear throughout: a 16’ semi-balloon otter trawl. The trawl has 1 1/4” stretch mesh body, a 1 1/8” stretch mesh cod end with a ½” stretch mesh liner. Additionally the trawl has a 3/16” footrope and a 3/16” tickler chain. Data from the survey were recorded in two different ways. Prior to 1989, crabs caught in a tow were counted and binned into predetermined size categories representing age-0, age-1 and age-2+ crabs. No size measurements were taken. From 1989 onward, size measurements of individual crabs were taken. For the analyses reported here we used the size designations from the early part of the survey. In addition, for all tows day, month, strata (tributary or region), water temperature, salinity and water depth were recorded. Distributions of the three environmental variables are presented in Fig 3.7.

Overall, the survey caught an average of 4.87 ± 16.81 age-0 crabs.tow^{-1} (mean ± SD, min=0, max=539). Comparable values for males and females were 2.719 ± 9.31 (mean ± SD, min=0, max=309), and 2.14 ± 7.78 (min=0, max=230) respectively. The distribution of age-0 catches was highly skewed (Fig. 3.8). Catches of age-1+ crabs were also highly variable. Overall the survey caught 14.01 ± 22.16 age-1+ crabs (min = 0, max=375). The average catches of male and female age-1+ crabs were 8.11 ± 14.37 (min=0, max=319) and 5.89 ± 11.08 (min=0, max=314). As with age-0 crabs, the distribution of catches of age-1+ crabs was also highly skewed (Fig. 3.9).

We developed standardized survey indices for age-0 male, female and combined and age-1+ male, female and combined. After consideration of the life history of blue crab, the age-0 indices were based on samples collected in September – November and the age-1 indices were based on samples collected in May-July. The percentage of positive tows varied among size and sex categories (Table 3.3). The lowest percentage was for age-0 females (41.3%) and the highest was for age-1+ combined (88.5%). Standardized index values are provided in Table 3.3.

For age-0 female and for age-0 crabs combined, AIC values indicated that the best fitting models for each stage (occurrence and abundance) involved only design factors (month and strata) and water depth (Table 3.4). Only in one case (age-0 male occurrence) did a model with all environmental parameters result in the best fit. But even here the difference between the design factors and temperature model and the design factors and all environmental parameters was marginal (Table 3.4). Accordingly, all age-0 indices were developed using both design factors and water depth alone.

For age-1+ crabs the best fitting models were more varied. All models of the positive tows (abundance given presence) were best modeled with both design and environmental factors. However the specific environmental factor involved varied with sex (Table 3.5). Similarly, the best fitting models for occurrence varied among crab categories. For age-1 crabs generally, no environmental variables were included in the best fitting model of occurrence. For age-1+ females both design factors together with temperature was the best fitting model whereas, for age-1 males, both temperature and salinity were necessary (Table 3.5).

The indices for age-0 crabs are presented in Fig 3.10. Indices for all three categories of age-0 crabs (female, male and combined) were highly variable. Each showed a common pattern of peaks in the early 1990s and again in the mid-2000s. In general, the GLM indices described the underlying simple mean values well. The agreement was particularly good in the first half of the time series, but became more variable later on (after 2000). All three GLM indices of age-0 abundance were highly correlated with each other (Fig. 3.11), with Pearson linear correlation coefficients of r>=0.98. The two sex-specific indices appear well described by a 1:1 relationship (Fig. 3.11), whereas the individual sex-specific indices and the aggregate index appear better described by a 1:2 relationship.

The indices for age-1+ crabs are presented in Fig. 3.12. Indices for all three categories of age-1+ crabs exhibit similar behavior. All show an increase from the beginning of the survey (1977) until the mid-1990s. Thereafter, all three indices decline steadily. The GLM indices describe the simple mean estimates from the survey well. All three GLM indices of age-1+ abundance were highly correlated with each other (Fig. 3.13). However, the correlations for age-1+ GLM indices are not as high as those for age-0 crabs, particularly so for the correlation between male and female age-1+ abundances. Moreover the relationships among the age-1+ indices appear to deviate from the expected 1:1 and 1:2 relationships observed for the age-0 indices.

Regression of lagged age-0 abundance in year t on age-1+ abundance in year t+1 indicated that the Maryland DNR blue crab trawl survey may provide accurate information on the dynamics of the entire population (Fig. 3.14). Correlations between age-0 and lagged age-1 were moderate (r~0.38 – 0.49). This is a substantial improvement in correlations between sequential age class lagged by one year compared to the previous assessment in which lagged correlations in the MD blue crab survey were ~ r = 0.1 (Miller et al. 2005). This suggests that efforts to account for environmental effects may have improved the signal in these data substantially.

3.2.4. Winter Dredge Survey

When winter water temperatures get below ~ 10 C blue crabs are unable to continue growing (Brylawski and Miller 2006). During these periods, blue crabs become quiescent and are closely associated with or even buried in sediments (Bauer and Miller 2010b). This period of inactivity is exploited as a favorable time to conduct a baywide, synoptic survey. Designed and initially implemented by Rothschild and colleagues (Volstad et al. 2000, Sharov et al. 2003), the baywide winter dredge survey has been conducted cooperatively by the states of Maryland and Virginia since the winter of 1989/1990. The survey is designed as a stratified random sample. In the first two years of the survey, there were multiple area-, sediment- and depth-based strata. However, since the 1991/1992 winter, the survey has been conducted with three consistent, regional strata: the upper Bay, the mid-Bay and the lower Bay. Stations are allocated randomly each year in proportion to stratum area. Sampling is restricted to waters > 1.5 m depth. On average about 1200 stations are visited each winter (Fig. 3.2). A single tow of 1.83-m wide Virginia crab dredge is taken at each station. The dredge is towed along the bottom at a fixed speed and the beginning and ending coordinates are recorded with a differential GPS. All crabs collected during a tow are measured for carapace width and sexed. Crabs are categorized as age-0, or age-1+ based on size-age conventions. Temperature, salinity and water depth are recorded. During each survey year, trials are conducted to estimate vessel- and year-specific catchability coefficients. These catchability coefficients are used, together with tow-specific area, to estimate the absolute density of crabs caught at each station. Standard design-based statistical approaches are used to expand station abundances to a total baywide abundance (Sharov et al. 2003).

In addition to the standard survey, selected stations at which high abundances of crabs were recorded are revisited after the survey is completed to provide an estimate of winter mortality. These estimates have been used to correct baywide winter abundance to provide an estimate of the number available at the beginning of the fishing year. Empirical estimates from the winter dredge survey are similar to model based estimates developed from laboratory-based geostatistical models (Bauer and Miller 2010a).

Over the course of the winter dredge survey monitored environmental parameters have varied (Fig.3. 15). Temperature has varied among years and within each year. Temperatures have ranged from -4.5 – 26 C. The mean ±SD is 5.037±2.67 C. Experimental results indicate this range of temperature is biologically significant in terms of winter mortality (Bauer and Miller 2010b). Salinity also exhibited inter- and intra-annual variability. Salinities have range from 0-35, with a mean ± SD of 15.47 ± 6.45. Depth has also varied considerable from 3 – 60 ft. with a mean ±SD of 25.5 ± 12.98 ft.

Individual crab catches have also been highly variable (Fig. 3.16). Analyzing these data further requires correcting for variation in tow duration among tows and catchabilities among years. Estimates of the absolute crab density are given in Table 3.6. Based on stratified mean densities, and combining all crabs, regardless of age and sex, the average baywide density is 48±20.6 (mean ± SD, crabs.1000m^{-2} – Fig 3.17). The lowest baywide density was 26.64 crabs.1000m^{-2} which was observed in 2008, and the highest was 88.32 crabs.1000m^{-2}, observed in 1993. Assuming an area for the bay of 9814.57 m^{2}, these numbers are equivalent to a baywide average abundance of 471,099,360 crabs, ranging from 261,460,145 – 866,822,822.

Time series of abundance show common patterns regardless of age or sex. Crabs in all three age categories (Age-0 crabs, age-1+ and all crabs combined) have generally declined in abundance over the course of the survey (Fig. 3.18). Age-0 crab abundance appeared to decline sharply after 1997 and has not recovered. Prior to 1997 the density of age-0 crabs in the winter dredge survey varied around ~ 15 crabs.1000m^{-2} for both sexes. After 1997, the average density of both sexes dropped by ~50% to 10 crabs.1000m^{-2}. Both male and female age-0 crabs demonstrate the same pattern. Indeed the sex ratio of age-0 crabs in the winter dredge survey appears remarkably constant but demonstrates a slight female bias (Fig. 3.19). The average proportion of age-0 crabs in the winter dredge survey that are female is 0.52±0.033 (mean ± SD).

The baywide density of age-1+ crabs does demonstrate a decline over time (Fig. 3.18). However, unlike the age-0 crabs, the decline appears more gradual and consistent. At the beginning of the survey age-1+ crabs were caught at densities of approximately 20 crabs.1000m^{-2}, and they declined steadily until the mid-2000s to 5-10 crabs.1000m^{-2}. However, unlike age-0 crabs, age-1+ crabs do appear to demonstrate sex-specific differences in their responses. The sex ratio of age-1 + crabs in the winter dredge survey has not been consistent over time (Fig. 3.19). The proportion of female age-1+ crabs appears to have increased substantially since the mid-2000s. Not all of this change can be accounted for by direct, targeted action by management (see Section 4).

We developed standardized winter dredge survey indices using the delta-lognormal approach described above (Table 3.6). We only used data from 1991/1992 onwards in these analyses because of the changes in the stratification schemes in the first two years. For all age- and sex-categories, the best fitting GLM models include all design (year, stratum, month) and environmental (depth, salinity and temperature) variables (Table 3.7-3.8). In general, the age-0 standardized indices explained the patterns in the data well, largely following the estimated annual stratified means from the survey (Fig. 3.20). Indices for age-0 males and females were highly correlated (r=0.96- Fig. 3.21). The scatter of data for the correlation between single sex indices fall on the 1:1 line, reinforcing the near equal proportion of age-0 males and females in the survey portrayed in figure 3.19. Moreover, both sex-specific indices were highly correlated with indices for both sexes combined. The scatter of data for the correlation between single sex indices and the combined index fall on the 1:2 line, again reinforcing the near equal proportion of age-0 males and females in the survey.

In general, the age-1+ standardized indices explained the patterns in the data well, largely following the estimated annual stratified means from the survey (Fig. 3.22). There is a consistent bias in the indices for female age-1+ crabs that has yet to be fully understood. Indices for age-1+ males and females were correlated (r=0.72- Fig. 3.23), but to a much lower degree than for age-0 crabs. The scatter of data for the correlation between single sex indices do not appear to be well described by ether the 1:1 or the 1:2 lines, reinforcing the varying proportions of age-1+ males and females in the survey portrayed in figure 3.19. The correlation between age-1+ males and age-1+ crabs combined is very strong (r=0.95 and well described by the 1:2 line (Fig. 3.23). However, although the correlation between age-1+ females and the combined abundance of age-1+ crabs is high (r=0.9), the data are more widely distributed around the 1:2 line than is the case for the male correlation.

Finally, we examined the internal coherence of the winter dredge survey estimates by regressing the sex-specific abundance of crabs in year t+1 on the abundance of age-0 crabs of the same sex in year t (Fig. 3.24). The lagged correlations all indicate that the sex-specific abundance of crabs in one year explains at least 30% of the variation in the sex-specific abundance of crabs in the subsequent year. Given the uncertainty over the age-structure of crabs in the survey age-classes, correlations of the magnitude shown in figure 3.24 are viewed as support for the contention that the winter dredge survey can serve as a reliable indicator of the dynamics of the blue crab population in the Chesapeake Bay.

4. Chesapeake Bay Fisheries

There is not a single fishery for blue crab in the Chesapeake Bay; rather there is a diversity of sectors, both recreational and commercial. Here we review the development and current status of the principal fisheries. Because management regulations vary among the jurisdictions, we present each jurisdiction separately. Information regarding the status and importance of recreational fisheries is so limited that we are unable to include them in the assessment.

Kennedy et al.(2007) reviewed the history of commercial fisheries for blue crab along the Atlantic and Gulf coasts of the United States. Sette and Fiedler (1925) reported that the modern crabbing industry dates to 1873. Van Engel (1999) suggested that the growth of the commercial fishery at this time resulted from the successful development of methods for shedding and shipping crabs out of the region. The decline of landings in New York and New Jersey created a demand for crab meat that further encouraged development and expansion of the fishery. In response to the developing fishery, the States of Maryland and Virginia mandated oversight of the fisheries by their respective state agencies (Van Engel 1999, Kennedy et al. 2007). Virginia vested authority over the crab fishery in the Virginia Board of Fisheries in 1898. The situation in Maryland was more fluid until 1939 when the Maryland Commission of Fisheries was created.

During the early development of the crab fishery, crabs were harvested principally by dipnet, trotlines and scrapes (Van Engel 1999). Use of dredges to harvest overwintering crabs was limited to Virginia. Wire mesh crab pots were introduced in 1928 in Virginia, although they were not legalized in Maryland until 1941. Crab pots became the principal gear for hard crabs after World War II and remains so today.

The first regulations for the fisheries recognized gear, region and season differences. The establishment of a closed winter season occurred early in the history of the fishery. Local winter closures occurred in individual counties in Maryland as early as 1902 (Van Engel 1999), but it was not until 1930 in Maryland and 1932 in Virginia that the winter closure of the fishery was broadly enforced. Size limits on crabs were also established early on. The first successful implementation of size limits occurred in 1916, which Van Engel (1999) credited to a lack of relevant biological information and a focus on the oyster fishery prior to this date. Size limits on peeler crabs date to the 1920's. Perhaps the most important early regulation enacted were regulations to ban capture and possession of sponge crabs in 1916, although the duration of the ban has varied.

Data on the harvest from the fishery are available from as early as 1880. Many of these data were compiled by Sette and Fielder (1925) and Cronin (1987). The accuracy and potential biases in these early data are not fully understood. Since then several approaches to collecting data on the crab harvest, its characteristics and the effort expended to land the catch have been implemented, revised and modified. However, it is only in very recent years that attempts have been made to verify the level of compliance or accuracy of the various reporting systems. Accordingly, the reliability of indices of effort and harvest developed from the available time series remain an open question. Rugolo et al. (1997), Van Engel (1999) and Fogarty and Miller (2004) all commented on the need for caution in interpreting both the catch and effort time series (see Section 5).

4.1. Virginia

Commercial fishing for blue crab in the Commonwealth of Virginia is regulated by the Virginia Marine Resources Commission (VMRC). There are a variety of gear types that can be legally used to harvest crabs within the Commonwealth, but crab pots, peeler pots and dredges predominate. Crab pots can be fished in both the mainstem of Chesapeake Bay and in the tributaries. No person may place, set or fish more than a combined total of 500 hard crab pots in Virginia tidal waters. Peeler pots are fished on a more seasonal basis, and can be "baited" with live adult crabs. Crab dredges were restricted historically to the mainstem of the bay during winter months. Since 2008, Virginia and the other jurisdictions in the Chesapeake Bay have implemented a management strategy aimed as conserving females. For Virginia, this policy led to a closure of the season for females from October 27 through November 30 and a closure of the winter dredge fishery since 2008. Together these two regulations were expected to reduce the female harvest by 23%. Virginia also extended the closure period of the blue crab spawning sanctuary in 2008, having it begin on May 1st rather than June 1st in order to protect female crabs that spawn in the spring (VMRC 2008).

Season and time restrictions have been enacted, and differ among the different fishery sectors. Minimum size limits have been set for male hard crabs, immature female hard crabs, and soft and peeler crabs. No size limits exist for adult female hard crabs. Dark sponge (brown through black coloration) crabs must be returned to the water alive. For a complete listing of regulations, see the VMRC website (http://www.mrc.state.va.us/regindex.htm).

A principal feature of blue crab management in Virginia has been the use of sanctuary areas in the lower Bay to protect females on the spawning grounds. The Virginia Blue Crab Spawning Sanctuary was established in 1941 and has expanded since that time, now covering 264,438 hectares from VA/MD border to the Bay mouth and out in ocean waters as far south as the NC border (R. O'Reilly, VMRC, pers. com. -- Lipcius and Stockhausen 2002, Lipcius et al. 2003). The sanctuary is closed to commercial harvest from 1 May to 15 September.

4.2. Maryland

The state of Maryland recognizes both commercial and recreational fishery sectors. Currently, in the commercial fishery Maryland prescribes seven legal methods for harvesting blue crab: scrapes, dipnets, trotlines, handlines, seines, bank traps and pots (http://www.dnr.state.md.us/fisheries/regulations/regindex.html). However, the fishery is dominated by the hard crab pot fishery, and the trotline fishery. There are numerous temporal and spatial regulations that limit when, where and how these gear types can be used. The hard crab pot fishery is seasonal as a result of both regulation and the life history of the crab. Like the pot fishery in Maryland, the trotline fishery is also seasonal. The trotline fishery is limited principally to the tributaries in Maryland, where pot fishing is banned. The number of pots or length of trotline is regulated by the commercial license that each waterman holds. The limited crab catcher license allows for the commercial use up to 50 crab pots. The tidal fishing license and crab harvester license permit waterman to employ up to 300 crab pots. Two additional authorizations, the CB6 and CB9, increase the number of pots allowed to 600 and 900 respectively. All commercial licenses allow for use of scrapes and unlimited trotline length. As noted in the description of the Virginia fisheries, Maryland implemented a strategy to conserve female spawning stock. This has involved mid and late season bans on the harvest of female hard crabs in Maryland waters and bushel limits, which correspond to season and license type.

4.3. Potomac River Fisheries Commission (PRFC)

Under the *Maryland and Virginia Potomac River Compact of 1958* (Compact), fisheries in the Potomac River are managed by the Potomac River Fisheries Commission which is charged with the establishment and maintenance of a program to conserve and improve the fisheries resources in the river. The PRFC has established regulations limiting the number of pots that can be used in both the hard crab and peeler pot fisheries. Various size limits have also been established. See the PRFC website for a full listing of regulations (http://www.prfc.state.va.us/index.htm). The Potomac River was historically closed to crabbing from 1 December to 31 March each year. However, as with other jurisdictions, the PRFC has implemented late season bans on female harvest.

We note that daily harvest and effort data are available from the Potomac River. The potential of these data to serve as a commercial CPUE time series in an assessment model have yet to be fully evaluated.

5. Fishery-dependent Data

An accurate determination of the levels of total removals by the fisheries are central to the reliability of any assessment (National Research Council 1998). Accordingly, fisheries agencies have invested heavily in trying to get accurate estimates of the level of total removals (Fabrizio and Richards 1996). Typically, the most common concern is that of misreporting of the landings or missing entire sections of the landings. However, when dealing with fisheries that have a long history, it is often common to find changes over time in the way that removals have been reported. Adjusting for such reporting changes, when present, is an important consideration in developing accurate time series of removals (Fogarty and Miller 2004). The reporting systems for commercial crab landings in both Maryland and Virginia have undergone changes since 1929. Indeed, an area of controversy in prior blue crab assessments has been how such reporting changes were taken into account (Rugolo et al. 1997, Miller and Houde 1999). Thus, it is critical that we assess fully and where necessary adjust for the effects of these reporting changes. The principal reporting changes for the blue crab fisheries in VA and MD are as described below.

5.1. Reporting Changes

5.1.1. Virginia.

Through consultation with staff at VMRC, we identified three time periods that differ in how removals were estimated:

1956 - 1973. National Marine Fisheries Service was responsible for collecting data. Data were recorded by region (Chesapeake and Landings by State). Estimates are based on dealer reports by month subsequently aggregated by year. Landings are available by gear.

1973 – 1992. VMRC instituted a more detailed dealer-based reporting based system. A large, but haphazard sample of principal dealers was included in the survey. VMRC agents “picked” the principal dealers involved in the fishery. Each dealer provided a monthly report of the crabs sold to him by commercial fishers. The reports identify the gear, and region within the Chesapeake producing the landings. The reporting system was reviewed and critiqued in 1984-1985 by a group from Pennsylvania State University. Their report highlighted a lack of uniformity in data collection procedures and high variability in reported monthly landings among dealers. However, these deficiencies are balanced by the observation that the top 20 dealers handled 76.5% of the hard-shell catch, and 95% of the soft-shell trade. Moreover, reported landings of key dealers appeared stable over time. However, concerns over the reporting system led Virginia to implement a mandatory reporting scheme in 1993. Knowledge of the impending change meant that some of the principal dealers failed to report their removals data in 1992, and so estimates for this year are considered unreliable.

1993 – present. A mandatory, fisher-based reporting scheme was instituted in 1993. Fishers report daily catch and daily effort on standardized forms. Data reported is consistent with the Atlantic Coastal Cooperative Statistics Program standards. Data is checked for quality control on a routine and consistent basis and compliance and oversight procedures are in place to ensure accurate reporting. VMRC staff believe that the data are consistent from 1994/1995 onward, and are particularly reliable from 1997 onwards. However, VMRC staff remain skeptical over reported landings in 1993.

5.1.2. Maryland

Three reporting periods can be recognized in the data maintained by the Maryland Department of Natural Resources (MD DNR)

1929 – 1980. Prior to 1981, the MD DNR employed a self-reporting system in which harvesters reported directly to the state. Data for the 1929-1980 period are available by month and by gear. Raw data are no longer available – all information is now held in computer files.

1981 – 1993. Concerns over the deficiencies in the self-reporting system lead to a change in reporting in 1981. From 1981 – 1993, MD DNR employed a statistical survey to estimate removals. Commercial harvesters were stratified according to gear, participation and effort. A sample of volunteer harvesters was selected each month to provide detailed removals information to MDNR. Total removals were subsequently estimated by expanding data to total number of crabbers within license strata. Expansion assumes that people with a given license type that did not report, fished at a similar level to those that did report with that same license type.

1994 – 2007. In 1994, MD DNR implemented a mandatory reporting scheme. This scheme collected information on the removals by month, license type, gear, area fished, effort and market category. Concerns over continuing misreporting were addressed by the continued use of the expansion program used to calculate total removals for the 1981-1993 period.

2008 - present. Due to management actions implemented in 2008, which based daily catch limits on harvest history, Maryland experienced significant and systemic over-reporting from the commercial fishery. This problem has continued through 2010. Instead of relying on catch reports, MDNR has been able to estimate commercial harvest using a combination of fishery dependent and fishery independent surveys. Catch per unit effort data from a sentinel fleet was applied to an estimate of effort (number of crab pots) generated by Versar (Slacum et al. 2010). Details of the reporting issues and harvest estimate calculations can be found in the 2009 CBSAC blue crab advisory report (Chesapeake Bay Stock Assessment Committee 2009).

5.1.3. Potomac River Fisheries Commission

There have been no changes to how the Potomac River Fisheries Commission records its data. Data are reported by individual watermen on a daily basis. Prior to 1964, landings from the Potomac River were allocated back to either Maryland or Virginia according to which portion of the river from which they were taken.

5.2. Analytical Approach to Adjusting Reporting Changes

As documented above, there have been significant changes to how landings are reported and estimated in both states, although not in the Potomac River. Fogarty and Miller (2004) applied time series analysis to assess the impact of the 1981 reporting change in Maryland. They used a time series model with both an intervention term and a transfer function to represent underlying changes in abundance as measured by fishery-independent surveys. These authors concluded that the 1981 reporting change in Maryland had a significant impact on the landings reported. Miller et al. (2005) used a similar approach involving both intervention and transfer functions. These authors identified significant reporting impacts in Maryland in 1981 and in Virginia in 1993. The finding of a significant reporting effect of the 1993 change in Virginia is controversial.

For this assessment, we again used time series analyses to quantify the impacts of reporting changes on estimates of landings in the commercial fisheries. However, importantly, we did not use a transfer function in these analyses. We chose to abandon the use of the transfer function because, to an extent, inclusion of the transfer function amounts to a stock assessment in its own right. Thus, we suggest that it is inappropriate to use landings time series that have been adjusted for both survey abundance estimates and reporting changes in a subsequent assessment model to estimate abundance. Such an application appears somewhat circular and likely biases results. Thus for this assessment, all time series approaches to correct for reporting changes in landings time series used only intervention terms in classical Box-Jenkins time series methodologies. The overall model can be written as

$$c_t = \Theta + \omega(B)I_t + \frac{\theta_i(B)}{\phi_i(B)} z_t \qquad \text{Eq. 2}$$

where c is the catch, Θ is a constant, B is the backshift operator, ω is an estimated parameter related to the impact of the intervention I which is a 0,1 variable whose value is 1 for years after the intervention and 0 in prior years, and θ and ϕ are polynomial parameters related to a moving average and autoregressive time series model that result from the model fitting so that the residuals from the model (z) are a pure white noise process. The approach to fitting was to first check the raw landings time series for stationarity. Where necessary the time series was differenced or otherwise filtered to achieve stationarity. The appropriate order of the moving average and autoregressive terms was then determined by using the auto.arima function in R (v.2.11.1), which uses the Akaike's Information Criterion (AIC) to determine the order for the two polynomial parameters that will give the best model fit and have residuals that do not significantly differ from a pure white noise process. The estimated regression parameters (ω, θ, φ) from the model fitting were sequentially tested to determine if the magnitude of the effect was significantly different from zero using a t-test. If the effect was significant it was included and the ARIMA model rerun. In the case that an intervention was found to be significantly different from zero, the portion of the time series that occurred prior to the intervention was adjusted based on the most recent period of the time series. This assumes that current management strategies for reporting in each state are the most accurate and therefore the landings from this period are the most reliable.

Assessment of stationarity and the intervention analyses were conducted in R v. 2.11.1.(Appendix II -- R Core Development Team 2007). Both Virginia and Maryland time series had to be 1st order differenced in order to achieve stationarity and significant interventions were found for both states. Details of the results of the reconstructed landings are presented in section 5.3.

5.3. Reconstructed Commercial Landings

We only reconstructed landings for Virginia and Maryland as these were the only jurisdictions that had reporting changes during the time series considered.

5.3.1. Virginia

Virginia commercial landings data were provided by Robert O'Reilly and Hershel Shackelford (VMRC, Newport News, VA). Raw monthly data, summarized by market category, gear type and water code were available for the period 1973 – 2009. Only annual totals were available for the period prior to 1973. The response variable in all analyses was the total annual landings of blue crab by weight (metric tonnes, MT) for the period considered (Table 5.1, Fig. 5.1).

The average annual commercial landings in Virginia over the period 1950-2009 was 16,394 ± 4,953MT (=36.14 x 10^6 Lbs). Virginia commercial blue crab landings varied from 7,791 MT (17.18 x 10^6 Lbs in 1958) to 29,374 MT (64.77 x 10^6 Lbs in 1966). Although, highly variable, there is no global trend evident in the time series (Fig 5.1). There is some indication of cycles in the time series of annual landings, with peaks in landings in 1950, 1966, 1984 and 1993. A rapid drop in landings, followed by an equally abrupt increase is apparent in 1992-93. When the first differenced (i.e., $L_{t+1} – L_t$) time series is examined, the landings anomalies for 1992-1993 become more evident (Fig. 5.2). As discussed above (see Section 5.1.1), VMRC has concerns regarding the validity of reported landings in these two years. However, similar abrupt changes are evident in the winter dredge survey time series (Fig. 3.17) and in the Maryland commercial landings reported below. Accordingly, we conducted all time series modeling with the raw data as reported rather than leaving out the 1993 estimate as had been done previously (Miller et al. 2005). Time series analyses indicated the presence of a significant reporting change intervention in 1993, which marked a switch from a dealer-based reporting system to a mandatory fisher-based reporting system (Table 5.2). The inclusion of the 1993 intervention suggests that under the dealer-based reporting system (pre-1993) landings were underestimated (Fig. 5.3). Neither polynomial parameter from the ARIMA model was found to be significant so they were excluded from the model.

The reconstructed time series is shown in Table 5.1 and Figure 5.3. The average of the reconstructed 1950-2009 landings was 25,757 ±9,155 MT. This represents a 57.11% increase from the unadjusted values. The lowest adjusted landing was 20,856 MT (1958), and the highest adjusted landing was 42,440 MT (1966). The average landings in the most recent five years (9,541 MT) indicates that landings are near a time series minimum. The period of decline apparent in the recent years in Figure 5.3 is of a similar magnitude to the declines that occurred in the 1950's.

5.3.2. Maryland

The raw landings time series for Maryland is provided in Table 5.1 and shown in Fig 5.4. The abrupt increase in reported landings that occurred in 1981 is clear in this figure. Landings prior to 1981 averaged 11,188 ±2,330 MT (~25x10^6 Lbs). In 1981, landings jumped substantially to 26,150 MT. After a period of relatively stable landings until the early 1990's landings have declined such that they are now equivalent to landings observed prior to 1981.

It is important to determine the contribution to the observed increase in landings throughout the 1980s and early 1990s of changes in underlying abundance during this period that are evident in the survey data (see Section 3.2.7) and of changes that reflect the contribution of the reporting change. In the 1997 assessment, Rugolo et al. (1997) assumed that all of the change was the result of changes in underlying abundance. In their assessment, Miller and Houde (1999) assumed the contrary, that all of the change resulted from the reporting change. Fogarty and Miller (2004) concluded that both a change in underlying in abundance and the reporting change contributed to the change in abundance.

When Fogarty and Miller (2004) analyzed the Maryland commercial landings data they initially determined that the data for the period 1929 – 1980 were stationary and that the 1981-1994 data were similarly stationary. Since their analysis, data from subsequent years have been added to the time series. These new data have caused the recent time series to become non-stationary. Stationarity is a principal assumption of time series analysis and a breach of this assumption has serious consequences. For example, if we fit an intervention model to a decaying time series, the intervention term will be significant because of the pattern of decay, not because of some underlying shift. Accordingly, the analysis was conducted on a differenced time series (Fig. 5.5). Differencing removed the impact of the recent decline in landings. However, differencing still allows the potential impact of the 1981 and 1993 reporting changes to be examined. For example, first differenced estimates for these two years are both > 10, whereas the remainder of the data fall between $-7.5 < d < 7$ (Fig. 5.5).

We tested both the 1980-1981 and the 1993-1994 reporting changes to determine if either had a significant effect on the reported landings. We did not attempt to adjust for the 2008 reporting change given how recently it occurred. Only the 1981 intervention was found to be significant ($p<0.05$; Table 5.3). The adjusted time series suggested that landings were underreported during the years of self-reporting, which occurred prior to 1981. A moving average polynomial parameter was included in the model as the parameter was significantly different from zero (Table 5.3).

We used the estimated intervention term parameter to reconstruct the Maryland commercial landings. The reconstructed Maryland landings are shown in Table 5.1 and in Figure 5.6. The mean of the adjusted annual 1950 –2009 landings time series was 20,444 ± 5,017 MT. This represents a 45.72% increase in the estimated average annual landings with the landings of years prior to 1981 increasing 110.94% on average. The lowest adjusted landing was 9,180 MT (2000), and the highest adjusted landing was 27,610 MT (1965). The landings over the last decade have remained fairly stable at an average of about 12,000 MT, indicating a cause for concern because this represents an extended period of time series lows when compared to the rest of the adjusted time series.

5.3.3. Baywide

We present the combined, adjusted baywide landings for 1950-2009 in Table 5.1 and Figure 5.7. The average baywide annual landings for this period was 47,523 ± 13,304 MT. The reconstructed landings indicate that removals have been 49.7% higher over the period 1950-2009 than previously reported. The highest recorded baywide harvest was 70,574 MT (155.6 Million Lbs) in 1966. The lowest recorded baywide harvest was 20,207 MT (44.5 Million Lbs) that occurred in 2007.

5.4. Estimates of Fishing Exploitation and Mortality

Estimates of exploitation can be generated based on the estimated number of crabs available at the beginning of the season and the total catch during the season.

5.4.1. Sex-specific Catch

The availability of sex-specific landings varies between Maryland, Virginia, and PRFC, with Maryland being the earliest to report landings by sex beginning in 1985. By 1994, landings by sex were being collected baywide. However, each of the three jurisdictions have categories of unclassified, or mixed, crabs and soft/peeler crabs for which reports are not broken down by sex. Thus, the composition of the landings for these sectors had to be estimated. We used the state-specific sex ratio averaged from 1994-2006 in order to obtain sex-specific landings in all market categories, including soft and peeler (Table 5.4). The three most recent years (2007-2009) were excluded from the sex ratio calculation in order to eliminate any male bias in the landings ratio due to regulations put in place to increase conservation of female blue crabs. These sex ratios were then applied to those landings not-reported on a sex-specific basis. The final sex-specific landings by the three jurisdictions are provided in Table 5.5.

5.4.2. Estimating Bay wide Catch in Numbers

Commercial harvest of hard crabs is generally reported to the Maryland Department of Natural Resources (MD DNR), Virginia Marine Resources Commission (VMRC) and the Potomac River Fisheries Commission (PRFC) in bushels. The harvest of peelers and soft crabs is reported in numbers. The three jurisdictions convert reported bushels of hard crabs into pounds using a standard conversion of 40 pounds per bushel. Although it has been shown that the 40- pound conversion for bushels to pounds of hard crabs is reasonably accurate (Stagg and Knotts 1991, Sharov and Volstad 2002), the average weight of individual crabs within a 40 pound bushel varies by year, sex and region.

Thus for the last few years, the CBSAC has taken a different approach to estimating the catch in numbers. The first step is to estimate the average carapace width of crabs in the population. This is done on an annual- and sex-specific basis using the Maryland and Virginia fishery independent trawl surveys (Fig. 5. 6). These estimates are assumed to represent the mean size of crabs available to the fishery (Davis et al. 2001, Bonzek and Latour 2003). This mean size is then used to estimate the average weight for individual crabs using regression equations developed from Maryland trawl data pooled over years 1994 to 2004.

Males: $W = 21.45 - CW*0.927 + CW^2*0.014$ ($df=16{,}372$, $p<0.0001$, $r^2=0.94$) Eq. 3
Females: $W = 2.59 - CW*0.247 + CW^2*0.008$ ($df=10{,}382$, $p<0.0001$, $r^2=0.95$)

Average individual weight by sex was determined separately for Maryland, and Virginia for each year from 1994 through 2009 using the conversions above and then averaged by state (Table 5.6). Since PRFC has no fishery independent survey individual weights from Maryland are used for this region. The resulting individual weight estimates were then used to convert landings reported in pounds to landings reported by individuals by sex.

To determine the number of individuals by sex, we again had to account for those market categories that are not reported on a sex specific basis. In Maryland, all mixed crabs are assumed to be best represented by the mean weight of females, even though the sex ratio is thought to be the same as that for hard because less marketable males are generally smaller individuals and are therefore more likely to weigh about the same as a female crab. In Virginia and PRFC, the weights by sex are used for the mixed category of crabs. The number of individual hard crabs harvested for each jurisdiction were summed and added to the number of peeler/soft crabs harvested to estimate the total number of crabs harvested from the Bay. The percentage of the baywide harvest that is soft and peeler has generally been less than 10% by number of the total harvest. The harvest of soft and peeler crabs is not reported separately for males and females, so we assumed the same sex ratio in the soft and peeler fishery as reported in the hard crab fishery. Ongoing fishery dependent monitoring by MD DNR supports this assumption.

Table 5.7 presents estimate of the sex-specific numbers of crabs caught in all commercial fisheries in the Chesapeake Bay from 1994-2009.

The recreational harvest has been estimated to be 5.3 to 8.5% of the total harvest based on surveys of recreational crabbers conducted in 2001 and 2002 (Ashford and Jones 2001, 2002). More recently, empirical estimates of recreational harvest have become available from long-term tagging studies of adult blue crabs in Maryland (Johnson et al. unpublished data). These studies suggest that earlier estimates recreational harvest (Ashford and Jones 2001, 2002) may underestimate current recreational harvest, and that recreational harvest varies substantially among subestuaries (<1 to 60% of the total recaptures). However, accurately scaling these regional estimates to calculate Baywide recreational catch is problematic. Further, the magnitude and sex-specific composition of the recreational catch is not known and likely varies substantially between MD and VA due to biological factors, unequal recreational effort and differences in regulations between jurisdictions. We have not made any attempt to adjust the reported estimates of Bay wide catch presented in Tables 5.1, 5.5, or 5.7 to include recreational harvest However, we do subsequently use an estimate of recreational landing as being an additional 8% of commercial landings in all subsequent analyses.

We estimated the fraction of the total numerical catch that was female. These data are plotted in Fig. 5.7. Over the entire sex-specific time series available (1994-2009), the harvest of crabs taken from the Chesapeake Bay was 62.8% female. Only in the last two years does this appear to have changed. The percentage of the harvest that was female in 2008 and 2009 dropped by about 10%, such that the average for these two years is 53.1%. It is likely that this change reflects the impact of management measures implemented to conserve female spawning stock since 2008.

5.4.3. Estimating abundance

The abundance of over wintering blue crabs in the Chesapeake Bay was estimated from the winter dredge survey (see Section 3.2.4 and Sharov et al. 2003). It is assumed that the estimated mean density of blue crabs in any year is representative of the entire distribution area for blue crabs in Chesapeake Bay. Absolute abundance is estimated by expanding crab density for every year to the total bay area, estimated at 9,814 km^2 by GIS. It should be noted that the dredge survey does not sample waters less than 1.5 m depth, which account for approximately 10% of the total bay area. These shoal waters were sampled with a limited number of stations in 1992 and 1993 using a small, modified dredge. Density estimates derived from these shallow water sites were not significantly different than those derived for the area deeper than 1.5 (Rothschild et al. 1992).

Our goal in these analyses was to provide an estimate of blue crab abundance at the beginning of the fishing year, nominally April 1. Accordingly, we did correct the estimates of total abundance by empirical, annual estimates of winter mortality that are estimated directly from the winter dredge survey by resampling sites of high crab abundance later in the season to estimate the fraction of those crabs caught early in the winter that had died. The time series of total crab abundance, both corrected and uncorrected for winter mortality is presented in Figure 5.8.

5.4.4. Estimating Exploitation Fractions

Using estimates of total abundance developed above from the winter dredge survey (1990-2009 – section 5.4.3 above) and estimates of Bay-wide catch in numbers (section 5.4.2 above), the annual exploitation fraction for the Chesapeake Bay blue crab fishery can be calculated as:

$$U_t = \frac{C_t}{N_t} \qquad \text{Eq. 4}$$

where C_t is the total annual catch in numbers and N_t is total population size at the beginning of the fishing year (Sharov et al. 2003). This exploitation fraction is calculated for the entire population, since we assume that all crabs sampled during the winter (N_t) will become vulnerable to the fishery at some point during the subsequent fishing season, i.e. we are assuming that the partial recruitment for age-0 crabs in the winter dredge survey is 1. It also implicitly assumes that the winter dredge survey provides an absolute estimate of abundance for age-0 and age-1+ crabs – that is there is no substantial fraction of crabs that are not vulnerable to the gear. We note that we did increase reported catches used in these calculations by 8% to adjust for recreational harvests.

Based on these calculations, we developed a time series of empirical estimates of exploitation fraction that have operated in the blue crab fishery in Chesapeake Bay (Fig. 5.9). Inspection of this time series indicates that estimated exploitation fractions increased from approximately U=0.4 at the beginning of the time series, to a peak of U=0.78 in 1999. Thereafter, exploitation fractions generally decline until the 2009 when the estimated exploitation fraction was U=0.44, approximately that at the beginning of the time series.

5.4.5. Sex-specific Exploitation Fractions

The blue crab fishery is unique in that male and female crabs are marketed separately. Thus there is a potential that exploitation patterns between the two sexes may differ. To explore this potential, we calculated sex-specific exploitation rates for each sex. We used the same approach as adopted for aggregate landings given above (Section 5.4.4), except that we used estimates of sex-specific catch, and sex-specific abundances to estimate the exploitation fraction.

The pattern in exploitation rates in both sexes during the period 1994 – 2009 was broadly similar (Fig. 5. 10). Exploitation rates for both species were at a low in 1996 and increased until 2001. Prior to 2007 the exploitation rate on females was substantially higher than that for males (Fig. 5.10). The average exploitation rate on females for the period 1994-2007 was 0.67, whereas that for males for the same period was 0.46. However, after 2007, the exploitation on females declined to approximately 35-40% as result of management actions designed to specifically conserve spawning females. In contrast, and at the same time, the exploitation fractions for males increased to approximately 55-60%, such that for 2008-2009, the exploitation rate on males was higher than those for females for the first and only time in the time series.

5.4.6 Depensatory analysis

Conservation of exploited species requires an intimate understanding of the relationships between levels of exploitation (e.g. exploitation rate [*u*]) and population size (*N*). Whether or not exploited marine species will recover from overexploitation or persist in the face of heavy exploitation depends not only on the intensity of exploitation but also on the functional relationship between *u* and *N*. In this component of the assessment, we present empirical evidence that *u* for the blue crab fisheries varies inversely with *N*, and therefore that exploitation rate is depensatory, which increases the likelihood of collapse at low population abundance.

We present a more detailed analysis in Assessment Working Paper 2, and only summarize results here. Temporal patterns in *N* and *u* over time were approximately mirror images of each other (Figure 5.11A), and the relationship between *u* and *N* declined exponentially (Figure 5.11B), suggesting depensatory exploitation. To assess statistically whether or not exploitation was occurring, we analyzed the relationship between *C* and *N* (Figure 5.11C). A linear function fit the relationship well (r^2 = 0.83), with randomly distributed residuals about the regression line. More importantly, the *y*-intercept was significantly greater than 0 (β_0 = 86.23, SE = 14.49), indicating that exploitation rate was depensatory. Given that we would theoretically expect *C* to approach 0 as *N* approaches 0, we also fit a hyperbolic function to the data using nonlinear least squares regression (Figure 5.11C). As with the linear regression, the hyperbolic function fit the data well (r^2 = 0.82), again with randomly distributed residuals about the regression. This function corroborated the results from the linear regression indicating that exploitation is depensatory.

To define the relationship between *u* and *N*, we generated predicted values of *u* from the linear function (Figure 5.11C): $C = \beta_0 + \beta_1 N$, and from the hyperbolic function without a *y*-intercept (Figure 5.11C): $C = \beta_1(1 - e^{-\beta_2 N})$. In both cases, the relationship between predicted *u* and *N* was depensatory, with predicted *u* ranging from about 0.37 at high population abundance (*N* = 850 million crabs) to over 0.60 as population abundance decreased to the lowest level at N = 250 million crabs. Consequently, precautionary and adaptive management measures will be required when the blue crab population is at low abundance to prevent population collapse.

6. Reference Points and Assessment Models

6.1. Previous Reference Points

In all previous assessments reference points were estimated independently of the analyses used to assess population abundance and exploitation. We summarize the approaches below.

6.1.1. BBCAC Reference Points

The BBCAC TSC recommended overfished and overfishing definitions and a target exploitation rate (Miller 2001b). The overfished definition was based on the average abundance of age-1+ crabs in the four principal fishery-independent surveys (see Section 3.2). Survey Z-scores from each survey were averaged to yield a single abundance measure for age-1+ crabs. The threshold reference point was chosen as the lowest survey Z-score in the time series – the 1968 abundance. This recommendation was based on purely empirical reasoning that abundances lower than this level could not be shown to have supported a sustainable fishery. Both exploitation rate reference points were developed from a traditional Beverton-Holt yield per recruit analysis. The overfishing definition was selected as the exploitation rate that maintained 10% of the spawning potential ($F_{10\%}$) and the target as that level that maintained 20% of the spawning potential ($F_{20\%}$). These reference points were used for management from 2001- 2006.

6.1.2. Individual-based Per Recruit Reference Points

New reference points were adopted for management of the blue crab population in Chesapeake Bay based on analyses carried out for the 2005 assessment (Bunnell and Miller 2005). As with the BBCAC reference points, these newer reference points were estimated independently of the analyses to assess stock status. The adopted approach used an individual-based simulation model to track the yield of a hypothetical cohort of 300 million crabs over three years. During the simulation crabs grew according to a temperature-dependent molt-process model (Brylawski and Miller 2006). Reproduction was estimated using published estimates of maturity (Sharov et al. 2003), fecundity (Prager et al. 1990) and brood production (Hines et al. 2003). Crabs died in the model due to either natural mortality or fishing. The model was used to forecast spawning potential per recruit isoclines as a function of natural mortality and fishing mortality. In a change from the BBCAC reference points, exploitation was represented as an exploitation fraction (i.e. catch / initial abundance) rather than as the instantaneous rate. However, Bunnell and Miller still recommended use of the 10% and 20% SPR levels as reference points.

These reference points have been the foundation for management decisions since 2006.

6.1.3. CBSAC Interim Target

Stakeholders and managers began expressing concerns over the exploitation-based management strategy soon after the 2005 assessment. Managers increasingly relied on the abundance estimate from the winter dredge survey as the primary indicator of stock status. Thus, managers were concerned that focusing on an exploitation rate strategy removed attention from the efforts to sustain the crab population at desirable levels of abundance. Accordingly, CBSAC recommended an interim abundance target of 200 million age-1+ crabs baywide. This figure was based on analyses of the relationship between winter dredge-based estimates of abundance and harvest, and abundance and recruitment (Chesapeake Bay Stock Assessment Committee 2008). Thus from 2008 onwards, the management control rule involved an empirical overfished definition, spawning potential per recruit exploitation fraction limits and targets and an interim abundance target.

The current control rule for the Chesapeake Bay blue crab fishery is depicted in Figure 6.1. Shown on this figure are the four key management reference points

Limits
    Overfishing definition: exploitation rate, U=0.53
    Overfished definition: 86 million age 1+ crabs
Targets
    Exploitation target: Exploitation rate, U=0.46
    Interim abundance target: 200 million age-1+ crabs

Estimation of the status of the crab population and its fisheries in each year rely on reported catches in the fishing year together with empirical estimates from the winter dredge survey in the preceding winter (Sections 5.4.3 – 5.4.4). Data presented in Figure 6.1 indicate that the blue crab population was above the interim abundance target, and the fishery was operating below the target exploitation rate in 1990, the first year in which data from the winter dredge survey were available. Exploitation rates increased and abundances declined, such that by 1995 the crab population was below the interim abundance target and the fishery was operating above the overfishing definition. This situation continued and in fact worsened for the next five years, such that by 1999, the fishery was removing almost 80% of the available crabs. Subsequent management actions effectively reduced exploitation fractions, but failed to lead to significant increases in population abundance. For example in 2008, the exploitation fraction (U=0.49) had declined to below the overfishing threshold. This represented a 37% decline in exploitation rates from its 1999 peak. However, the population abundance in 2008 had only increased by 48% and was still substantially below the interim target. Subsequently, the effect of the female conservation measures on abundance have been substantial. Exploitation rates have changed on only modestly (U_{2009}=0.44), but abundances in 2009 almost doubled from their 2008 values (N_{2009}=235.1 million).

Although the current reference points and approach to management appear to be working, in making its 2008 recommendation, CBSAC noted that the interim target was not fully integrated in the existing reference point framework. Specifically it was noted that it was possible that attaining the exploitation rate target of $U_{20\%}$ and the interim abundance target of 200 million crabs may be mutually exclusive. Thus CBSAC recommended that a principal goal of any subsequent assessment was to bring forward new reference points from an integrated analysis that simultaneously estimates reference points and stock status.

6.2. Sex-specific catch, multiple survey model

To address management needs for integrated determination of reference points and stock status, we undertook a sex-specific catch multiple survey analysis (SSCMSA) for assessing blue crabs in Chesapeake Bay. The model has two significant differences to the catch-multiple survey analysis (CMSA) conducted for the 2005 assessment (Miller et al. 2005). Most importantly, the model includes an internal renewal function through which the number of recruits in year t+1 are generated from the abundance of adults in year t. The earlier CMSA did not include a renewal function and it was thus impossible to use this model to generate management reference points. In contrast, the inclusion of the renewal function in the SSCMA allows both spawner per recruit and MSY-based reference points to be estimated. The details of the implementation of the renewal function are provided below. Second, and of importance to this particular application, the model tracks the dynamics of males and females separately. This allows us to specifically represent the impacts of the new management approach to conserve the female spawning stock. Thus the model estimates abundances and exploitation rates for males and females separately. As in the CMSA, the new SSCMSA represents the population as being comprised of two stages- pre-recruit age-0 crabs, and fully recruited age-1+ crabs. Thus, the model tracks the dynamics, susceptibility to the fishery and catches of four stages of blue crab: age-0 males, age-0 females, age-1+ males and age-1+ females (Fig. 6.2).

As with the CMSA approach, the SSCMSA developed here uses a population dynamic model to project the population forward in time and a separate observation error model to estimate survey indices. Finally, the model used a penalized maximum likelihood approach to maximize the fit between observed and predicted indices of abundance from three surveys, total catch for 1968-1993, and sex-specific catch for 1994-2009. Table 6.1 provides definitions of all variables used in the model. The model was implemented in ADMB. The full model code is provided in Appendix III. A sample data input file is provided in Appendix IV.

6.2.1. Population Dynamics Model

We used a sex-specific version of the Ricker stock-recruitment model as a renewal function to estimate age-0 abundance in the beginning of each year. To reflect expert knowledge regarding the nature of density dependence in blue crabs, productivity at low abundance was a function of female abundance, while density dependence was a function of male and female abundance,

$$R_{y+1,s} = x_s \alpha SP_{y,f} e^{-\beta\left(SP_{y,f}+SP_{y,m}\right)} e^{\delta_y} \qquad \text{Eq. 5}$$

Each parameter in equation Eq. 5 and subsequent equations are defined in Table 6.1. Compensatory mortality of age-0 blue crabs is likely driven by cannibalism from ages 1+, which makes the Ricker model particularly apt for this stock. The model also included a lognormal process error, $\delta_y \sim N(0,\sigma_R^2)$. WE note that the form of the Ricker stock recruitment model used in this assessment is nontraditional. However, we argue strongly that this formulation provides several benefits over the more common form that pools males and females. In particular, when abundance of mature females is zero, there will be zero recruitment, but male abundance is still included in the compensation term. If we had used a traditional model that combined both sexes, it would make the nonsensical prediction of positive recruitment with zero females if male abundance was non-zero. However, care should be exercised when considering the results of this model because it does not contain a term for sperm limitation, which will cause the model to overestimate production at very low abundance of adult males. Thus, we do not recommend extrapolating the stock-recruitment model beyond the range of the observed sex ratio during the period included in the assessment.

Abundance in the age-1+ category was estimated as the sum of age-0 recruits and age-1+ adults that survived from the year before,

$$N_{y+1,s} = N_{y,s} e^{-(M+F_{y,s})} + R_{y,s} e^{-(M+\eta F_{y,s})} \qquad \text{Eq. 6}$$

Natural mortality was assumed to be the same for age-0 and age-1+, but we also conducted sensitivity runs which evaluated sex-specific natural mortality rates in a sensitivity analysis. We used M=0.9 as our assumed natural mortality based on the previous stock assessment (Miller et al. 2005, Hewitt et al. 2007). We also conducted sensitivity analyses in which M varied over the credible range of values 0.6 < M < 1.2.

The instantaneous fishing mortality rate was estimated for each year and sex. The partial recruitment was specified outside of model fitting, but was the same for males and females. Based on discussions with scientists and managers, we decided that 0.3-0.9 represented a plausible range for partial recruitment because of growth dynamics. About 90% of age-0 blue crabs in the beginning of the year grow large enough to enter the fishery during that year. A partial recruitment of 0.3 was considered a lower bound based on the amount of time age-0 crabs are vulnerable to the softshell/peeler fishery and the proportion of the catch from later months when most crabs that were age-0 in the beginning of the year have grown into the fishery. To initiate the model, we estimated the combined for age-0 and combined for age-1+. These estimates were divided by 2 to yield the initial abundance estimates for the four modeled stages. We adopted this approach because we had no a priori reason to expect a deviation from a 1:1 sex ratio initially.

The number of spawners was calculated by decrementing the number of age-1+ at the beginning of the year by mortality that occurred before spawning,

$$SP_{y,s} = N_{y,s} e^{-\kappa(M+F_{y,s})} \qquad \text{Eq. 7}$$

We note that this formulation assumes that the patterns of natural and fishing mortality are similar throughout the fishing year. Specifically, this approach to accounting for mortality prior to spawning assumes that the same proportion of M and F occurred during this period. The proportion of mortality that occurred before spawning was chosen to be 0.37 because we assumed a spawning date of July 1, and because empirical data indicate that 37% of the pot effort in Maryland has occurred by July 1 on average.

We modeled catch using a sex-specific Baranov catch equation with partial recruitment for age-0,

$$C_{y,s} = \frac{F_{y,s}}{F_{y,s}+M}\left(1-e^{-(M+F_{y,s})}\right)N_{y,s} + \frac{\eta F_{y,s}}{\eta F_{y,s}+M}\left(1-e^{-(M+\eta F_{y,s})}\right)R_{y,s} \qquad \text{Eq. 84}$$

The exploitation rate of fully selected blue crabs was calculated as the product of the annual mortality rate and the proportion of total mortality due to fishing,

$$u_{y,s} = \frac{F_{y,s}}{F_{y,s}+M}\left(1-e^{-(M+F_{y,s})}\right) \qquad \text{Eq. 9.}$$

6.2.2. Observation Model

The winter dredge survey and the VIMS spring trawl survey are treated as beginning of the year surveys,

$$\hat{I}_{R,y,s} = q_i R_{y,s} \qquad \text{Eq. 10}$$
$$\hat{I}_{N,y,s} = q_i N_{y,s}$$

where the surveys are assumed to have constant catchability over time. For the Maryland trawl survey, we treated the survey as occurring in the middle of the year, such that prerecruits from the beginning of the year were recruited to the Age-1+ category by the time of the survey,

$$\hat{I}_{N,y,s} = q_i\left(N_{y,s}e^{-\tau(M+F_{y,s})} + R_{y,s}e^{-\tau(M+\eta F_{y,s})}\right) \qquad \text{Eq. 11}$$

We assumed that 67% of the total mortality (F+M) had occurred by the time of the Maryland trawl survey based on a September 1 date for the trawl survey and the cumulative amount of crab pot effort in Maryland before September 1 (Fig. 6.3). The approach for including the timing of the Maryland trawl survey implicitly assumes that M and F follow the same distribution throughout the year. The age-0 portion of the Maryland trawl survey indexes recruitment at the beginning of the next year. We assumed that the winter dredge survey provided an absolute estimate of abundance (i.e., q=1) for age-1+ blue crabs. For all other survey indices of abundance, catchability was estimated using the MLE approach by calculating the average difference (on the log scale) between the observed index of abundance and predicted abundance (Miller et al. 2005),

$$\log_e q_i = \frac{\sum_y \log_e I_{R,y} - \log_e R_y}{k_i}$$

for recruits, and Eq. 12

$$\log_e q_i = \frac{\sum_y \log_e I_{N,y,s} - \log_e N_{y,s}}{k_i}$$

for ages 1+. Catchability was sex-specific for the age-1+ stage, but was combined for sexes for age-0.

6.2.3. Likelihood and Penalty Functions

We estimated the parameters by minimizing the objective function, which was the sum of the likelihood components for each data source and the penalties for recruitment deviations and deviations from the mean 1994-2006 ratio of male to female fishing mortality, using AD Model Builder (admb-project.org). We assumed lognormal observation errors for indices of abundance from the two trawl surveys and for catch,

$$L_i = k_i \log_e(\sigma_i) + \frac{1}{2\sigma_i^2}\sum_{y \in i}\left(\log_e E_{i,y} - \log_e O_{i,y}\right)^2 \qquad \text{Eq. 13}$$

where E and O are estimated and observed values of the indices of abundance. The variances were assumed for each data source, and constants were ignored to simplify the equations. We assumed that the recreational crab catch, which is not reported, represented 8% of the total commercial catch and was proportionally constant over time. For the winter dredge survey, we assumed normally distributed errors with a constant coefficient of variation (CV) because of the large sample sizes in the survey,

$$L_i = \sum_{y \in i}\log_e(E_{i,y}CV_i) + \frac{1}{2\left(E_{i,y}CV_i\right)^2}\sum_{y \in i}\left(E_{i,y} - O_{i,y}\right)^2 \qquad \text{Eq. 14}$$

The log-scale standard deviations of catch were specified at 0.1 to indicate that catch was relatively accurate. The CVs of the winter dredge survey were estimated from design-based estimators. The average CV for age-1+ males and females was approximately 10%, so we assumed a 10% CV for the winter dredge survey. The log-scale SDs of the trawl survey were iteratively tuned until the input value was approximately equal to the post-hoc value (McAllister and Ianelli 1997). Recruitment deviations followed a lognormal distribution,

$$L_R = k_R \log_e(\sigma_R) + \frac{1}{2\sigma_R^2}\sum_y \delta_y^2 \qquad \text{Eq. 15}$$

The recruitment log-scale standard deviation was estimated during model fitting.

A penalty on the relative fishing mortality between males and females was imposed on years before sex-specific catch data were available to constrain the model from having large interannual differences in the relative fishing mortality rates,

$$L_F = k_F \log_e(\sigma_F) + \frac{1}{2\sigma_F^2}\sum_y\left(\frac{F_{y,m}}{F_{y,f}} - \mu\right)^2 \qquad \text{Eq. 16}$$

The mean and variance for the ratio of male to female fishing mortality were calculated using years during which sex-specific catch data were available, but before sex-specific management measures were imposed, 1994-2006.

6.2.4. Reference Point Calculations

We calculated maximum sustainable yield (MSY) based reference points by adapting the methods of Shepherd (1982) for a sex-specific stock-recruitment model. Spawners per recruit (SPR) was calculated as the product of equilibrium age-1+ abundance and survival until spawning,

$$SPR_s = \frac{x_s e^{-\left((1+\kappa)M + \eta F_s + \kappa F_s\right)}}{1 - e^{-(M+F_s)}} \qquad \text{Eq. 17}$$

Yield per recruit (YPR) was calculated by applying the Baranov catch equation to equilibrium abundance per recruit of age-1+ and age-0,

$$N_{YPR,s} = \frac{x_s e^{-(M+\eta F_s)}}{1 - e^{-(M+F_s)}} \qquad \text{Eq. 18}$$

and

$$YPR_s = \frac{F_s}{M+F_s}\left(1 - e^{-(M+F_s)}\right) N_{YPR,s} + \frac{\eta F_s}{M+\eta F_s}\left(1 - e^{-(M+\eta F_s)}\right) x_s \qquad \text{Eq. 19}$$

Equilibrium abundance of age-1+ was calculated by rearranging the Ricker stock-recruitment function and applying the SPR for each sex,

$$N_{eq,s} = \frac{\log_e SPR_f + \log_e \alpha + \sigma_R / 2}{\beta} \times \frac{SPR_s}{SPR_f + SPR_m} \qquad \text{Eq. 20}$$

Equilibrium recruitment was the quotient of sex-specific equilibrium abundance of age-1+ and SPR,

$$R_{eq} = \frac{N_{eq,s}}{SPR_s} \qquad \text{Eq. 21}$$

Equilibrium catch was the product of equilibrium recruitment and YPR,

$$C_{eq,s} = R_{eq,s} YPR_s \qquad \text{Eq. 22}$$

and total equilibrium catch was the sum of equilibrium catch across sexes,

$$C_{eq} = \sum_{s} R_{eq,s} YPR_{s} \qquad \text{Eq. 23}$$

6.2.5. Base Model Run

Following considerable exploration of the response of the model to differing parameterizations, we selected as a base run a model parameterized with a natural mortality rate, M=0.9, a partial recruitment probability for age-0 crabs, η =0.6, and a sex-ratio at recruitment of 52% female. The estimate of M was equivalent to that used in the Miller et al. (2005) assessment. The estimate of the sex-ratio at recruitment was based on empirical evidence from the winter-dredge survey. The values of partial recruitment were based on expert judgment by members of the assessment team. The sensitivity of the model to these assumptions was explored in separate sensitivity runs.

Model output for the base run is provided in Appendix V. Results from the base model run indicate that the model was able to replicate time series of total catch quite accurately (Fig. 6.4). However, although the model replicated the trend in sex-specific catches, we note biases in predictions of female catch (under-estimated in the model) and male catch (over-estimated in the model). However, attempts to correct for this bias in sensitivity runs required either a sex ratio at recruitment (64% female) not supported by empirical evidence, or sex-specific Ms with a substantially higher male natural mortality rates.

The base run model was also able to replicate trends in the time series of each of the three surveys (Figs. 6.5-6.7). Several features to these fits are noteworthy. Fits to the age-1+ indices for both males and females are generally better than the fits to the recruitment time series. This suggests that neither of the trawl surveys provides a reliable index of recruitment. This is reinforced by a phase plot of the observed and predicted levels of recruitment for each survey (Fig. 6.8). It is apparent from this figure that both the VIMS trawl survey and the Maryland trawl survey provide little information to the model regarding interannual variation in recruitment. The performance of the winter dredge survey is considerably better than either of the state surveys.

Sex-specific abundance trends for age-1+ plus crabs are generally similar throughout the time series until the very most recent years (Fig. 6.9). In 2008-2010 the model results do indicate a substantial increase in female and male abundance in the population. We note two important features of the increases in age-1+ crab abundance predicted in the model. First, model predictions for the winter dredge survey are not able to fully match the observed increase in female age-1+ abundance evident in the survey data (Fig. 6.7). Indeed, there were none of parameter sets that we explored that were able to match the observed increase. Second, the model predicted increases in male abundances that are not observed in the survey data. Currently, it is not clear whether the mechanisms responsible for the mismatch between observation and prediction for the abundance of age-1+ crabs are the same as those that underlie the mismatch in sex-specific reported and predicted catches. We suggest that effort should be invested in future to understanding the mechanisms behind these discrepancies.

The ratio of sex-specific exploitation rates calculated in the model is of interest. The model predicts that from 1968-2007 the ratio of sex-specific exploitation rates appears to vary around a ratio of approximately 1 (Fig. 6.10). However, the ratio of sex-specific exploitation rates appears to have shifted to a ratio indicating high male exploitation rates after 2004. There is empirical evidence from estimated exploitation fractions of a shift to higher male exploitation rates (Fig. 5.10). In the empirical data, female exploitation had been substantially higher than that for males from 1994-2004. From 2005, empirical estimates of exploitation rates in each sex were similar, and male exploitation rates became greater than female exploitation rates in 2008-2010. Although the empirical estimates of sex-specific exploitation rates strongly support the impact of recent management actions to conserve females on the population, the overall trends in the empirical and model predictions suggest that there was a broader pattern favoring an increase in male exploitations after 2004. It will be important to continue monitoring the ratio of sex-specific exploitation fractions in the population.

The SSCMSA was able to estimate credible MSY-based reference points. Figure 6.11 shows maximum sustainable yield estimates as a function of the exploitation rate on age-1+ females. Two features of this figure are notable. The first is that the model predicts a limit to sustainability is achieved at an exploitation rate of age-1+ females of U=0.58. This value is invariant to the ratio of sex-specific exploitation rates in the population over the range $0.6<F_{male}:F_{female}<2.2$. The second notable feature is the maximum sustainable yield in the population is achieved at an exploitation rate on age-1+ females of U = 0.44 over the range $0.6<F_{male}:F_{female}<2.2$. This estimate is slightly affected by the sex-specific ratio of exploitation rates. Although this approach is a potentially viable foundation for determination of reference points, operationalizing such a reference point would be difficult currently because age-1+ crabs are not reported separately in the catch. Accordingly, we revised the foundation for reference point determination to one based on the exploitation age-0+ female crabs.

The SSCMSA was able to estimate credible MSY-based reference points based on the exploitation rate on age-0+ female crabs (Fig. 6.12). The SSCMSA estimates a limit to sustainability when 46% of all age-0+ crabs are harvested annually. This limit reference point is independent of the sex-specific ratio of exploitation active in the population. We note that this figure is substantially lower than that estimated above for age-1+ females. Two features of the population dynamics are responsible for this change. First, the SSCMSA estimates that the winter dredge survey does not provide an absolute estimate of the abundance of age-0 crabs. Indeed the SSCMSA estimates that the catchability coefficient of age-0 crabs in the winter dredge survey is q_0=0.4. We note that this estimate is not directly related to the empirical catchability coefficient estimated annual in the depletion studies conducted as a part of the winter dredge survey (Sharov et al. 2003). Instead the estimate of q_0=0.4 indicates that only 40% of the age-0 cohort of crabs is vulnerable to the survey. More specifically, the SSCMSA indicates that the density of age-0 crabs estimated in the winter dredge survey must be expanded by a factor of N/0.4 to provide an index of total cohort abundance. Further, existing approaches to estimating the exploitation rate in the fishery assumed that all of the crabs sampled as age-0 in the population during the winter months become vulnerable to the fishery during the next year. In contrast, the SSCMSA used an estimate of this partial recruitment as η=0.6. Thus the model estimates the exploitation fraction of age-0 + crabs in the population as:

$$U = \frac{C_t}{\left(\frac{N_{0,t}}{q_0}\right) + N_{1+,t}} \qquad \text{Eq. 24}$$

Based on these calculations, the SSCMSA estimates that MSY would be achieved with an exploitation rate of age-0+ females of U= 0.34. We recommend that a value of U_{MSY}=0.34 of age-0+ females is a reasonable foundation for reference point determination.

The estimate of U_{MSY} from the SSCMSA is independent of the sex-specific ratio of exploitation rates in the population. However, expressed in terms of female abundance (Fig. 6.13), the abundance that produces MSY (N_{MSY}) does change appreciably in response to increases in the male fraction in the catch. The MSY abundance target varies from N_{MSY} = 115 - 198 million age-1+ females as the range of sex-specific exploitation rates from $0.6<F_{male}:F_{female}<2.2$. For the ratio of sex-specific exploitation rates observed in the Chesapeake Bay blue crab fisheries from 1968-2006 (Fig. 6.10, and shaded in green on Fig. 6.13), the SSCMSA indicates an estimate of N_{MSY} =137 million age-1+ female crabs. Following the recent change in sex-specific exploitation rates induced by implementation of conservation measures protecting females, the SSCMSA indicates an estimate of N_{MSY} = 164 million age-1+ female crabs. Thus a value of N_{MSY}=140 million age-1+ female crabs seem to be a reasonable foundation for reference point determination.

Important for management is the observation that the model indicates that sex-specific exploitation rate ratios that change to favor more male based fisheries will produce increases in yield. Estimates of MSY over the range of sex-specific exploitation rates from $0.6<F_{male}:F_{female}<2.2$ varied from 283 - 758 million crabs. More specifically, if we use the sex-specific ratio of exploitation rates predicted in the model (Fig. 6.12), these yield curves suggest that the MSY in the fishery will have increased from a harvest of approximately 413 million crabs prior to the new management (1968-2006) to a new value of almost 542 million crabs if the current pattern of exploitation is maintained. We strongly note that caution should be exercised when considering potential production outside of the range of observed sex ratios. At some low level of male abundance, sperm limitation will cause lower productivity of the population than predicted by the stock-recruitment relationship used in this assessment. However, the level of male abundance at which this limitation occurs is unknown, but is outside of the range observed in the data.

6.2.6. Sensitivity Runs

We conducted several sensitivity runs of the SSCMSA to evaluate effects of assumptions on some of the model estimates (Table 6.2). In particular, we reran the model assuming values of 0.6 and 1.2 for natural mortality, 0.3 and 0.9 for partial recruitment of age-0 crabs, and conducted runs that estimated the natural mortality rate for males, the sex ratio of recruits, and the partial recruitment of age-0 crabs. We also conducted two additional analyses suggested by the reviewers: a model that estimated catchability of adults for the winter dredge survey and one that included a traditional, combined sex stock recruitment model. We summarized several outputs from each of the sensitivity runs (Table 6.2). Assessment working paper 3 provides graphical output from all sensitivity runs. The estimates of age-1+ female abundance in 2010 were quite similar among the different models. Likewise, the estimated female exploitation rate that would produce MSY only range from 0.30-0.38. The models that either estimated the sex ratio at recruitment or estimated a separate natural mortal rate for males had substantially lower negative log likelihoods than the base model because they were better able to match sex-specific patterns in the catch and winter dredge survey. All of the models estimated that the ratio of male to female fishing mortality increased substantially by the end of the time series, and almost all the models estimated that the fishing mortality was higher on females than males before 2006. Another common result was that all of the models indicated that age-1+ female abundance in 2009 was less than the target level. The models that estimated the sex ratio at recruitment or natural mortality for males had higher target levels of female abundance than the other models. The sensitivity run that produced the largest change in the results was the run in which the catchability of adults in the winter dredge survey was estimated. Allowing the model to estimate catchability for this survey caused a four-fold decrease in the estimated abundance and also estimated a substantially higher value for u_{MSY}.

6.2.7 Reference points

Although the blue crab fisheries in Chesapeake Bay do not fall under federal jurisdiction, we recommend following the guidelines established by both the Mid-

Atlantic and New England Fishery Management Councils in developing reference points for managed species These Council are bound by the terms of the federal Magnuson Stevens Fishery Conservation Act (2006). In implementing the requirements of this Act, NOAA has published National Standard 1, which provides specific guidance on developing reference points.

In developing the reference points below, we base exploitation-based reference points on estimates of the exploitation rate of all age-0+ females. We make this recommendation to account for the recruitment of crabs that are age-0 at the beginning of the year into the fishable stock during the course of the fishing year. Further, we base abundance-based reference points on the abundance of age-1+ females. We justify this decision on two grounds. First, age-1+ female crabs represents the spawning stock for the coming year and as such is an index of the reproductive potential in the population. Second, the abundance of age-1+ crabs can be determined empirically in the winter dredge survey with a high degree of precision.

We recommend adopting U_{MSY} as the exploitation limit reference point. The SSCMSA provides an estimate of this, expressed in terms of the exploitation rate on age-0+ females of U_{MSY}=0.34. We recommend this value based on the range of sex-specific exploitation rates observed historically and currently in the fishery $0.8<<F_{male}:F_{female}<1.6$ (Fig . 6.10). We note that strong caution should be exercised when considering ratios of male to female fishing mortality rates outside of the range observed. At some low level of male abundance, sperm limitation will cause lower productivity of the population. However, empirical evidence suggests that this level of male abundance is likely outside the range of the observed data. Thus, in implementing this reference points, management jurisdictions should bear two important considerations in mind. First, should the sex-specific ratio of exploitation rates move beyond these bounds, the U_{MSY} reference point should be re-calculated. Second, between assessment updates, the status of the stock with regard to this reference point can be estimated from the empirical estimate of age-0+ female exploitation based on reported females harvests and the abundance of age-0+ females in the winter dredge survey, calculated using the SSCMSA estimates of q_0 in Eq. 24.

Further, following precedent in federal fisheries management, we recommend adoption of an abundance limit reference point, corresponding to one half the abundance at MSY – $0.5*N_{MSY}$. The equivalent abundance limit reference point varies from 68.5 – 82 million age-1+ female crabs for the range of sex-specific exploitation rates observed historically and currently in the fishery $0.8<<F_{male}:F_{female}<1.6$. We recommend adoption of an overfished definition (abundance limit reference point) of 70 million age-1+ females as a working value. The same considerations for management jurisdictions as expressed above for U_{MSY} apply to the abundance limit reference point as well. As noted above, adoption of these limit reference points imply sustainable yields to the fishery of 400-600 million crabs annually.

We consider blue crab a data poor species in light of uncertainties over the age structure in the population, uncertainties over key vital rates (e.g., natural mortality, reproduction) and uncertainties in the reliability of the harvest time series. Therefore, we recommend adoption of a target reference point equivalent to 0.75 U_{MSY}. This precautionary approach provides a buffer against uncertainty in estimates of exploitation rates without foregoing substantial amounts of yield. This standard of 0.75 U_{MSY} is used by several federal management councils, including the Mid-Atlantic and New England Fishery Management Councils as well as being an approach recommended by National Standard 1 to the federal Magnuson Stevens Act (2006). This recommendation implies a target exploitation reference point of U=0.255 based on the exploitation of age-0+ female crabs. Furthermore, based on the SSCMSA, the equivalent abundance target reference point varies from 210 – 340 million age-1+ female crabs for the range of sex-specific exploitation rates observed historically and currently in the fishery $0.6<<F_{male}:F_{female}<1.2$. We recommend adoption of an abundance target reference point of 215 million age-1+ females as a working value.

Based on these recommendations, we present a revised control rule for blue crab in Chesapeake Bay in Fig. 6.15. The interpretation of the stock history from the revised control rule (Fig. 6.15) differs somewhat from that of the existing control rule (Fig 6.1). The revised control rule indicates that the crab population in Chesapeake Bay experienced overfishing from 1998- 2004 and was technically overfished from 2001-2003. The existing control rule indicated that the crab population was experiencing overfishing during the same period. In contrast, the existing control rule indicated that the crab population had never been overfished – as a result purely of the empirically-derived overfished definition that was set at the lowest observed abundance recorded. Importantly however, the revised and existing control rules do not differ in their interpretation of the current population status. The revised control indicates that in 2009 the blue crab stock in the Chesapeake Bay was not overfished, nor was it experiencing overfishing. More specifically, the exploitation rate in 2009 (U_{2009} =0.24 age-0+ female crabs) was below the U_{target} = 0.255. Also, the blue crab population in 2009 was above the overfished definition of 70 million age-1+ females. The best estimate of the abundance in 2009 (N_{2009} = 174.3 millon age=1+ female crabs) was lower than the target abundance. We note that the abundance of crabs in the winter dredge survey of 2009-2010 suggest that the population was above target abundance in 2010.

6.3. Alternative Assessment models

We explored two other assessment modeling approaches as a check on the results produced by the SSCMSA model.

6.3.1. Production modeling of Chesapeake Bay blue crab

There is a long history of the application of production models in fisheries stock assessment (Quinn and Deriso 1999). Simple equilibrium production models were developed by Tang (1983) and by Rugolo et al (1997). These authors used estimated baywide catch and nominal effort in a simple Schaefer (1954) production model. These efforts produced an estimated maximum equilibrium yield of ~85 million pounds. However, concerns over the reliability of the effort time series used as input to the models and over the model fits themselves precluded use of these estimates for management. No production modeling was included in more recent assessment efforts (Miller and Houde 1999, Miller et al. 2005). For this assessment we developed a simple production model (Assessment Working Paper 4).

Both production models examined provided credible yield-based reference points. The yields predicted by both models are comparable to observed values and comparable with results of the SSCMSA. Abundance-based reference points, however, were more variable. Production model-based overfished definitions were 255 million age-1+ crabs or 410 million crabs of all ages. In both cases, production model estimates were greater than those predicted by the SSCMSA.

6.3.2. Catch-Multiple Survey Analysis (CMSA) from 2005 Assessment

In the last assessment (Miller et al. 2005), a Catch-Survey Analysis (CSA, e.g., Mesnil, 2003) was presented, modified to permit multiple fishery-independent surveys and to estimate both observation and process error. This model assessed the current population status and its historical trajectory relative to biological reference points estimated outside of the assessment model. Although this approach continues to be valid, we view the fact that it relies on management reference points estimated external to the model as a significant weakness. In the 2005 assessment, Miller et al. compared output from this CMSA to reference points developed in an individual-based yield-per-recruit analysis.

We have not developed the CMSA model further because of its inability to provide integrated reference points. However, we updated the results of the CMSA in this assessment for comparative purposes to allow us to assess the degree to which any changes in the inferred status or trajectory of the stock reflect true underlying changes or changes in the model framework (Assessment Working Paper 5).

A comparison model run was conducted with parameters used in the base model run of the 2005 assessment. These are: natural mortality M=0.9, ratio of survey selectivities, L =0.4 for MD and VA trawls and L=0.5 for the winter dredge survey. Likewise the ratio of observation to process errors was set to 0.65 for both trawl surveys and to 0.4 for the dredge survey. The CMSA model was still able to capture trends in the abundance of age-1+ females. However, comparison run results predicted considerably higher exploitation fractions than are currently observed or estimated in the fishery. These results led to control rule plot that suggested the blue crab population is currently experiencing overfishing. CMSA results were not considered further.

6. 3.3 Alternative models and reference points.

To evaluate the effect of the changes in approach and data on inferred stock status, we compare the following scenarios: a) 2005 reference points with updated survey averages and commercial data, b) 2005 reference points with standardized survey data and updated commercial data, and c) the proposed new 2011 reference points and data.

We have previously presented the updated version of the current control rule (Fig. 6.1). This figure employs the winter dredge survey as an index of abundance for the coming fishing year. It calculates an exploitation fraction, u, as the ratio of the total commercial catch (plus 8% for recreational harvest) and the winter dredge abundance. Using this approach, we infer that the crab population in the Chesapeake Bay is not overfished, is close to or above target abundance and is not experiencing overfishing. To assess the impact of the change of the survey time series on the overall conclusions, we also completed an update of the CMSA model (Miller et al. 2005) using the updated survey indices and commercial data. We term this run the updated CMSA run. This run of the model re-estimated the trajectory of the crab population as far back as 1968. As with the original CMSA presented in the 2005 assessment, the updated run generates exploitation fractions early in the time series that are >1, with a large number > 1.5. This gives rise to concern about the performance of the model in the early years. However, for the most recent years, the performance of the updated model is more reliable (Fig. 6.16). The model results infer that the population is not overfished, but was experiencing overfishing in 2009 (Fig. 6.16). The model also inferred that the population was above target abundance and at or below target exploitation rate in 2006-07. Since then, the model results suggest exploitation has increased and abundance has decreased.

For a final comparison, we also re-ran the CMSA model but used the standardized indices rather than the simple index means. Comparison of the results from this model to the previous model will indicate the overall impact of the standardization on inferences regarding stock status. We term this run the standardized CMSA run. The results from the standardized CMSA run are provided in Fig. 6.17. As with the updated CMSA runs many of the estimates of u > 1.5 in the early part of the time series. Again, more recent estimates are more credible. The standardized run indicates that the population is not overfished, and is above the interim target of 200 million crabs. The standardized run indicates that the population is not experiencing overfishing. The exploitation estimate for 2009 was u2009=0.46. The model infers that exploitation rates have been <1 since 1994.

Comparison of the current control rule, the updated CMSA run and the standardized CMSA run and the new sex-specific reference point control rule proposed here all indicate that the blue crab population in the Chesapeake Bay is not overfished. Three of these models, including the new sex-specific reference point control rule, indicate that the population is not experiencing overfishing. The models differ to as to whether they indicate that the population has achieved target abundance. Half of the four models indicate that we are below target abundance, two indicate that we are above target abundance.

From the comparison of models we present here we argue that evidence suggests that the blue crab fishery in the Chesapeake Bay is operating in a sustainable manner. All analytical results suggest that the population is in excess of abundance levels that would give cause for concern. Current exploitation rates also appear sustainable.

8. Discussion and Recommendations

Based on revised management reference points, the blue crab population in Chesapeake Bay was not overfished, nor was it experiencing overfishing in 2009. The SSCMSA and the control rule implemented using the winter dredge survey both suggest that in 2009 the population is currently being exploited at a rate below the target exploitation rate, but that it had not reached the target abundance in 2009. We note that if preliminary data from 2010 are included, both approaches conclude that the population is above the target abundance. This central conclusion of the assessment is the same whether we used revised control rules recommended within this assessment or the existing control rules used to manage the fishery currently. From this we infer that the current configuration of the fishery is such that it can be expected to yield sustainable harvests of blue crab for all three management jurisdictions.

The SSCMSA developed for this assessment can be used to indicate expected levels of yield to the fishery. If management jurisdictions maintain the stock at target levels of abundance and exploitation, the stock can be expected to yield sustainable harvests in the region of 400-600 million crabs annually. If we use a simple conversion of 3 crabs per pound, this is equivalent to 133 – 200 million pounds of harvest annually.

The SSCMSA was used to develop a suite of credible, integrated reference points for the blue crab population and fishery. The recommended reference points are logically consistent such that it is possible to attain the target reference point and the target abundance or the U_{MSY} and N_{MSY} reference points simultaneously. This is not the case for the existing reference points for which there was no guarantee that the target exploitation rate and the interim abundance target could be achieved simultaneously. The recommended overfishing definition is based on U_{MSY} – the exploitation fraction that maximizes the sustainable yield from the fishery. The recommended overfished definition is based the abundance equivalent to half that at MSY – based on widespread convention. It does not reflect a critical level that implies some critical change in population dynamics. The $0.5*N_{MSY}$ overfished reference point is used to suggest a level of abundance that should be avoided for conservation reasons. We note that the target reference points ($0.75*U_{MSY}$ and $N_{0.75*UMSY}$) we recommend are arbitrary but not capricious. They are selected to provide a buffer from the overfishing definition without foregoing substantial amounts of yield. Moreover, we note that the abundance target of 215 million age-1+ females is achievable over the long term. It was exceeded in 2010 and was routine exceeded from 1980-1990. We also note that because these levels are arbitrary, managers and stakeholders have some latitude in selecting the target exploitation abundance and exploitation rate.

Our analyses indicate that the ratio of sex-specific exploitation rates in the population likely varied around unity from 1968-1988. Subsequently, between 1989-2004 the ratio of sex-specific exploitation rates changed to indicate a higher exploitation rate on females than on males. It is not clear whether management actions or natural processes, such as a shift in spatial distribution of crabs, caused this pattern. Regardless of causation, this pattern indicates a female dominated fishery during this period. However, more recently from 2005 onwards, the ratio of sex-specific exploitation rates has changed to one suggesting a decrease in female-specific exploitation rates.

The pattern of sex-specific exploitation rate is important because the sustainable yield available to the fishery is quite sensitive to the sex ratio of exploitation rates in the population. If the fishery switches to become a more male dominated fishery, we anticipate yield will increase. For example at the pattern of exploitation present in the fishery from 1968-2006, we predict the sustainable yield at the target exploitation rate was ~ 400 million crabs. In the current configuration of a male dominated fishery, we predict yield should increase to ~ 600 million crabs. Indeed the model indicates that the highest possible yield is obtained when all males are harvested. This is clearly not a sustainable pattern as reproductive potential of the population would clearly be compromised because of sperm limitation. We caution that we lack guidance on what sex-ratios in the population lead to limitation of reproductive potential.

The SSCMSA used in this analysis was able to fit the data well with credible parameter values as inputs. We strongly recommend adoption of reference points derived from this model as the foundation for future management. However, accuracy in model structure and input parameter estimation is vital for the reliability of any assessment model. The base assessment model represented the blue crab population as comprising four stages: age-0 males, age-0 females, age-1+ males and age-1+ females. Based on expert opinion, and on the cumulative distribution of catch and effort in several fisheries, we estimated that the age-0 crabs would experience 60% of the full rate of exploitation in their first full summer. The base assessment used a value of the rate of natural mortality, M = 0.9. This value was the same as used in the Miller et al. (2005) assessment, and is supported by available direct and indirect estimates of natural mortality (Hewitt et al. 2007). The base assessment model used an empricial estimate of the proportion of females in the cohort at recruitment of 52%. This value is based on observations from the winter dredge survey. Using these core parameter estimates the predicted values of sex-specific catches and sex-specific abundances in fishery independent surveys were similar to those observed.

We do note that the model was less able to replicate sex-specific patterns in catch and in the abundances in the winter dredge survey than expected. Currently, we are unclear of the reasons for the inability of the model to match the observed patterns. We suggest several viable alternative hypotheses to explain the discrepancies including several related to model miss-specification (incorrect specification of the partial recruitment of age-0 crabs, errors in the sex ratio at recruitment, miss-specifcation of stock-recruitment relationship) and several related to miss-interpretation of data (errors in survey catchability, changes in the spatial distribution of crabs, presence of sex-specific exploitation rates, biases in reported sex-specific harvest). We used simulation studies to explore several of these hypotheses. Model results indicate that the proportion of females at recruitment needed to be increased to 63% to resolve the biases in sex-specific catches and winter dredge abundances. This level of female bias at recruitment does not match observations. In simulations which allowed the natural mortality rate to be sex-specific, we found that if we maintained the natural mortality rate of females at M=0.9, the natural mortality rate on males needed to be increased from 0.9 to 1.33. Little is known about sex-specific patterns of natural mortality. Bauer and Miller (2010b) found no evidence for sex-specific differences in over winter mortality. In contrast Rome et al. (2005) suggests that rates of female natural mortality may be higher than those for males. Evaluation of other hypotheses remains a research priority.

To partially validate the recommended reference point, we compared the MSY reference points from the SSCMSA and the simple production model presented in this assessment (Assessment Working Paper 4). The production indicated an MSY of 271-356 million crabs depending on the abundance time series used in the model. These are broadly similar to those predicted by the SSCMSA. In contrast, the production model-based estimates of the overfished definitions (821 million) were considerably higher than those predicted by the SSCMSA, even when the SSCMSA estimates were expanded to reflect the total population abundance (age-0+ crabs). Despite these differences, we suggest this general similarity in estimated reference points between the two models reinforces the appropriateness of the recommended reference points.

The results of the assessment models continue to rely on fishery-dependent and fishery-independent sources of data. We again attempted to correct for reporting changes in both Maryland and Virginia. It seems clear from these analyses that the 1981 reporting change in Maryland and the 1993 reporting change in Virginia had significant impacts on the estimated level of landings. However, even though these time series approaches can potentially adjust for changes in reporting methodology, they cannot verify whether landings reported under any system are correct. The accuracy and completeness of the landings time series remain an area of concern.

Fishery-independent estimates of abundance remain vital to assess the status of the blue crab population in Chesapeake Bay. This assessment has relied heavily on the baywide winter dredge survey as an index of absolute abundance of age-1+ crabs. It is critical for the ongoing assessment of blue crab that this survey be continued. However, we note that the abundance estimates developed from the winter dredge survey depend on annual and vessel-specific estimates of catchability. The reliability of these estimates deserves more attention than they have been given heretofore. In particular, we note that the spatial distribution of male and female crabs during winter is different (Jensen and Miller 2005). Thus there is the potential for differences in gear efficiency between survey vessels in Virginia and Maryland to compound biases in estimates of sex-specific abundances in the winter dredge survey.

Similarly, the SSCMSA indicated that although estimates of recruit abundance in the winter dredge survey were highly predictive of the values generated in the model, empirical estimates are unlikely to be reliable as absolute estimates. The SSCMSA indicated a catchability coefficient for age-0 crabs in the winter dredge survey of approximately 40%. This suggests a substantial number of age-0 crabs present in the population are not available to be caught in the survey. Additional research on the reliability of the winter dredge survey as an index of recruit abundance appears warranted.

Abundances of age-1+ crabs in the Maryland and Virginia trawl surveys appear to be reliable indicators of abundance, even though they are not highly coherent. Both surveys appear internally consistent – in that a high abundance of age-0 crabs in one year is followed by a high abundance of age-1 crabs in the next year. However, the value of both surveys as indices of recruitment is highly questionable. Consideration of how these surveys might be altered to improve their reliability as indices of recruitment is justified.

In summary, the application of sex-specific assessment model to fishery-dependent and fishery-independent data for blue crab in the Chesapeake Bay provided revised estimates of reference points for fishery management. Application of these new reference points to current data from the fishery and the winter dredge survey indicate that the blue crab population is not currently overfished nor is it experiencing overfishing. The ratio of sex-specific exploitation in the fishery has changed since 2004 to favor a more male-based fishery. We caution that managers must continue to monitor the sex-ratio in the fishery to assess the potential that reproductive potential may be compromised in the future.

8.1. Research Recommendations

1. Assessment models
    1. The new SSCMSA is a substantial step forward as it provides integrated estimation of reference points and stock status. However, a more complete understanding of the sensitivity of model outputs to parameter values. We also recommend an evaluation of the impacts of uncertainty in parameter estimates on reference points.
    2. Evaluate the effects of possible miss-specification of model structure to explain the inability to match the sex-specific catch levels in the model (sex specific ratio at recruitment, sex-specific differences in M, sex-specific differences in catcability, alternative stock recruitment models).
    3. The efficacy of alternative fishery-independent time series, such as the ChesMAPP samples, in assessment models should be evaluated.
    4. The ecology and fisheries for blue crab exhibit considerable spatial variability – much of which coincides with the divisions among management jurisdictions. We recommend evaluation of spatially-explicit assessment models.
    5. Additionally modeling work that specifically represents the diversity of fishery sectors, with different seasonalities and catchabilities would be beneficial.
2. Fishery-dependent data
    1. The monitoring of removals by the different fisheries has improved. However, efforts to validate landings are currently inconsistently implemented across jurisdictions. Efforts to validate landings should be a high priority. These approaches could include directing monitoring of purchases by wholesalers or by indirect expansion of sentinel fishery data.
    2. Although time series approaches to correcting landings for reporting changes appear successful, their use for any future reporting changes should be discouraged in favor of direct empirical estimates of the effects of the change from studies implemented contemporaneously with the reporting change.
    3. We recommend that attention be given to ensuring that the biological characteristics of each fishery be quantified, and that the spatial and temporal distribution of the removals be quantified.
    4. The recreational catch remains poorly described and its inter annual variability is largely unknown. Monitoring programs and surveys to quantify the recreational harvest should have a high priority.
    5. There have been efforts to improve information on the distribution and dynamics of effort in the different fisheries exploiting blue crab in the

    Chesapeake Bay. These efforts should be expanded to a consistent baywide coverage and continued.

3. Fishery-independent data
    a. Fishery-independent surveys are critical to the assessment, particularly the winter dredge survey. Continuing investments in these surveys are important for ongoing assessment efforts.
    b. Efforts to estimate gear catchability coefficients should be expanded. In particular, these efforts should focus on the interaction between the spatial distribution of crabs and area-specific patterns in catchability.
    c. Additional analysis of the survey time series to understand their coherence, and their ability to track population variation would be beneficial. A thorough evaluation of survey efficiency and options for enhancing their utility should be undertaken.
    d. Indices for age-0 and recruits are lacking other than for WDS. Exploration of alternative indices of age-0 crabs is a priority.
4. Ecology and Biology
    a. Research that quantifies size-dependent, sex-specific and inter-annual patterns in natural mortality would greatly improve future assessments.
    b. Understanding of growth as it affects recruitment of age-0 crabs to different fishery sectors is uncertain. Studies of the temporal and spatial variability in growth would improve our understanding.
    c. The reproductive potential of the crab population likely varies with stock abundance and the sex ratio on the stock. Research on the variability of reproductive parameters (e.g., maturity, fecundity and batch production) is a high priority. Additionally, research on the impact of variation in the sex-ratio on the reproductive potential of the population would be beneficial.
    d. Evaluation of how productivity may have changed over time in response to changes in availability of quality habitat

5. Management
    a. Coordination among management jurisdictions is commendable. However, there remain important difference in the availability and format of data. We recommend that efforts be implemented to make harvest and survey data widely available and consistently managed. This would reduce time invested in data qa/qc during the assessment process and likely improve the reliability of future assessments.
    b. The sex-specific approach to management recommended here has implications for new decisions management has to make regarding the future of the fisheries. Management should engage stakeholders to develop a vision for the fishery in light the adoption of a sex-specific approach.

c. There have been no efforts in this assessment to consider blue crab management from an ecosystem view point. The exploration of both the impact of the ecosystem on the productivity of blue crab fisheries and of the impacts of the blue crab fisheries on the ecosystem are warranted.

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Table 3.1. Summary of size, times and areas used in calculating fishery-independent crab abundance indices for the Chesapeake Bay

Survey	Age Class					
	Age-0			Age-1+		
	Size	Month	Areas	Size	Month	Areas
VA Trawl	< 70 mm	May-June	James, York and Rappahannock	> 70 mm	May- June	James, York and Rappahannock
MD Trawl	<=50mm	Sept & Oct	Pocomoke,Tangier, Choptank, Patuxent	>=51	June - Oct	not Potomac
Winter dredge survey	< 60 mm	Dec - March	Chesapeake Bay wide	> 60 mm	Dec - March	Chesapeake Bay wide

Table 3.2. Time series of area-weighted geometric means for blue crab from the spring VIMS trawl survey for 1956-2009.

YEAR	Age-0 crabs	Age-1+ Male	Age-1+ Female	Age-1+
1956	10.79	2.92	2.9	5.82
1957	3.51	1.26	1.25	2.51
1958	26.36	6.39	8.27	14.66
1959	1	0.67	1.27	1.94
1960	28.49	1.25	0.97	2.22
1961	27.24	2.44	2.11	4.55
1962	14.33	2.53	2.1	4.63
1963	15.28	2.74	1.03	3.77
1964	13.83	1.69	1.42	3.11
1965	31.89	4.14	2.4	6.54
1966	15.67	2.52	1.08	3.6
1967	17.44	1.35	1.34	2.69
1968	0.67	1.99	1.13	3.12
1969	22.01	1.09	0.56	1.65
1970	8.04	4.62	3.23	7.85
1971	84.52	6.24	4.67	10.91
1972	8.42	3.39	2.31	5.7
1973	7.03	0.98	0.56	1.54
1974	3.49	1.05	0.72	1.77
1975	7.96	1.08	0.47	1.55
1976	1.61	0.36	1.25	1.61
1977	3.9	1.46	1.03	2.49
1978	3.07	1.23	0.56	1.79
1979	6.42	2.46	3.01	5.47
1980	2.26	1.37	2.31	3.68
1981	37.77	6.98	5.95	12.93
1982	12.15	5.47	6.23	11.7
1983	45.6	5.81	5.92	11.73
1984	49.35	1.83	2.07	3.9
1985	24.66	4.31	5.78	10.09
1986	11.72	3.11	2.7	5.81
1987	15.09	2.03	2.64	4.67
1988	11.78	3.01	3.78	6.79
1989	14.1	3.75	4.32	8.07
1990	40.24	9.93	10.97	20.9
1991	4.26	4.35	5.27	9.62
1992	3.04	1.68	2.29	3.97

1993	8.14	1.58	1.52	3.1
1994	8.88	1.17	1.32	2.49
1995	4.94	1.77	1.26	3.03
1996	10.35	1.81	2.19	4
1997	5.04	1.68	1.3	2.98
1998	4.72	2.32	2.03	4.35
1999	2.6	1.12	1.5	2.62
2000	2	1.1	1.36	2.46
2001	4.46	1.65	2.47	4.12
2002	2.61	1.93	2.17	4.1
2003	2.54	0.74	0.87	1.61
2004	2.8	1.41	1.2	2.61
2005	1.43	0.49	0.54	1.03
2006	1.43	0.97	0.96	1.93
2007	1.69	1.25	1.17	2.42
2008	6.69	2.83	2.81	5.64
2009	1.54	0.69	1.08	1.77
2010	4.58	1.56	1.23	2.79

Table 3.3. Results of generalized linear modeling of the data from the Maryland DNR blue crab trawl survey (1977-2009)

	Age-0 Male			Age-0 Female			Age-0 Combined			Age-1+ Male			Age-1+ Female			Age-1+ Combined		
% +ve tows	40.65			33.67			48.45			82.65			66.78			0.86		
Year	Simple average	GLM index	SE	Simple average	Index	SE	Simple average	Index	SE	Simple average	Index	SE	Simple average	Index	SE	Simple average	Index	SE
1977	0.74	0.32	1.04	0.52	0.27	1.16	1.26	0.60	1.95	14.22	18.14	2.60	11.12	11.21	1.42	25.33	29.29	3.75
1978	0.23	0.14	0.16	0.13	0.06	0.16	0.35	0.21	0.31	1.90	2.47	1.48	1.81	1.22	0.37	3.72	3.83	2.00
1979	0.21	0.18	0.13	0.09	0.06	0.13	0.30	0.29	0.24	1.50	1.40	0.42	0.90	0.57	0.13	2.40	2.01	0.44
1980	0.88	0.45	0.06	0.42	0.23	0.05	1.30	0.70	0.10	0.64	1.44	1.00	0.23	0.30	0.12	0.87	1.76	1.27
1981	0.58	0.40	0.97	0.34	0.23	0.80	0.92	0.78	1.73	6.87	10.56	4.49	4.61	4.59	1.15	11.48	14.96	5.94
1982	0.44	0.25	0.39	0.18	0.10	0.39	0.61	0.36	0.73	4.81	6.05	0.97	2.10	2.46	0.41	6.91	8.62	1.24
1983	1.77	1.24	0.93	1.03	0.67	0.80	2.80	1.94	1.62	9.94	11.12	1.41	5.41	5.02	0.62	15.36	16.08	1.95
1984	1.67	3.38	1.50	1.00	2.59	1.01	2.67	6.27	2.23	12.88	12.60	2.57	7.08	4.51	1.18	19.96	16.84	3.51
1985	1.60	1.74	2.42	0.54	0.59	2.60	2.15	2.57	4.59	13.21	16.97	1.94	6.93	8.87	1.06	20.14	26.69	2.95
1986	2.48	2.13	1.25	2.67	2.43	1.12	5.16	4.13	2.16	12.27	16.14	1.76	6.34	9.95	1.27	18.62	26.34	2.92
1987	0.84	1.03	0.34	0.49	0.60	0.32	1.32	1.92	0.57	10.30	13.29	1.12	4.98	6.57	0.77	15.28	20.48	1.79
1988		2.80	0.80		2.55	0.70		5.23	1.38	7.36	9.10	1.16	4.68	5.26	0.73	12.04	14.24	1.74
1989	3.65	2.33	2.27	2.62	1.71	1.43	6.27	3.79	3.35	20.73	20.60	2.78	9.14	8.73	1.25	29.86	29.35	3.87
1990	14.49	8.67	1.91	10.95	7.03	1.55	25.43	14.73	3.22	8.62	10.36	1.14	3.92	4.74	0.59	12.54	14.93	1.64
1991	0.86	0.74	1.48	0.73	0.51	1.39	1.59	1.32	2.62	13.11	18.36	2.03	6.12	9.06	1.24	19.23	28.42	3.32
1992	11.22	5.34	0.83	10.41	5.20	0.59	21.63	10.62	1.30	7.81	8.09	1.51	4.39	3.72	0.64	12.19	11.84	2.11
1993	2.84	2.67	0.95	2.56	2.08	0.93	5.39	4.92	1.69	13.69	15.36	1.49	8.02	8.36	0.81	21.71	23.88	2.21
1994	0.76	0.57	0.94	0.68	0.49	0.75	1.49	1.16	1.65	13.64	13.90	1.67	7.14	7.23	0.87	20.78	20.77	2.40
1995	0.68	0.84	0.18	0.56	0.58	0.33	1.27	1.88	0.49	4.01	5.74	1.15	2.34	3.02	0.45	6.35	9.05	1.56
1996	2.30	1.51	1.82	1.79	1.21	1.51	4.10	2.70	3.42	16.27	17.95	2.43	11.70	14.05	1.95	27.97	32.73	4.46
1997	0.61	0.52	0.77	0.50	0.33	0.55	1.11	0.93	1.24	12.45	15.12	1.96	5.68	6.35	0.67	18.14	22.75	2.79
1998	1.55	0.99	0.11	1.62	1.01	0.13	3.18	2.02	0.26	5.90	6.63	0.88	2.33	2.74	0.35	8.23	9.55	1.10
1999	5.44	2.87	0.40	4.52	2.17	0.43	9.95	4.75	0.74	7.75	9.83	1.17	6.77	7.56	0.99	14.52	17.56	2.08
2000	1.20	0.95	0.29	1.12	0.68	0.24	2.38	1.78	0.50	4.86	6.80	0.90	2.68	3.20	0.46	7.53	10.27	1.25
2001	2.10	1.52	0.34	1.93	1.04	0.24	4.03	2.62	0.46	4.85	7.12	0.87	3.36	3.87	0.60	8.21	10.93	1.32
2002	1.41	1.36	0.53	1.16	1.09	0.34	2.58	2.53	0.70	3.96	7.21	1.07	2.53	3.99	0.86	6.49	11.35	1.76
2003	3.32	1.17	0.21	2.69	1.02	0.15	6.02	1.93	0.32	6.60	5.07	0.76	3.17	1.80	0.24	9.77	6.79	1.01

2004	4.83	4.13	0.11	3.44	2.72	0.11	8.27	6.77	0.20	6.28	5.81	0.66	3.06	2.22	0.24	9.34	8.20	0.87
2005	5.99	3.76	0.27	4.83	3.06	0.22	10.82	6.34	0.45	9.94	8.44	1.09	6.77	5.20	0.47	16.71	13.20	1.43
2006	3.30	2.35	0.57	3.57	2.33	0.64	6.86	4.67	1.19	10.35	7.31	1.63	7.47	4.43	1.04	17.82	11.30	2.58
2007	0.16	0.12	0.34	0.12	0.09	0.31	0.28	0.24	0.69	3.16	4.09	0.74	1.71	1.84	0.26	4.87	5.98	0.89
2008	2.88	2.88	0.56	2.28	2.30	0.45	5.16	5.25	0.99	6.83	7.38	1.03	4.29	4.39	0.54	11.12	11.48	1.39
2009	2.41	2.20	0.77	1.57	1.14	0.86	3.97	3.48	1.72	6.36	5.48	0.81	4.50	3.49	0.47	10.86	8.72	1.15

Table 3.4. Summary of model selection results for the Maryland DNR blue crab trawl survey for A) Age-0 male crabs, B) Age-0 female crab and C) Age-0 combined crabs. Shown are models for probability of occurrence and abundance given occurrence. A "+" indicates that the factor was included in the model. Models indicated by bold type face are the best fitting models according to the AIC criterion.

A) Age-0 Males

	Year	Month	Strata	Salinity	Temperature (^{o}C)	Depth (m)	AIC
Occurrence models	**+**	**+**	**+**	**+**	**+**	**+**	**2019.13**
	+	+	+	+	+		2034.23
	+	+	+	+			2034.69
	+	+	+				2035.41
	+	+	+		+		2036.65
	+	+	+			+	2019.72
	+	+					2548.51
	+		+				2055.85
Abundance models	+	+	+	+	+	+	4147.64
	+	+	+	+	+		4169.44
	+	+	+	+			4167.80
	+	+	+				4167.10
	+	+	+		+		4169.06
	+	**+**	**+**			**+**	**4144.70**
	+	+					4377.26
	+		+				4164.27

B) Age-0 Female

	Year	Month	Strata	Salinity	Temperature (^{o}C)	Depth (m)	AIC
Occurrence Models	+	+	+	+	+	+	1914.57
	+	+	+	+	+		1924.79
	+	+	+	+			1923.65
	+	+	+				1923.02
	+	+	+		+		1923.42
	+	**+**	**+**			**+**	**1912.27**
	+	+					1934.54
	+		+				
Abundance models							
	+	+	+	+	+	+	3358.05
	+	+	+	+	+		3378.96
	+	+	+	+			3378.00
	+	+	+				3376.02

	+	+	+		+		3377.10
	+	**+**	**+**			**+**	**3354.71**
	+	+					3541.34
	+		+				3378.58

C) Age-0 Combined

	Year	Month	Strata	Salinity	Temperature (^oC)	Depth (m)	AIC
Occurrence models	+	+	+	+	+	+	2030.81
	+	+	+	+	+		2046.60
	+	+	+	+			2044.75
	+	+	+				2044.48
	+	+	+		+		2046.46
	+	**+**	**+**			**+**	**2028.25**
	+	+					2631.41
	+		+				2073.94
Abundance models	+	+	+	+	+	+	5522.57
	+	+	+	+	+		5553.56
	+	+	+	+			5552.23
	+	+	+				5551.43
	+	+	+		+		5553.23
	+	**+**	**+**			**+**	**5519.77**
	+	+					5862.95
	+		+				5550.53

Table 3.5. Summary of model selection results for the Maryland DNR blue crab trawl survey for A) Age-1+ male crabs, B) Age-1+ female crab and C) Age-1+ combined crabs. Shown are models for probability of occurrence and abundance given occurrence. A "+" indicates that the factor was included in the model. Models indicated by bold type face are the best fitting models according to the AIC criterion.

D) Age-1+ Male

	Year	Month	Strata	Salinity	Temperature (°C)	Depth (m)	AIC
Occurrence models	+	+	+	+	+	+	2447.89
	+	**+**	**+**	**+**	**+**		**2446.46**
	+	+	+	+			2447.33
	+	+	+				2446.91
	+	+	+		+		2448.01
	+	+	+			+	2448.14
	+	+					2590.37
	+		+				2536.89
Abundance models	+	+	+	+	+	+	17238.68
	+	**+**	**+**	**+**	**+**		**17237.81**
	+	+	+	+			17250.50
	+	+	+				17277.14
	+	+	+		+		17278.09
	+	+	+			+	17277.09
	+	+					17568.70
	+		+				17438.76

E) Age-1 Female

	Year	Month	Strata	Salinity	Temperature (°C)	Depth (m)	AIC
Occurrence models	+	+	+	+	+	+	3166.93
	+	+	+	+	+		3169.58
	+	+	+	+			3169.74
	+	+	+				3168.68
	+	+	+		+		3169.92
	+	**+**	**+**			**+**	**3165.71**
	+	+					3685.19
	+		+				3447.39
Abundance models	+	+	+	+	+	+	12369.83
	+	**+**	**+**	**+**	**+**		**12367.89**
	+	+	+	+			12371.28
	+	+	+				12399.29
	+	+	+		+		12400.95

	+	+	+			+	12401.29
	+	+					12629.99
	+		+				12689.80

F) Age-1+ Combined

	Year	Month	Strata	Salinity	Temperature (^oC)	Depth (m)	AIC
Occurrence models	+	+	+	+	+	+	2065.28
	+	+	+	+	+		2063.39
	+	+	+	+			2064.61
	+	**+**	**+**				**2062.86**
	+	+	+		+		2063.12
	+	+	+			+	2064.67
	+	+					2211.09
	+		+				2184.73
Abundance models	+	+	+	+	+	+	20126.88
	+	**+**	**+**	**+**	**+**		**20126.32**
	+	+	+	+			20138.36
	+	+	+				20172.21
	+	+	+		+		20173.83
	+	+	+			+	20171.62
	+	+					20537.64
	+		+				20442.67

Table 3.6. Annual summary by sex and age of crabs collected in the winter dredge survey. Estimates provided in the table are absolute abundances

	Age-0									Age-1							
	Male			Female			Combined			Male			Female			Combined	
Spring Year	Simple	Stratified	GLM	Simple	Stratified	GLM	Simple	Stratified	GLM	Simple	Stratified	GLM	Simple	Stratified	GLM	Simple	Stratified
1990	45.15	24.38		39.10	20.29		84.25	44.66		38.02	19.46		19.86	14.45		57.89	33.91
1991	37.19	20.86		32.74	23.85		69.92	44.70		44.19	26.70		24.32	20.52		68.50	47.22
1992	6.09	5.04		6.54	5.58		12.63	10.63		11.07	9.10		15.59	17.82		26.66	26.92
1993	22.08	19.79	31.33	21.07	19.28	40.39	43.15	39.07	51.48	21.33	18.91	25.24	19.71	17.92	36.52	41.03	36.83
1994	16.58	17.11	18.25	16.82	17.98	31.73	33.40	35.09	33.55	12.54	13.03	18.11	19.19	15.23	26.24	31.73	28.26
1995	14.63	13.85	14.27	17.14	16.20	26.33	31.77	30.05	27.05	11.63	11.02	12.78	9.56	8.93	19.94	21.19	19.95
1996	26.72	26.91	29.20	27.09	27.49	40.02	53.81	54.40	51.12	12.02	12.12	15.55	16.09	14.40	25.88	28.12	26.51
1997	22.80	24.08	32.03	26.54	28.00	52.98	49.35	52.08	64.23	7.15	7.37	11.37	12.34	10.51	23.92	19.49	17.88
1998	7.34	7.55	8.37	8.92	9.29	17.38	16.27	16.84	15.86	8.12	8.21	10.44	12.01	10.86	18.07	20.12	19.07
1999	10.27	9.63	9.12	14.00	13.36	18.58	24.27	22.99	18.53	3.63	3.47	4.85	5.65	5.83	13.60	9.29	9.30
2000	6.42	6.41	7.08	7.45	7.44	14.38	13.86	13.84	13.42	4.39	4.39	6.25	10.43	10.27	19.15	14.82	14.66
2001	7.67	7.77	8.95	8.03	8.14	16.11	15.70	15.92	16.62	4.52	4.59	7.62	6.32	6.21	14.36	10.84	10.79
2002	8.78	8.49	10.73	11.70	11.35	20.15	20.48	19.84	20.83	6.89	6.67	10.11	5.42	5.88	15.77	12.31	12.56
2003	10.44	9.45	12.65	9.10	8.22	20.09	19.54	17.66	22.50	10.21	9.38	12.74	9.77	10.12	24.52	19.98	19.50
2004	7.82	7.51	8.64	7.24	6.96	14.10	15.06	14.46	15.73	5.02	4.76	7.12	8.56	9.82	20.68	13.58	14.58
2005	11.76	11.13	11.04	14.58	13.89	19.30	26.35	25.02	22.06	5.19	4.98	7.28	10.08	11.95	20.61	15.26	16.92
2006	11.16	9.12	10.41	12.51	10.56	20.66	23.67	19.67	21.03	4.22	3.59	5.76	8.05	8.99	19.40	12.27	12.58
2007	5.55	5.43	7.50	5.98	5.86	12.87	11.53	11.28	13.12	5.72	5.57	8.13	9.22	9.83	22.88	14.94	15.40
2008	8.46	7.74	7.88	9.77	9.02	13.28	18.22	16.76	14.14	4.09	3.87	5.73	8.44	9.27	16.37	12.53	13.14
2009	8.85	8.65	14.11	8.43	8.25	23.33	17.28	16.90	25.45	6.30	6.19	14.48	16.41	17.77	40.38	22.71	23.96

Table 3.7. Summary of model selection results for the Winter Dredge Survey for A) Age-0 male crabs, B) Age-0 female crab and C) Age-0 combined crabs. Shown are models for probability of occurrence and abundance given occurrence. A "+" indicates that the factor was included in the model. Models indicated by bold type face are the best fitting models according to the AIC criterion.

A) Age-0 Males

	Year	Month	Strata	Salinity	Temperature (°C)	Depth (m)	AIC
Occurrence models	**+**	**+**	**+**	**+**	**+**	**+**	**16812.50**
	+	+	+	+	+		17555.47
	+	+	+	+			19297.25
	+	+	+				22447.64
	+	+	+		+		18370.47
	+	+	+			+	21442.49
	+	+					25350.35
	+		+				22612.86
Abundance models	**+**	**+**	**+**	**+**	**+**	**+**	**39742.11**
	+	+	+	+	+		41421.44
	+	+	+	+			44599.09
	+	+	+				52762.24
	+	+	+		+		43287.49
	+	+	+			+	50490.91
	+	+					52934.63
	+		+				52777.04

B) Age-0 Female

	Year	Month	Strata	Salinity	Temperature (°C)	Depth (m)	AIC
Occurrence Models	**+**	**+**	**+**	**+**	**+**	**+**	**17784.04**
	+	+	+	+	+		18699.57
	+	+	+	+			20503.84
	+	+	+				23627.79
	+	+	+		+		19502.61
	+	+	+			+	22396.78
	+	+					26001.83
	+		+				23739.44
Abundance models							
	+	**+**	**+**	**+**	**+**	**+**	**42716.04**
	+	+	+	+	+		44796.16
	+	+	+	+			48181.44
	+	+	+				56015.65
	+	+	+		+		46534.07

	+	+	+			+	53250.14
	+	+					56160.40
	+		+				56052.72

C) Age-0 Combined

	Year	Month	Strata	Salinity	Temperature (°C)	Depth (m)	AIC
Occurrence models	**+**	**+**	**+**	**+**	**+**	**+**	**19890.15**
	+	+	+	+	+		20969.89
	+	+	+	+			23099.72
	+	+	+				26561.51
	+	+	+		+		21882.89
	+	+	+			+	25093.94
	+	+					29929.14
	+		+				26672.56
Abundance models	**+**	**+**	**+**	**+**	**+**	**+**	**60456.45**
	+	+	+	+	+		63343.71
	+	+	+	+			68555.76
	+	+	+				80130.13
	+	+	+		+		66013.81
	+	+	+			+	76230.00
	+	+					80461.47
	+		+				80142.27

Table 3.8. Summary of model selection results for Winter Dredge survey for A) Age-1+ male crabs, B) Age-1+ female crab and C) Age-1+ combined crabs. Shown are models for probability of occurrence and abundance given occurrence. A "+" indicates that the factor was included in the model. Models indicated by bold type face are the best fitting models according to the AIC criterion.

D) Age-1+ Male

	Year	Month	Strata	Salinity	Temperature (°C)	Depth (m)	AIC
Occurrence models	**+**	**+**	**+**	**+**	**+**	**+**	**13068.39**
	+	+	+	+	+		13891.79
	+	+	+	+			15754.93
	+	+	+				18340.49
	+	+	+		+		14625.53
	+	+	+			+	17227.88
	+	+					19594.56
	+		+				18400.84
Abundance models	**+**	**+**	**+**	**+**	**+**	**+**	**26660.46**
	+	+	+	+	+		28112.24
	+	+	+	+			32871.96
	+	+	+				38563.36
	+	+	+		+		29168.07
	+	+	+			+	36651.44
	+	+					38646.11
	+		+				38630.49

E) Age-1+ Female

	Year	Month	Strata	Salinity	Temperature (°C)	Depth (m)	AIC
Occurrence models	**+**	**+**	**+**	**+**	**+**	**+**	**15361.96**
	+	+	+	+	+		16578.86
	+	+	+	+			18645.37
	+	+	+				20841.36
	+	+	+		+		17263.19
	+	+	+			+	19361.74
	+	+					21446.21
	+		+				20884.20
Abundance models	**+**	**+**	**+**	**+**	**+**	**+**	**34434.58**
	+	+	+	+	+		37005.29
	+	+	+	+			42448.71
	+	+	+				46107.66
	+	+	+		+		37875.95

	+	+	+			+	42844.94
	+	+					46494.90
	+		+				46113.51

F) Age-1+ Combined

	Year	Month	Strata	Salinity	Temperature (°C)	Depth (m)	AIC
Occurrence models	**+**	**+**	**+**	**+**	**+**	**+**	**20508.21**
	+	+	+	+	+		21847.24
	+	+	+	+			24238.45
	+	**+**	**+**				27379.12
	+	+	+		+		22736.81
	+	+	+			+	25741.54
	+	+					27898.70
	+		+				27432.82
Abundance models	**+**	**+**	**+**	**+**	**+**	**+**	**52849.30**
	+	+	+	+	+		56242.90
	+	+	+	+			64387.70
	+	+	+				72092.71
	+	+	+		+		72092.71
	+	+	+			+	67788.46
	+	+					72222.15
	+		+				72113.40

Table 5.1. Reported commercial landings for Virginia, Maryland and the Potomac River. Shown in the table are values for the raw reported landings in million pounds and thousand metric tonnes. For the two states and baywide, the reconstructed landings are also shown in thousand metric tonnes which include corrections to the raw landings for reporting changes. See section 5.2 for a description of the time series analysis used to correct for reporting changes.

	Virginia			**Maryland**			**PRFC**			**Baywide**		
Year	Reported (lbs x 10^6)	Reported (MT x 10^3)	Reconstructed (MT x 10^3)	Reported (lbs x 10^6)	Reported (MT x 10^3)	Reconstructed (MT x 10^3)	Reported (lbs x 10^6)	Reported (MT x 10^3)	Reconstructed (MT x 10^3)	Reported (lbs x 10^6)	Reported (MT x 10^3)	Reconstructed (MT x 10^3)
1950	49.626	22.510	35.575	29.378	13.326	25.741	-	-	-	79.004	35.836	61.316
1951	41.579	18.860	31.925	28.198	12.790	25.205	-	-	-	69.777	31.650	57.131
1952	35.745	16.213	29.279	28.090	12.742	25.157	-	-	-	63.835	28.955	54.435
1953	32.775	14.866	27.932	27.305	12.385	24.801	-	-	-	60.080	27.252	52.732
1954	32.205	14.608	27.673	19.491	8.841	21.256	-	-	-	51.696	23.449	48.929
1955	26.980	12.238	25.303	15.870	7.198	19.613	-	-	-	42.850	19.436	44.917
1956	24.715	11.210	24.276	22.248	10.091	22.506	-	-	-	46.963	21.302	46.782
1957	23.746	10.771	23.836	30.748	13.947	26.362	-	-	-	54.494	24.718	50.198
1958	17.177	7.791	20.856	29.321	13.300	25.715	-	-	-	46.497	21.091	46.571
1959	18.927	8.585	21.650	22.367	10.145	22.561	-	-	-	41.294	18.731	44.211
1960	36.768	16.678	29.743	28.833	13.079	25.494	-	-	-	65.602	29.756	55.237
1961	40.418	18.333	31.398	28.345	12.857	25.272	-	-	-	68.763	31.190	56.671
1962	55.018	24.956	38.021	30.472	13.822	26.237	-	-	-	85.491	38.778	64.258
1963	47.087	21.358	34.424	18.390	8.341	20.757	-	-	-	65.477	29.700	55.180
1964	52.570	23.845	36.910	25.146	11.406	23.821	2.869	1.301	-	80.585	36.553	62.033
1965	51.642	23.424	36.490	33.504	15.197	27.612	3.285	1.490	-	88.431	40.112	65.592
1966	64.759	29.374	42.439	31.152	14.130	26.545	3.503	1.589	-	99.414	45.093	70.574
1967	56.041	25.420	38.485	25.857	11.729	24.144	2.450	1.111	-	84.348	38.259	63.740
1968	45.647	20.705	33.770	9.992	4.532	16.948	1.520	0.690	-	57.159	25.927	51.407
1969	35.611	16.153	29.218	24.399	11.067	23.482	1.624	0.736	-	61.633	27.956	53.437
1970	43.326	19.652	32.718	25.607	11.615	24.030	1.906	0.865	-	70.839	32.132	57.612
1971	48.459	21.981	35.046	26.660	12.093	24.508	1.902	0.863	-	77.021	34.936	60.416

1972	49.285	22.355	35.421	24.198	10.976	23.391	2.124	0.963	-	75.608	34.295	59.775
1973	35.085	15.914	28.980	20.331	9.222	21.637	1.603	0.727	-	57.019	25.863	51.344
1974	38.385	17.411	30.476	25.575	11.601	24.016	1.669	0.757	-	65.629	29.769	55.249
1975	31.988	14.509	27.575	25.030	11.353	23.769	2.079	0.943	-	59.096	26.806	52.286
1976	23.855	10.820	23.886	20.187	9.157	21.572	1.989	0.902	-	46.032	20.880	46.360
1977	36.100	16.375	29.440	20.593	9.341	21.756	2.993	1.358	-	59.686	27.073	52.553
1978	33.150	15.037	28.102	16.861	7.648	20.063	2.221	1.007	-	52.232	23.692	49.173
1979	37.443	16.984	30.049	24.899	11.294	23.709	2.917	1.323	-	65.258	29.601	55.081
1980	34.013	15.428	28.493	25.546	11.587	24.002	3.475	1.576	-	63.033	28.591	54.072
1981	40.588	18.410	31.476	57.650	26.150	26.150	5.229	2.372	-	103.467	46.932	59.997
1982	45.496	20.637	33.702	42.167	19.127	19.127	4.173	1.893	-	91.837	41.656	54.722
1983	42.172	19.129	32.194	50.673	22.985	22.985	4.898	2.222	-	97.743	44.336	57.401
1984	45.380	20.584	33.649	47.100	21.364	21.364	3.974	1.803	-	96.454	43.751	56.816
1985	39.132	17.750	30.815	55.527	25.187	25.187	6.041	2.740	-	100.700	45.677	58.742
1986	34.671	15.727	28.792	46.414	21.053	21.053	5.863	2.659	-	86.948	39.439	52.504
1987	30.060	13.635	26.700	42.648	19.345	19.345	4.791	2.173	-	77.499	35.153	48.218
1988	34.378	15.593	28.659	41.673	18.903	18.903	4.970	2.254	-	81.021	36.751	49.816
1989	41.586	18.863	31.928	42.352	19.211	19.211	5.322	2.414	-	89.260	40.488	53.553
1990	51.507	23.363	36.428	45.094	20.455	20.455	5.225	2.370	-	101.826	46.188	59.253
1991	44.849	20.343	33.408	47.491	21.541	21.541	7.224	3.277	-	99.563	45.161	58.226
1992	23.847	10.817	23.882	30.858	13.997	13.997	5.810	2.635	-	60.515	27.449	40.514
1993	52.651	23.882	23.882	56.821	25.774	25.774	7.549	3.424	-	117.021	53.080	53.080
1994	34.721	15.749	15.749	44.243	20.068	20.068	5.972	2.709	-	84.936	38.526	38.526
1995	33.105	15.016	15.016	41.173	18.676	18.676	4.049	1.837	-	78.328	35.529	35.529
1996	34.487	15.643	15.643	37.021	16.792	16.792	5.688	2.580	-	77.195	35.015	35.015
1997	38.984	17.683	17.683	40.160	18.216	18.216	9.061	4.110	-	88.204	40.009	40.009
1998	34.503	15.650	15.650	25.678	11.647	11.647	5.287	2.398	-	65.468	29.696	29.696
1999	32.472	14.729	14.729	31.570	14.320	14.320	5.289	2.399	-	69.331	31.448	31.448
2000	30.635	13.896	13.896	20.239	9.180	9.180	2.131	0.967	-	53.005	24.043	24.043
2001	26.682	12.103	12.103	22.668	10.282	10.282	2.440	1.107	-	51.790	23.492	23.492

2002	28.114	12.752	12.752	23.843	10.815	10.815	2.888	1.310	-	54.845	24.877	24.877
2003	21.137	9.588	9.588	25.261	11.458	11.458	2.005	0.910	-	48.404	21.956	21.956
2004	25.507	11.570	11.570	32.305	14.653	14.653	2.729	1.238	-	60.541	27.461	27.461
2005	24.334	11.038	11.038	30.149	13.675	13.675	4.263	1.934	-	58.746	26.647	26.647
2006	20.833	9.450	9.450	27.874	12.643	12.643	3.985	1.808	-	52.692	23.901	23.901
2007	17.381	7.884	7.884	24.745	11.224	11.224	2.424	1.099	-	44.549	20.207	20.207
2008	16.726	7.587	7.587	29.370	13.322	13.322	2.485	1.127	-	48.582	22.036	22.036
2009	22.500	10.206	10.206	28.527	12.940	12.940	2.871	1.302	-	53.898	24.448	24.448

Table 5.2. Results of intervention analysis for the Virginia commercial landings for the period 1950-2009

Parameter	Estimate (± SE)
ω_{1993}	- 13.0652 (3.3509)
AIC	314.12
AIC_c	314.34
RMSE	3.3228

Table 5.3. Results of intervention analysis for the Maryland commercial landings for the period 1950-2009.

Parameter	Estimate (± SE)
ω_{1981}	- 12.4151 (2.2862)
θ	- 0.6246 (0.1019)
AIC	299.72
AIC_c	300.16
RMSE	2.8795

Table 5.4. The average sex ratio in the catch based on data from sex-specific landings 1994-2006

	Sex Ratio (in % averaged from 1994-2006)		
	Virginia	Maryland	PRFC
Male	25.9	56	62
Female	74.1	44	38

Table 5.5 Reported sex-specific landings for the three Chesapeake Bay jurisdictions.

	Virginia				**Maryland**				**PRFC**				**Baywide**			
Year	Males (lbs x 10^6)	Females (lbs x 10^6)	Male (MT x 10^3)	Female (MT x 10^3)	Males (lbs x 10^6)	Females (lbs x 10^6)	Male (MT x 10^3)	Female (MT x 10^3)	Males (lbs x 10^6)	Females (lbs x 10^6)	Male (MT x 10^3)	Female (MT x 10^3)	Males (lbs x 10^6)	Females (lbs x 10^6)	Male (MT x 10^3)	Female (MT x 10^3)
1985					33.955	21.572	15.402	9.785								
1986					31.870	14.544	14.456	6.597								
1987					29.472	13.176	13.368	5.976								
1988					26.998	14.676	12.246	6.657								
1989					28.216	14.137	12.798	6.412								
1990					30.165	14.930	13.682	6.772								
1991					33.247	14.244	15.081	6.461								
1992					19.344	11.514	8.774	5.223								
1993					34.285	22.536	15.552	10.222								
1994	9.081	25.641	4.119	11.630	24.201	20.042	10.977	9.091	3.243	2.729	1.471	1.238	36.524	48.412	12.448	10.329
1995	8.516	24.589	3.863	11.153	23.195	17.978	10.521	8.155	2.441	1.608	1.107	0.730	34.152	44.175	11.628	8.884
1996	9.530	24.957	4.323	11.320	18.252	18.768	8.279	8.513	3.272	2.416	1.484	1.096	31.054	46.141	9.763	9.609
1997	10.803	28.181	4.900	12.783	21.771	18.389	9.875	8.341	5.414	3.647	2.456	1.654	37.988	50.217	12.331	9.995
1998	9.096	25.407	4.126	11.525	14.911	10.766	6.764	4.883	3.564	1.723	1.616	0.782	27.571	37.897	8.380	5.665
1999	8.103	24.370	3.675	11.054	17.739	13.831	8.046	6.274	3.453	1.836	1.566	0.833	29.294	40.037	9.612	7.107
2000	6.716	23.919	3.046	10.849	10.881	9.357	4.936	4.244	1.339	0.792	0.607	0.359	18.936	34.069	5.543	4.604
2001	7.358	19.323	3.338	8.765	13.134	9.535	5.957	4.325	1.459	0.982	0.662	0.445	21.951	29.840	6.619	4.770
2002	7.050	21.065	3.198	9.555	13.325	10.517	6.044	4.770	1.867	1.021	0.847	0.463	22.242	32.603	6.891	5.234
2003	5.611	15.526	2.545	7.042	13.555	11.706	6.148	5.310	1.303	0.703	0.591	0.319	20.469	27.935	6.739	5.629
2004	6.737	18.770	3.056	8.514	20.281	12.024	9.199	5.454	1.809	0.920	0.821	0.417	28.827	31.714	10.020	5.871
2005	6.327	18.007	2.870	8.168	17.310	12.839	7.852	5.823	2.770	1.493	1.257	0.677	26.407	32.338	9.108	6.501
2006	4.940	15.893	2.241	7.209	15.884	11.989	7.205	5.438	2.331	1.654	1.057	0.750	23.155	29.537	8.262	6.189
2007	4.612	12.768	2.092	5.792	13.583	11.162	6.161	5.063	1.607	0.816	0.729	0.370	19.803	24.747	6.890	5.433
2008	5.953	10.773	2.700	4.887	19.450	9.920	8.822	4.500	1.353	1.132	0.614	0.514	26.756	21.826	9.436	5.013
2009	7.278	15.222	3.301	6.904	20.440	8.086	9.272	3.668	1.942	0.930	0.881	0.422	29.660	24.238	10.152	4.090

Table 5.6. The average size (carapace width) and resultant average weights (based on Eq. 3) in each of the three jurisdictions for the period 1989-2009. Note the sizes in the PRFC area of jurisdiction are assumed to be equivalent to those in Maryland.

	Male		Female	
State	Mean Size (mm)	Mean Weight (lbs)	Mean Size (mm)	Mean Weight (lbs)
Virginia	142.750	0.384	141.440	0.281
Maryland	148.041	0.421	147.792	0.310
PRFC	148.041	0.421	147.792	0.310

Table 5.7 Estimated landings in the Chesapeake Bay by number (Millions) for the years 1985-2009. Although Maryland started reporting its harvest figures by number in 1985, all jurisdictions did not do so until 1994.

	Virginia			**Maryland**			**PRFC**			**Baywide**		
Year	Males	Females	Total	Males	Females	Total	Males	Females	Total	Males	Females	Total
1985				80.736	69.565	150.301						
1986				75.777	46.901	122.678						
1987				70.076	42.489	112.565						
1988				64.192	47.326	111.519						
1989				67.089	45.587	112.676						
1990				71.723	48.145	119.868						
1991				79.052	45.933	124.985						
1992				45.994	37.130	83.124						
1993				81.521	72.673	154.193						
1994	24.486	92.545	117.031	61.757	63.847	125.604	7.787	8.834	16.621	94.030	165.226	259.256
1995	23.185	89.079	112.264	60.478	60.407	120.885	5.910	5.231	11.141	89.573	154.717	244.290
1996	25.812	90.364	116.176	49.573	61.120	110.694	7.888	7.836	15.724	83.273	159.320	242.593
1997	29.350	102.189	131.539	57.870	61.043	118.912	12.994	11.813	24.807	100.213	175.045	275.258
1998	25.086	92.620	117.706	39.124	36.160	75.284	8.603	5.613	14.216	72.814	134.392	207.206
1999	22.325	88.646	110.971	46.502	46.177	92.679	8.317	5.967	14.284	77.144	140.790	217.934
2000	18.665	86.968	105.633	30.462	33.084	63.546	3.305	2.605	5.910	52.432	122.656	175.088
2001	20.540	70.946	91.486	36.871	35.120	71.990	3.546	3.198	6.744	60.957	109.263	170.220
2002	19.570	76.872	96.443	33.303	33.762	67.065	4.483	3.311	7.794	57.356	113.946	171.302
2003	15.531	56.699	72.230	37.123	40.261	77.384	3.139	2.284	5.423	55.792	99.245	155.037
2004	18.478	68.263	86.741	50.319	40.317	90.636	4.341	2.984	7.325	73.138	111.565	184.702
2005	17.099	65.048	82.146	44.097	41.346	85.443	6.615	4.828	11.443	67.811	111.221	179.032
2006	13.368	57.338	70.707	39.379	37.983	77.363	5.572	5.350	10.922	58.320	100.671	158.991
2007	12.404	46.044	58.448	33.689	34.481	68.171	3.859	2.649	6.507	49.952	83.174	133.126
2008	16.014	39.136	55.150	48.146	32.930	81.075	3.249	3.665	6.914	67.409	75.731	143.140
2009	19.498	55.012	74.511	50.600	27.066	77.666	4.648	3.012	7.661	74.747	85.090	159.838

Table 6.1 . Variable and parameter definitions for SSCMA model.

Variable	Description
y	Year
s	Sex
i	Index of abundance
f	Female
m	Male
k	Number of observations
x	Sex ratio at recruitment
M	Natural mortality rate
η	Partial recruitment to the fishery
κ	Proportion of mortality before spawning
τ	Proportion of mortality before Maryland trawl survey
Estimated values	
R	Recruitment
N	Adult abundance
I_R	Recruitment index of abundance
I_N	Adult index of abundance
Natural parameters (estimated)	
N_0	Initial adult abundance
R_0	Median recruitment
δ	Log-scale deviations from median recruitment
F	Instantaneous fishing mortality rate
α, β	S-R parameters
q	Catchability
Variance terms	
σ_R	Log-scale SD for recruitment deviations
σ_i	Log-scale SD for observation error in indices of abundance
σ_F	SD for variability in the ratio of male to female fishing mortality during 1968-2006
μ	Mean of the ratio of male to female fishing mortality during 1968-2006
Reference point variables	
YPR	Yield per recruit
N_{YPR}	Abundance per recruit for YPR calculations
SPR	Spawners per recruit

N_{eq}	Equilibrium age-1+ abundance
R_{eq}	Equilibrium age-0 abundance
C_{eq}	Equilibrium catch in numbers

Table 6.2 Results of sensitivity analyses of the SSCMSA. Results of sensitivity analyses for the SSCMSA. Columns indicate model specifications or model estimates. Model specifications included Mf (female natural mortality), Mm (Male natural mortality), rf (partial recruitment of age-0), sex_r (sex ratio of age-0). Values that were estimated are marked with an asterisk. Model estimates included neg_LL (value for the negative log likelihood), Nf2010 (age-1+ female abundance in 2010, Frat 68-06 (average quotient of male instantaneous fishing mortality rate to the female instantaneous fishing mortality rate during 1968-2006), Frat2009 (quotient of male instantaneous fishing mortality rate to the female instantaneous fishing mortality rate during 2009), Nf_MSY2009 (equilibrium number of age-1+ females at MSY given the F ratio in 2009), Nf/Nftarg (estimated age-1+ female abundance in 2009 relative to the equilibrium abundance at the target exploitation rate in 2009), and uMSY (the exploitation rate for age-0+females that would produce MSY given the F ratio in 2009).

Name	Mf	Mm	rf	sex_r	neg_LL	Nf2010	Frat 68-06	Frat2009	Nf_MSY2009	Nf/Nftarg	uMSY
Base	0.90	0.90	0.6	0.52	248.4	180.6	0.97	1.39	158.2	0.84	0.34
low M	0.60	0.60	0.6	0.52	232.9	178.7	1.21	1.70	183.5	0.73	0.38
High M	1.20	1.20	0.6	0.52	246.2	181.7	0.84	1.25	144.6	0.92	0.30
low r	0.90	0.90	0.3	0.52	252.7	181.2	0.99	1.42	173.9	0.80	0.33
high r	0.90	0.90	0.9	0.52	247.1	180.4	0.97	1.37	153.4	0.86	0.34
est male M	0.90	1.39*	0.6	0.52	86.7	196.9	0.73	1.72	211.3	0.68	0.35
est sex ratio	0.90	0.90	0.6	0.64*	78.3	199.4	0.90	2.19	244.7	0.60	0.36

est rf	0.90	0.90	1.0*	0.52	246.9	180.3	0.97	1.37	150.2	0.86	0.34
Est WDSq	0.9	0.9	0.6	0.52	41.9	16	0.41	0.55	45.7	0.35	0.65
Comb SR	0.90	0.90	0.60	0.52	248.5	180	0.88	1.39	129.3	NA	0.34

Figure 1.1. Conceptual management control rule used in managing blue crab fisheries in Chesapeake Bay. Shown on the figure are the two exploitation rate levels (threshold U= 0.53, target U=-4.6) and the two abundance levels (target- 200 million age-1+ crabs, and limit = 86 million age1+ crabs).

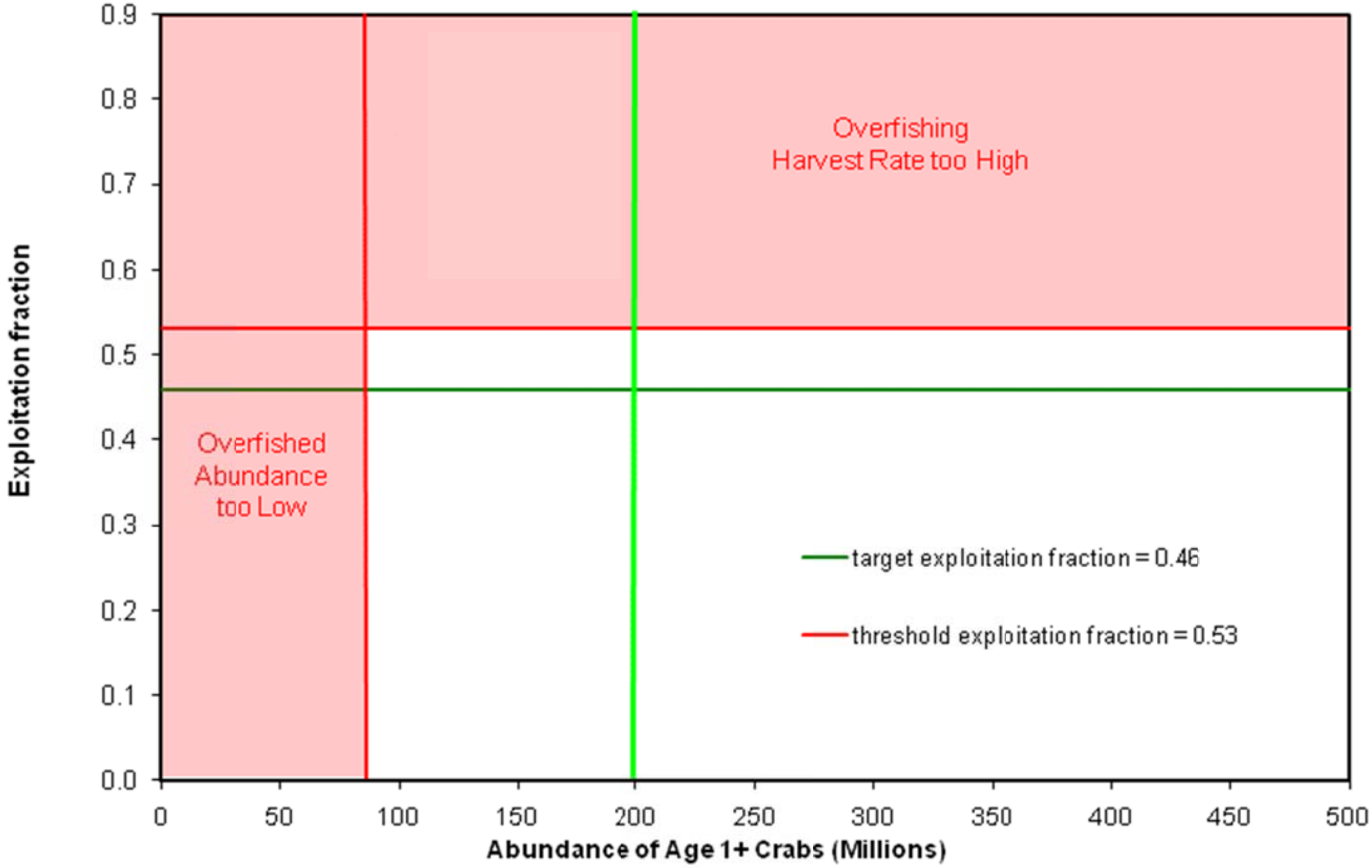

Figure 2.1. Cumulative partial recruitment of field-collected blue crabs grouped into lipofuscin-based age-classes in (A) the peeler–soft crab fishery and (B) the hard crab fishery by month from June to October (from Puckett et al. 2008).

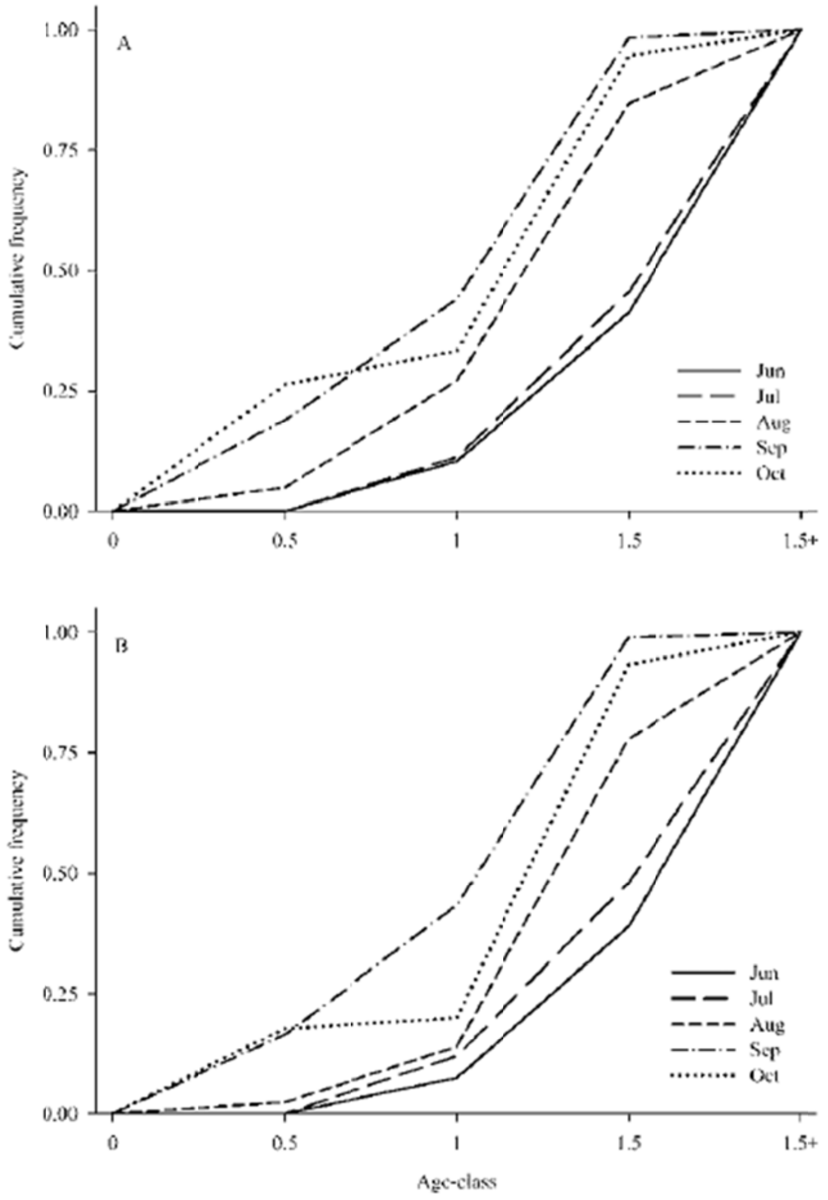

Fig. 2.2. Summary of direct empirical (symbols) and indirect (histogram) estimates of natural mortality rate (M) of blue crab (Hewitt et al. 2007). The direct estimates are from the results of tag-recapture studies conducted in the Chesapeake Bay in 2002-2004 reported by Lambert et al. (2006). These data are based on estimates of Z for mature females. Indirect estimates resulted from eight different life history models and yielded ranges of estimates of either Z or M. In all cases, estimates of Z were converted to M using estimates of F calculated in the winter dredge survey. The vertical dashed lines indicate the M values used in the last assessment (0.375, 0.6, 0.9, 1.2 per year).

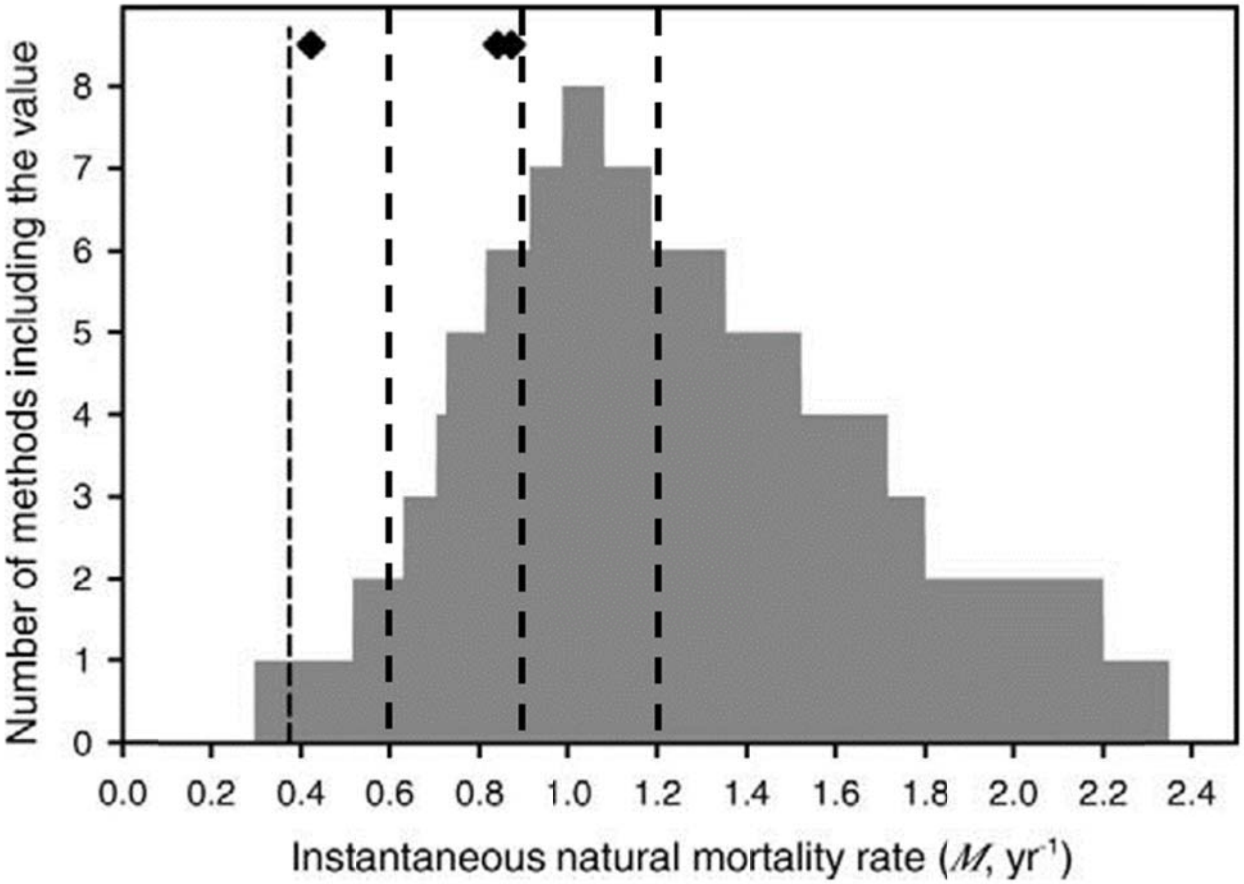

Figure 2.3. Annaul survival estimates (S) of mature female blue crab from a tag-recapture program conducted in the Chesapeake Bay from 2001-2010. Estimates are derived from data that came either from all fisheries (including the winter dredge fishery) or from just pot fisheries. This comparison attempted to account for the impacts of the closure of winter dredge fishery as a source of crab returns after 2007.

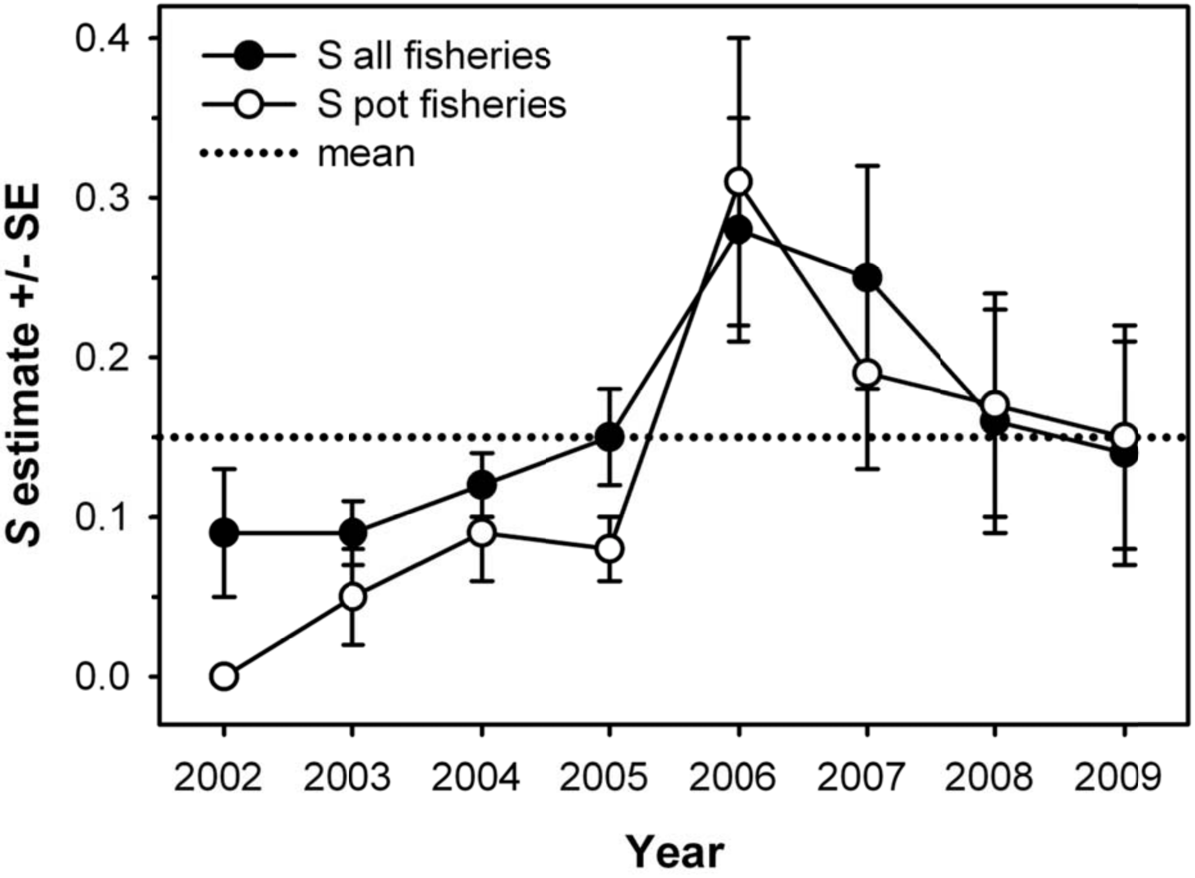

Figure 3.1 Size frequency plots from the winter dredge survey for 1990-2010. The vertical line on each figure represents the 60 mm carapace width size bin.

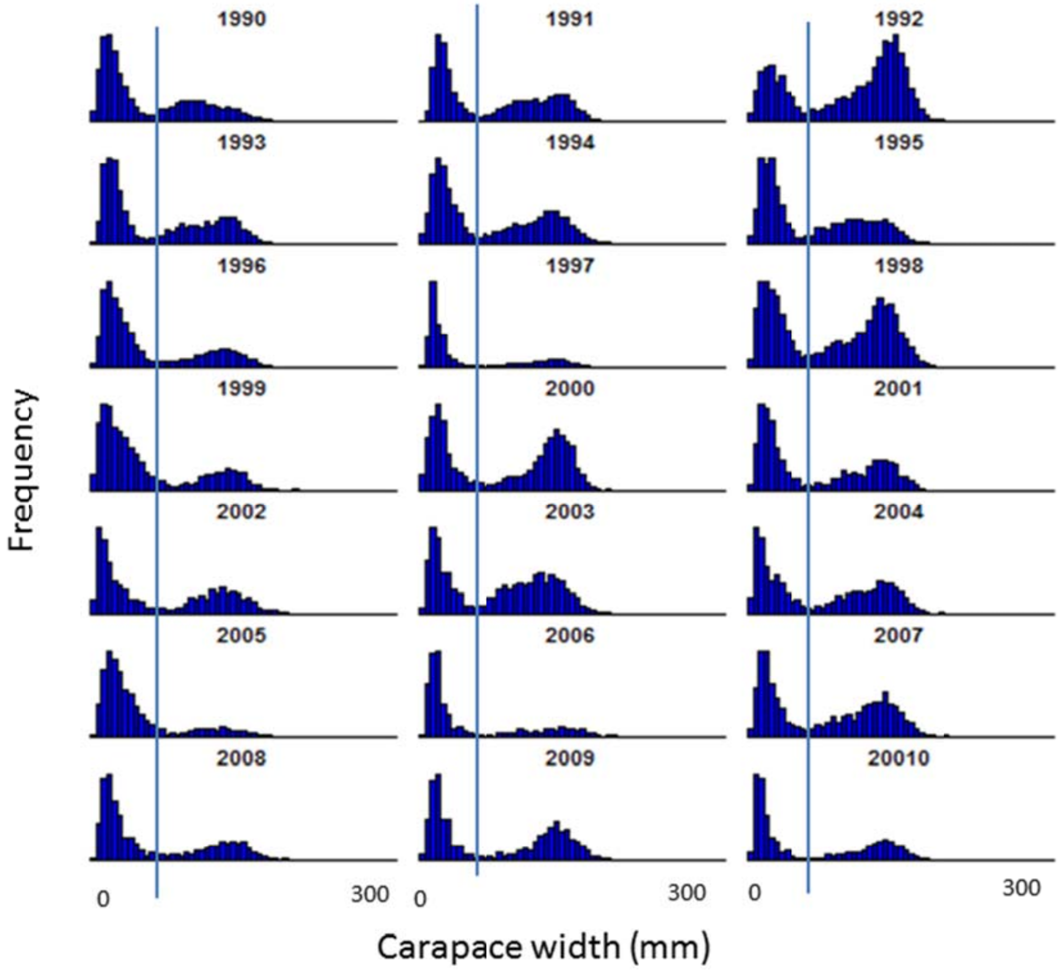

Figure 3.2. Example distribution of stations in the three principal fishery-independent surveys. A) Maryland DNR summer trawl survey, B) VIMS spring trawl survey and C) winter dredge survey.

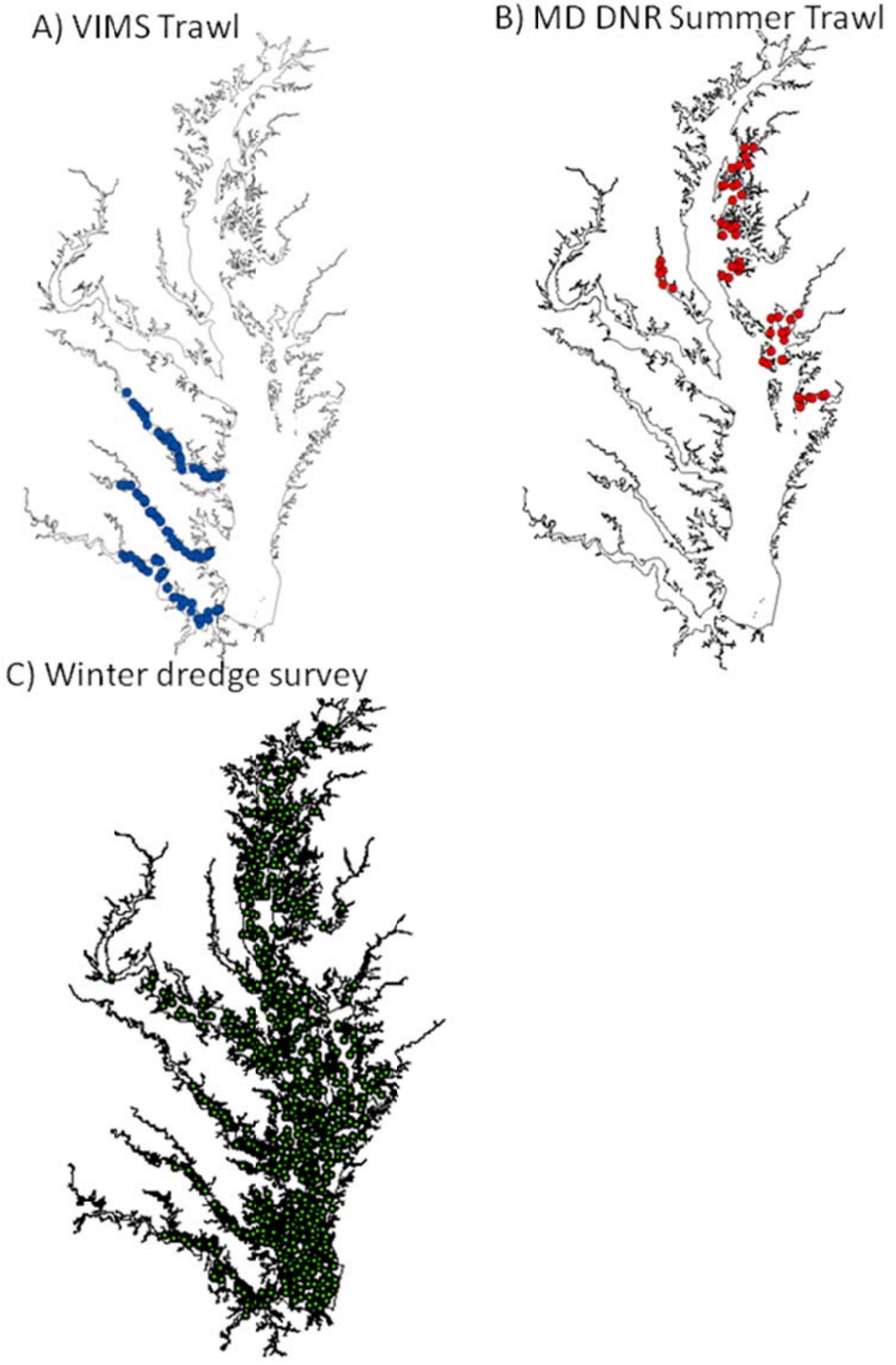

Figure 3.3. Time series of age-0 crab abundance in the VIMS spring trawl survey (1956-2009).

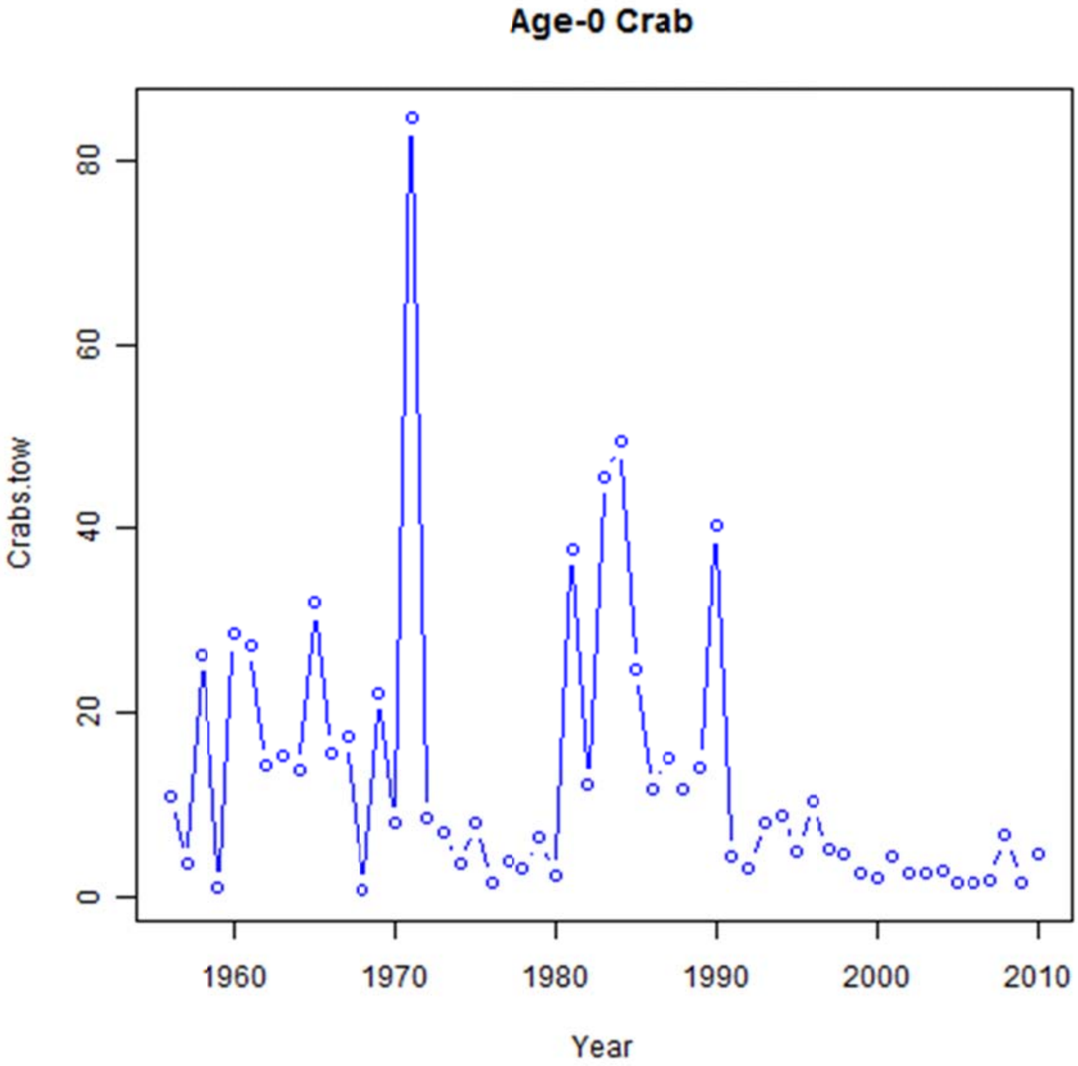

Figure 3.4. Age-1+ crab indices for the VIMS spring trawl. Shown are plots for age-1+ male, age-1+ female and age-1+ combined. Each panel shows the simple annual weighted geometric mean of reported survey data.

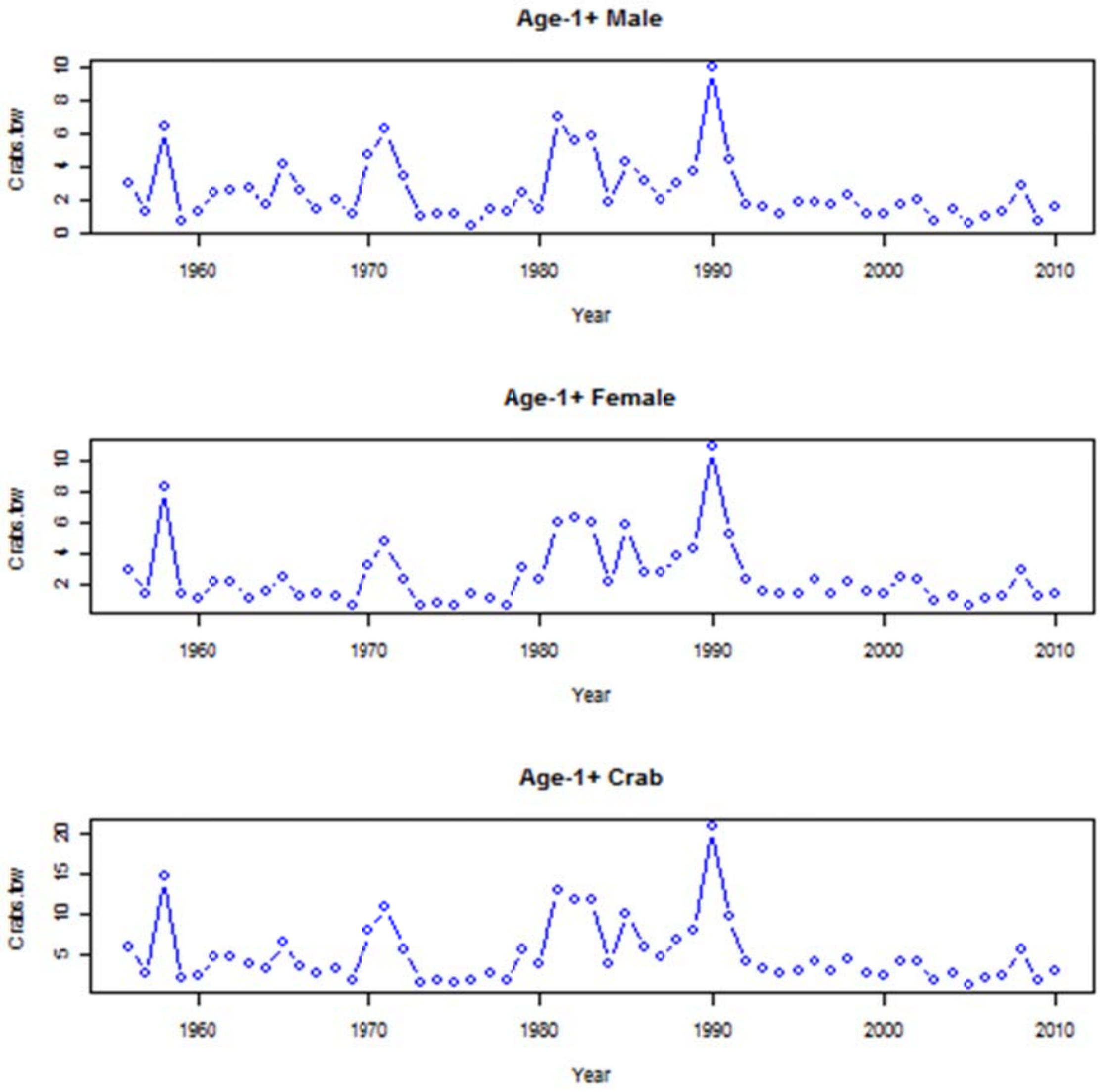

Figure 3.5. The relationship between survey indices of age-1 crab abundance for females, males and both sexes combined for the VIMS spring trawl survey. The upper panels show the correlation scatter plots. The two lines provide a context for comparing survey indices. The red line on the upper panel plots is the 1:1 line, which is appropriate for comparing sex-specific indices. The blue line is a 1:2 line, which may be more appropriate for comparing the individual sex-specific indices with the aggregate index. The lower panels present the Pearson linear correlation coefficients.

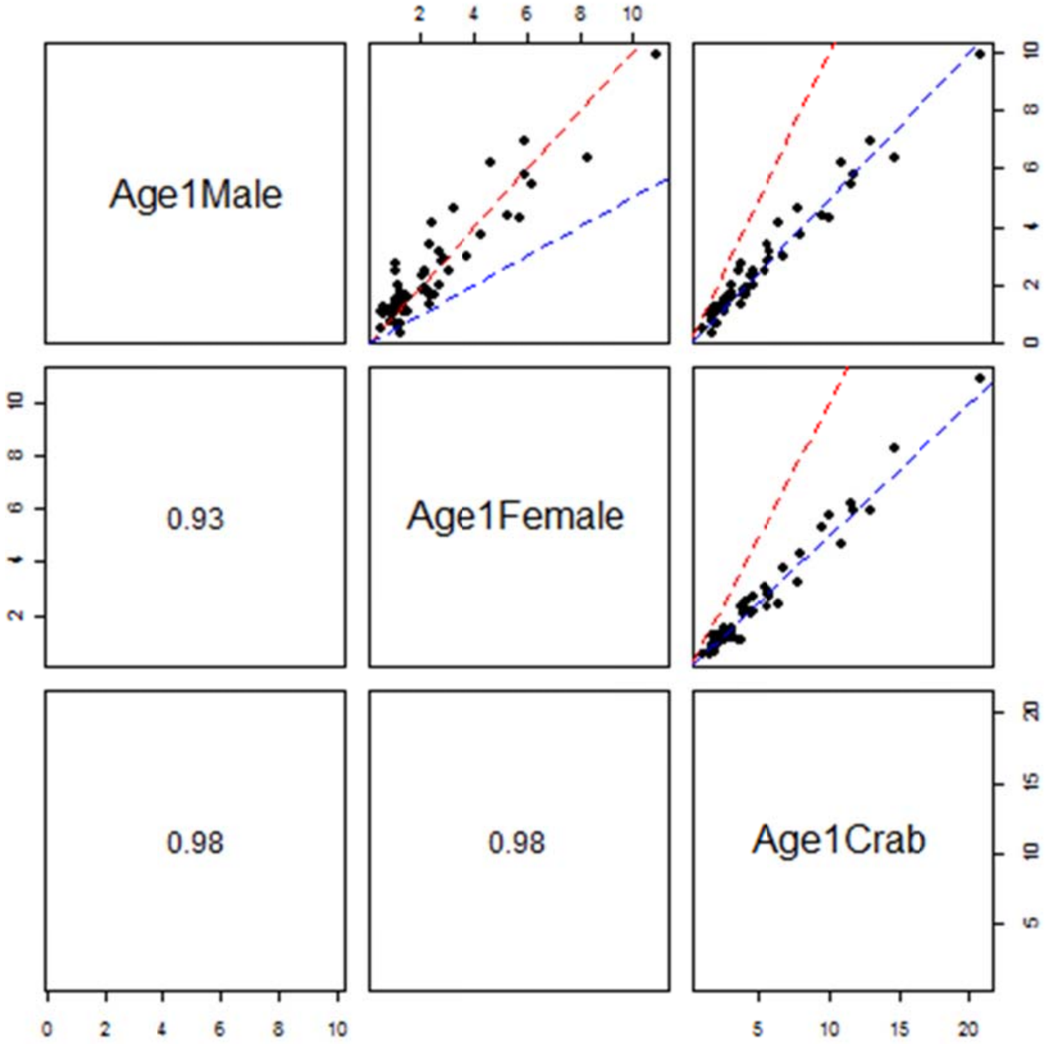

Figure 3.6. Correlation of lagged indices for the VIMS spring trawl survey. Plot is for correlation of age-0 indices in year t with age-1 indices in year t+1. The blue line is the least squares linear fit to the data. The r-statistic is given in the plot.

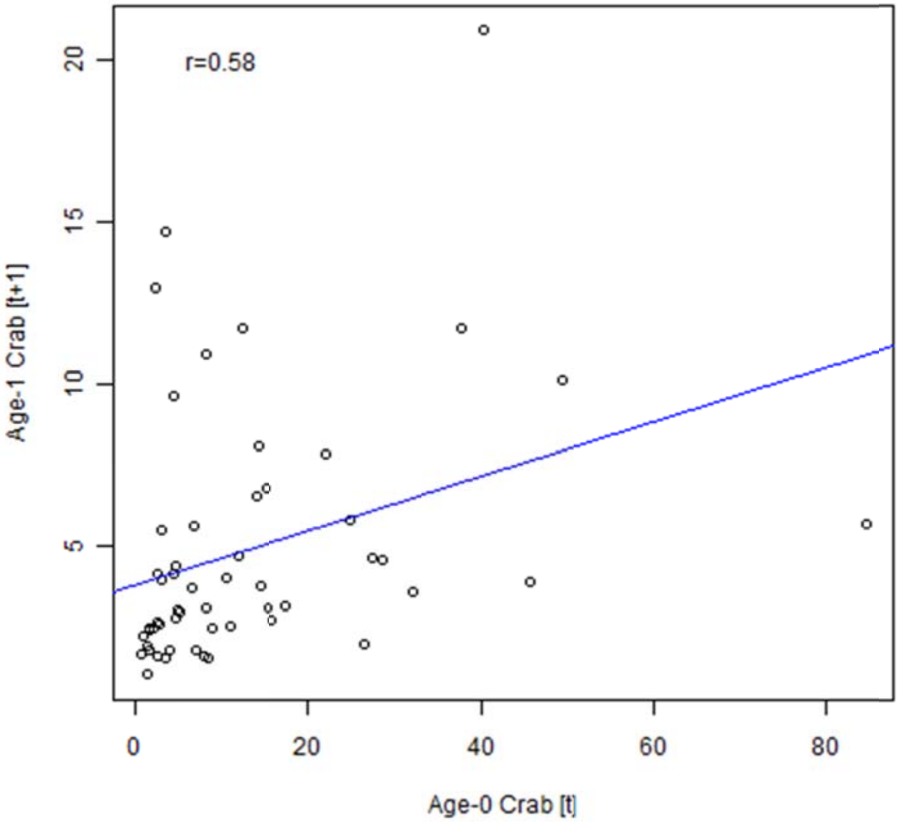

Figure 3.7 Frequency distribution of observed values of environmental parameters measured during the Maryland DNR blue crab trawl survey (1977-2009).

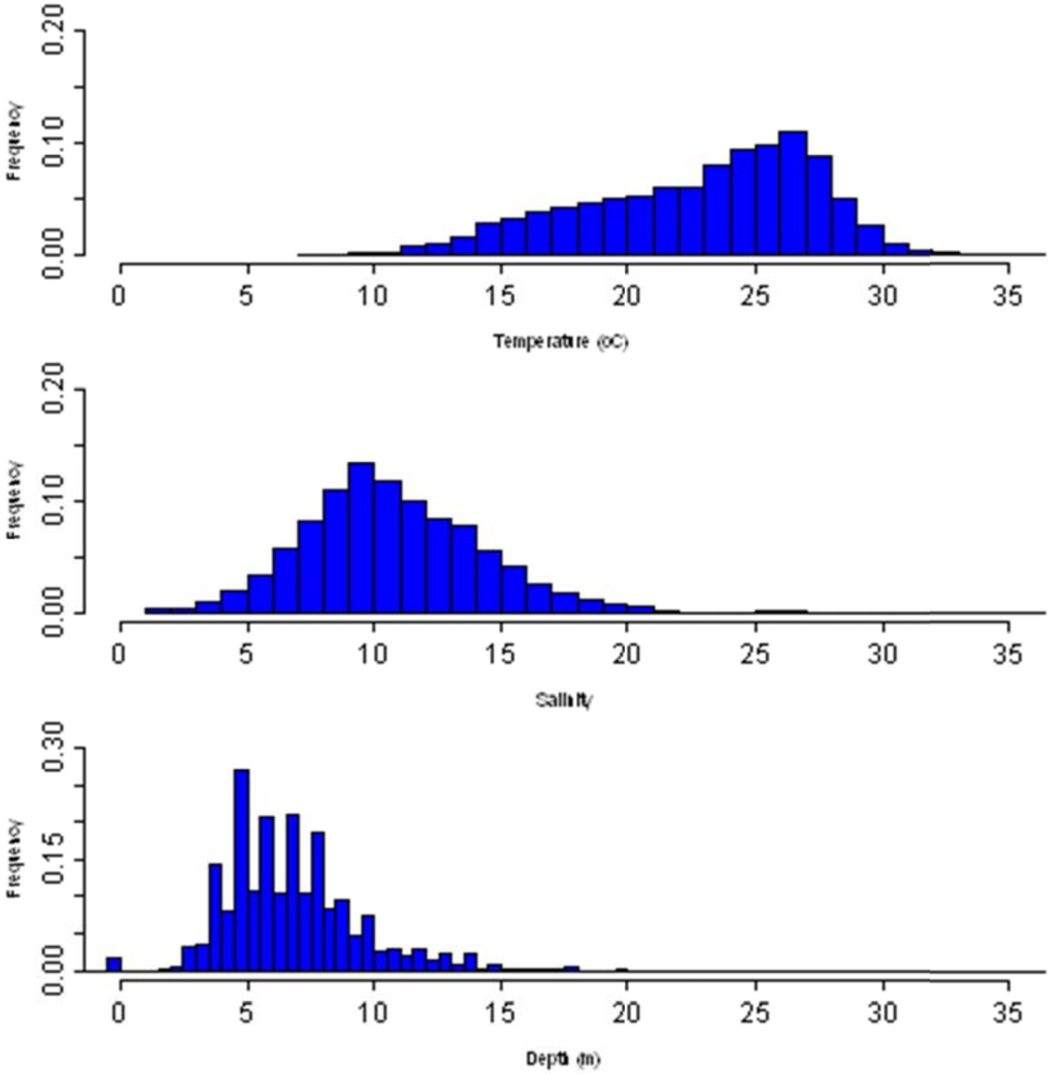

Figure 3.8. The distribution of catches of age-0 crabs in the Maryland blue crab trawl survey (1977-2009) for A) Male crabs, B) Female crabs and C) Both sexes combined.

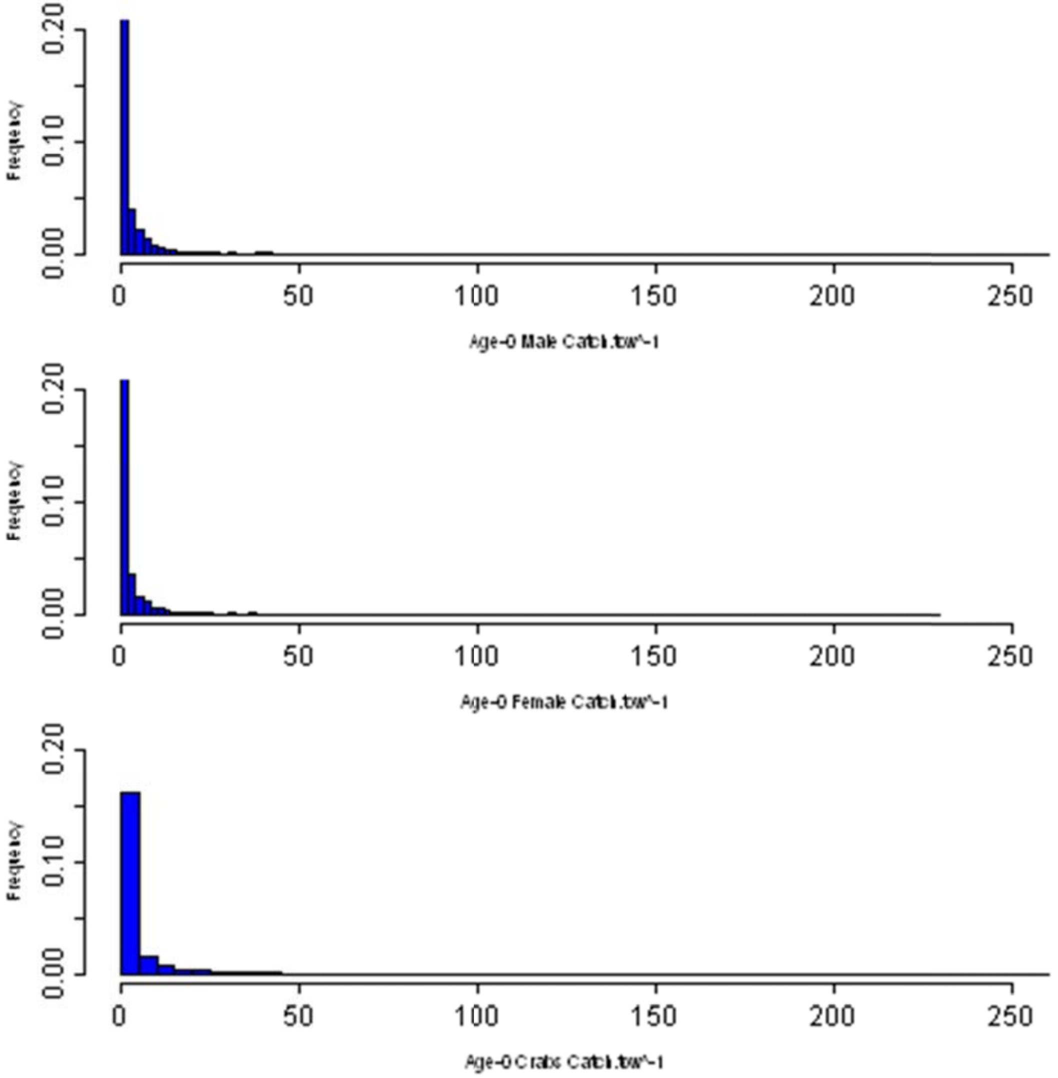

Figure 3.9. The distribution of catches of age-0 crabs in the Maryland blue crab trawl survey (1977-2009) for A) Male crabs, B) Female crabs and C) Both sexes combined.

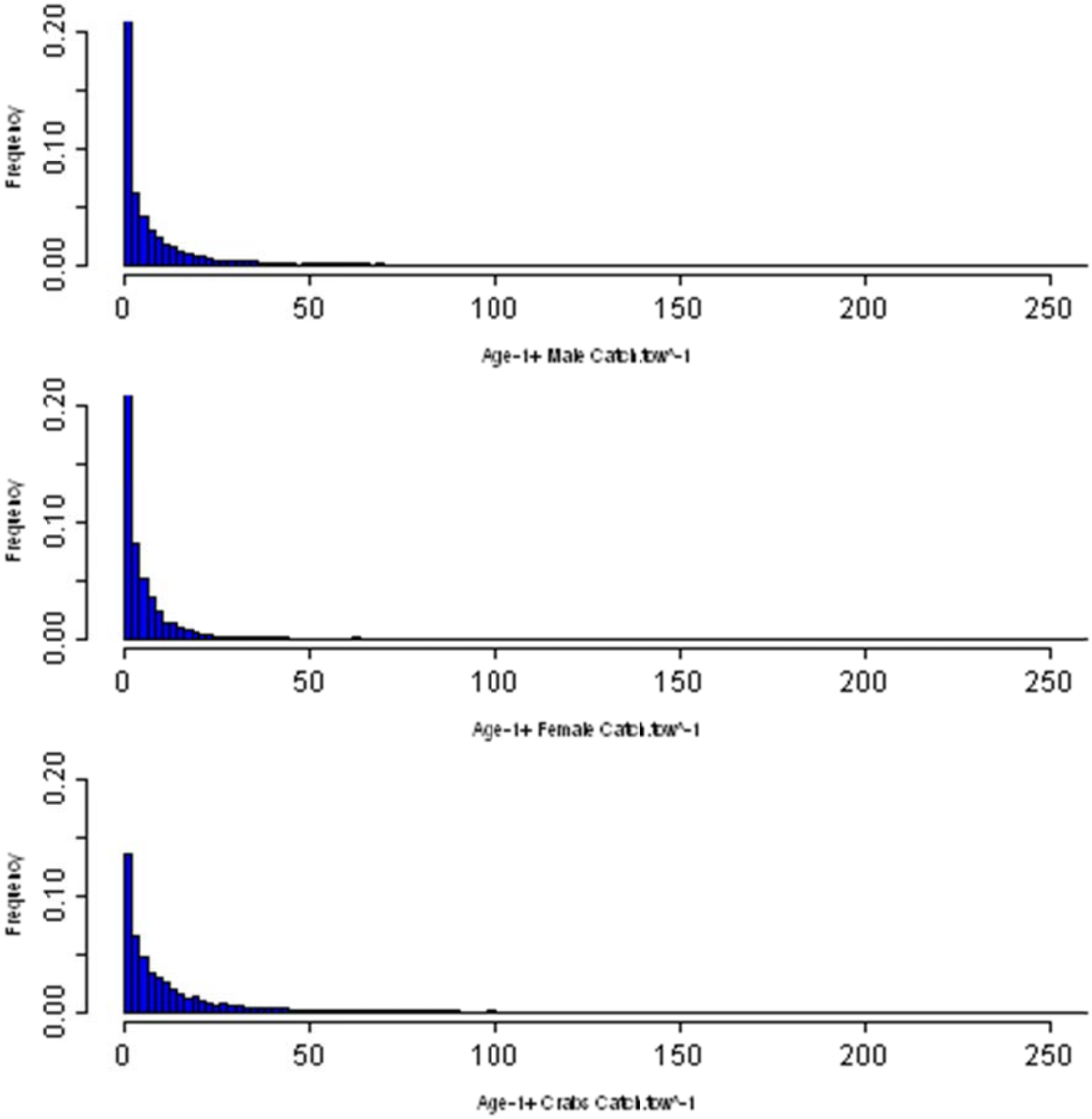

Figure 3.10. Age-0 crab standardized indices for the Maryland blue crab trawl survey. Shown are plots for age-0 male, age-0 female and age-0 combined. Each panel shows the best fitting GLM index time series (solid blue line), plus and minus standard errors. Each panel also depctes the simple annual mean (open symbol) and its associated standard error (as whiskers) for reported survey data.

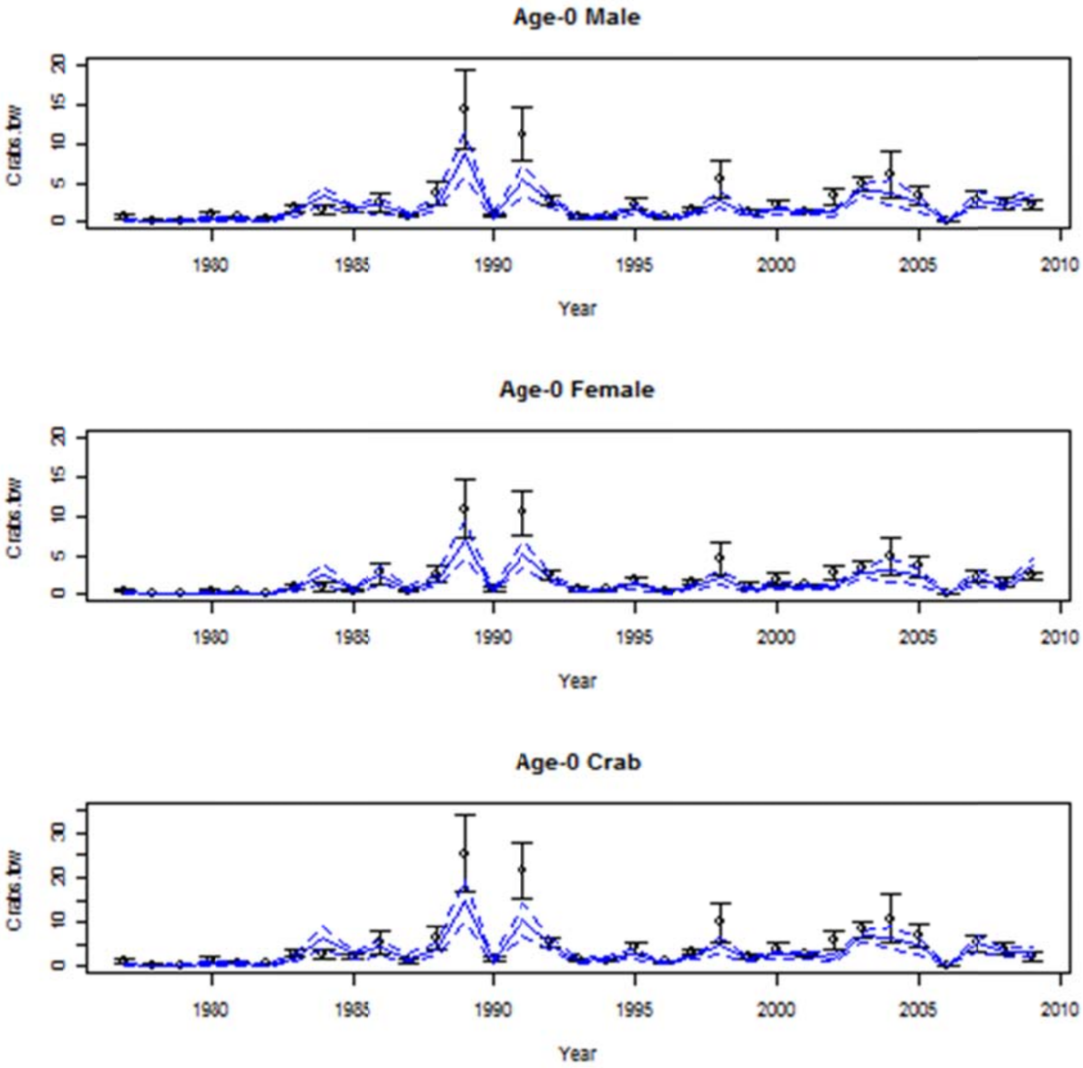

Figure 3.11. The relationship between GLM indices of age-0 crab abundance for females, males and both sexes combined for the Maryland blue crab trawl survey. The upper panels show the correlation scatter plots. The two lines provide a context for comparing survey indices. The red line on the upper panel plots is the 1:1 line, which is appropriate for comparing sex-specific indices. The blue line is a 1:2 line, which may be more appropriate for comparing the individual sex-specific indices with the aggregate index. The lower panels present the Pearson linear correlation coefficients.

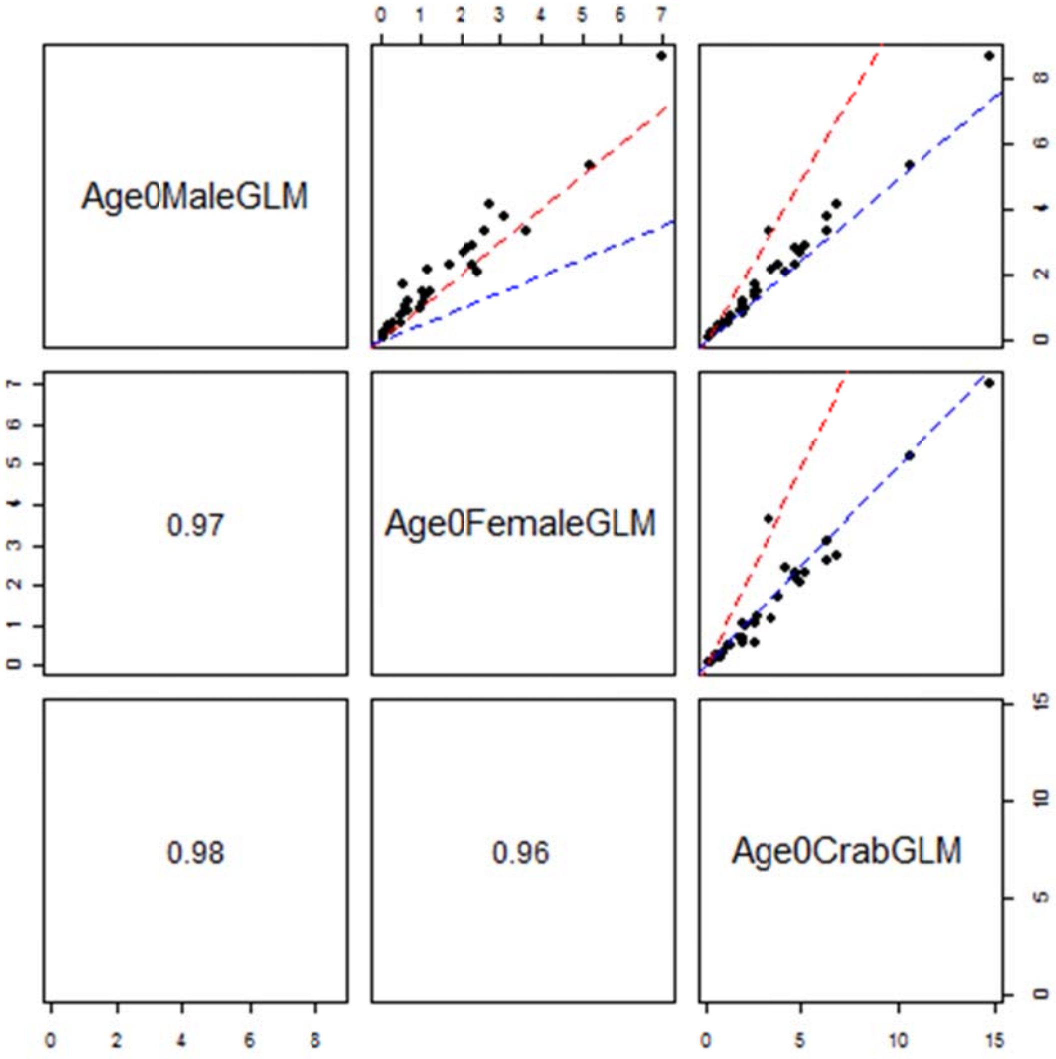

Figure 3.12. Age-1+ crab standardized indices for the Maryland blue crab trawl survey. Shown are plots for age-1+ male, age-1+ female and age-1+ combined. Each panel shows the best fitting GLM index time series (blue line) and the simple annual mean of reported survey data. Each panel shows the best fitting GLM index time series (solid blue line), plus and minus standard errors. Each panel also depctes the simple annual mean (open symbol) and its associated standard error (as whiskers) for reported survey data.

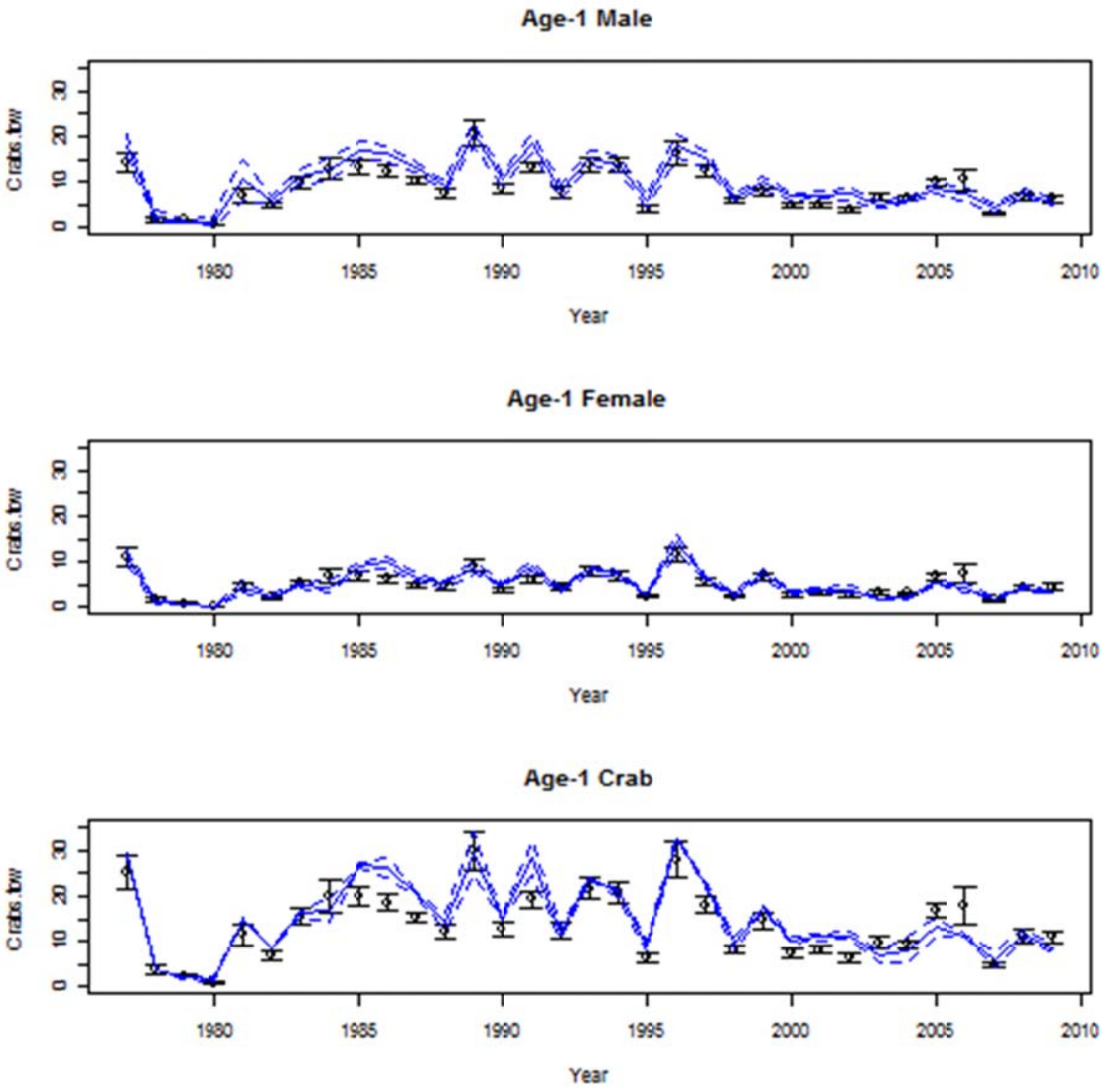

Figure 3.13. The relationship between GLM indices of age-1+ crab abundance for females, males and both sexes combined for the Maryland blue crab trawl survey. The upper panels show the correlation scatter plots. The two lines provide a context for comparing survey indices. The red line on the upper panel plots is the 1:1 line, which is appropriate for comparing sex-specific indices. The blue line is a 1:2 line, which may be more appropriate for comparing the individual sex-specific indices with the aggregate index. The lower panels present the Pearson linear correlation coefficients.

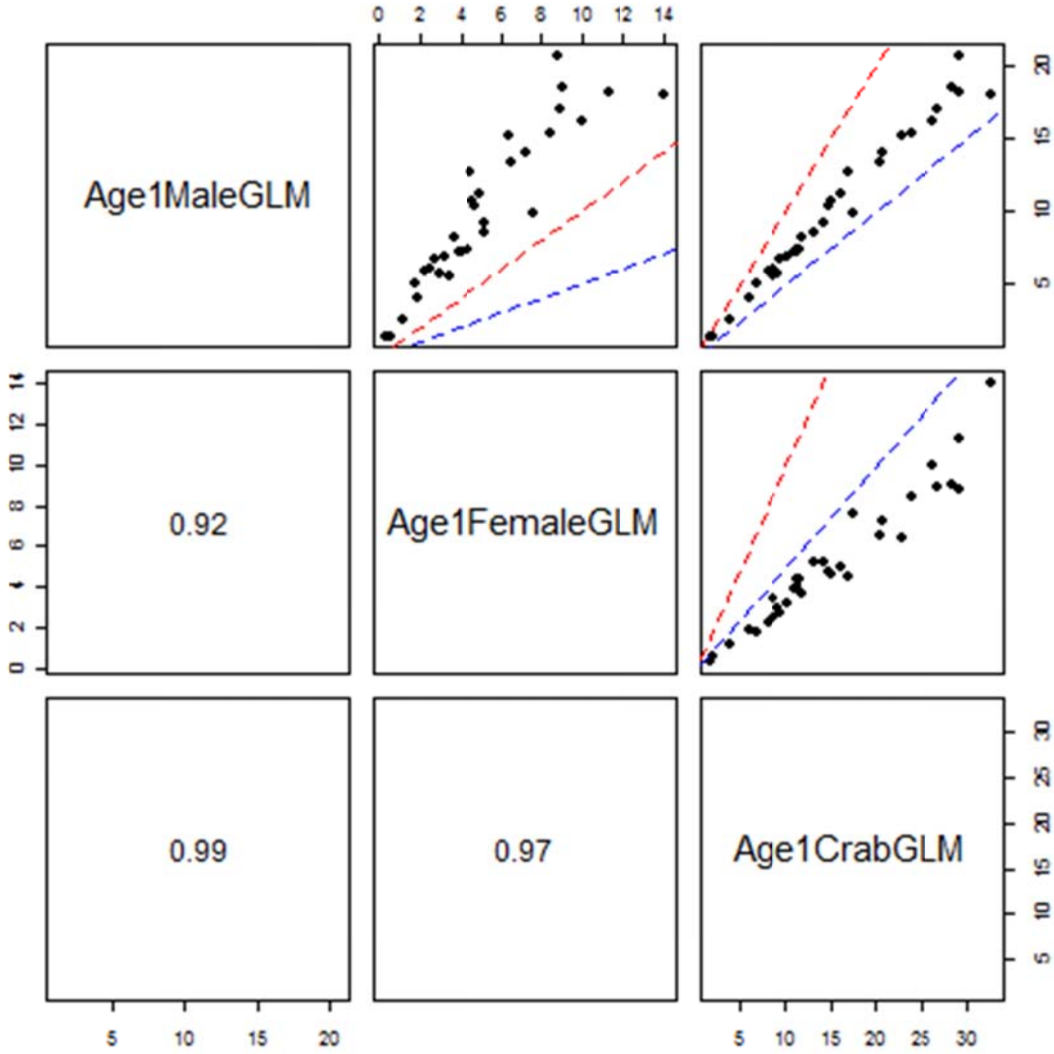

Figure 3.14. Correlation of lagged indices for the Maryland blue crab trawl survey. Plots are for correlation of age-0 indices in year t with age-1 indices in year t+1. The blue line is the least squares linear fit to the data, and the r-statistic is given in each plot.

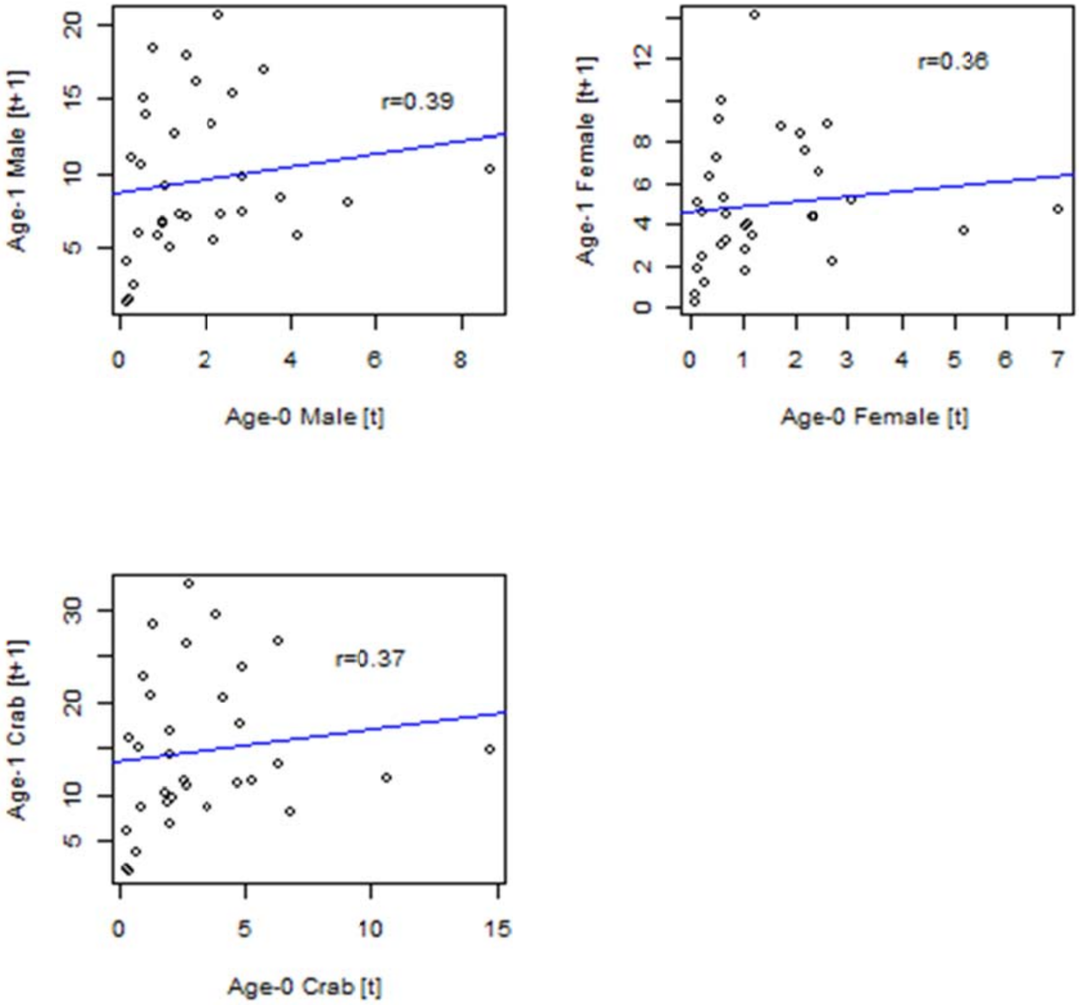

Figure 3.15 Frequency distribution of observed values of environmental parameters measured during the Winter Dredge Survey (1998/1990 -2009/2010).

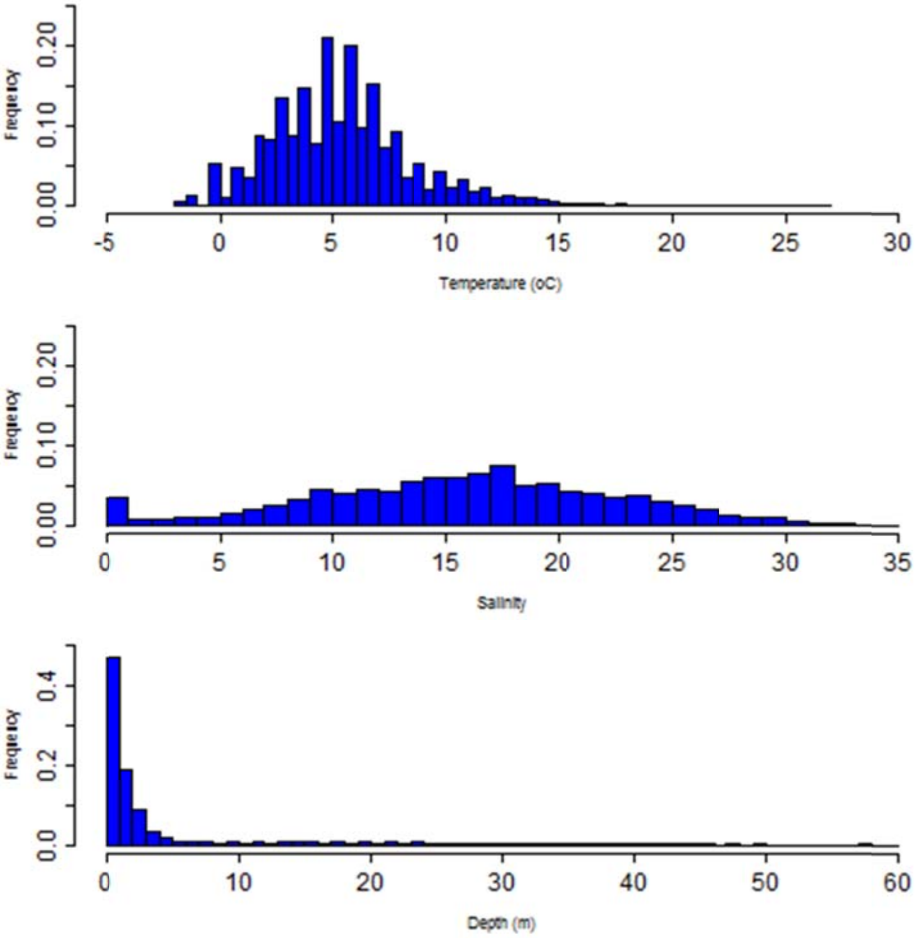

Figure 3.16. Distribution of catches in the winter dredge survey.

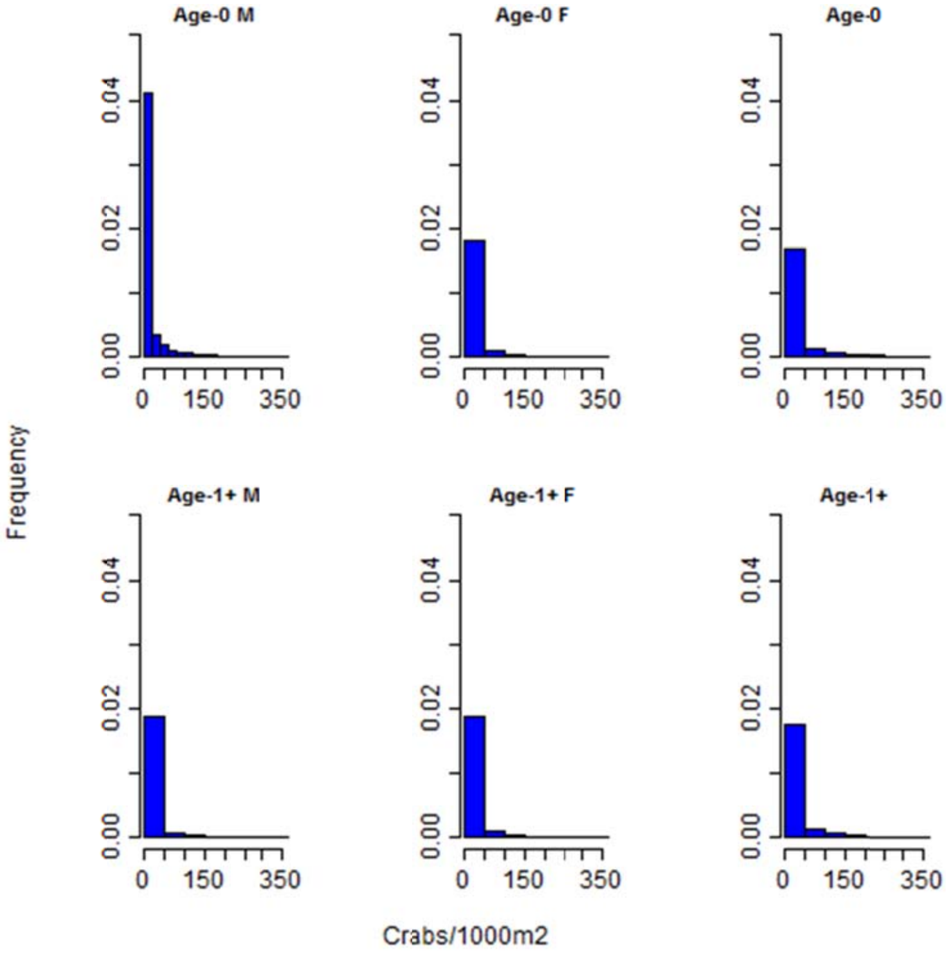

Figure 3.17 Summarized catch distributions in the winter dredge survey by age and sex. Shown are box-and-whisker plots for males, females and both sexes combined and for age-0, age-1+ and age-0+ within each sex category.

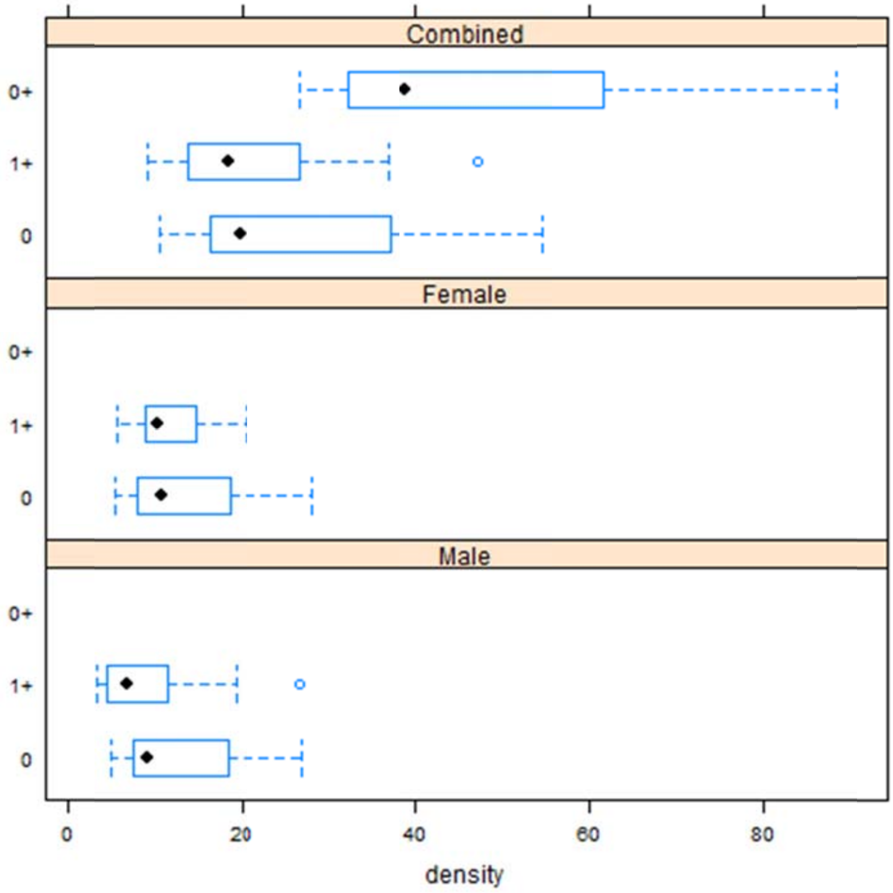

Figure 3.18. Time series of average baywide crab densities (crabs.1000m2) from the winter dredge survey. Shown are trends for age-0, age-1+ and all crab combined for both males (blue) and females (red).

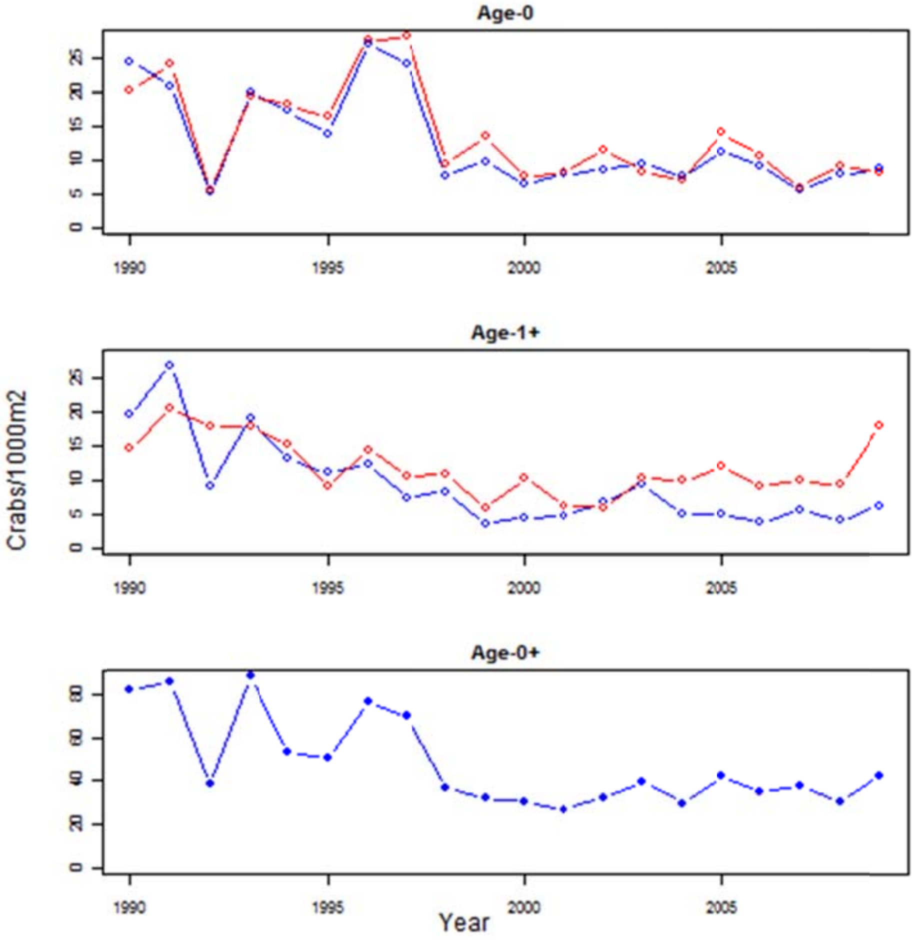

Figure 3.19. Time series of the proportion of males and females in the winter dredge survey for age-0 and age-1+.

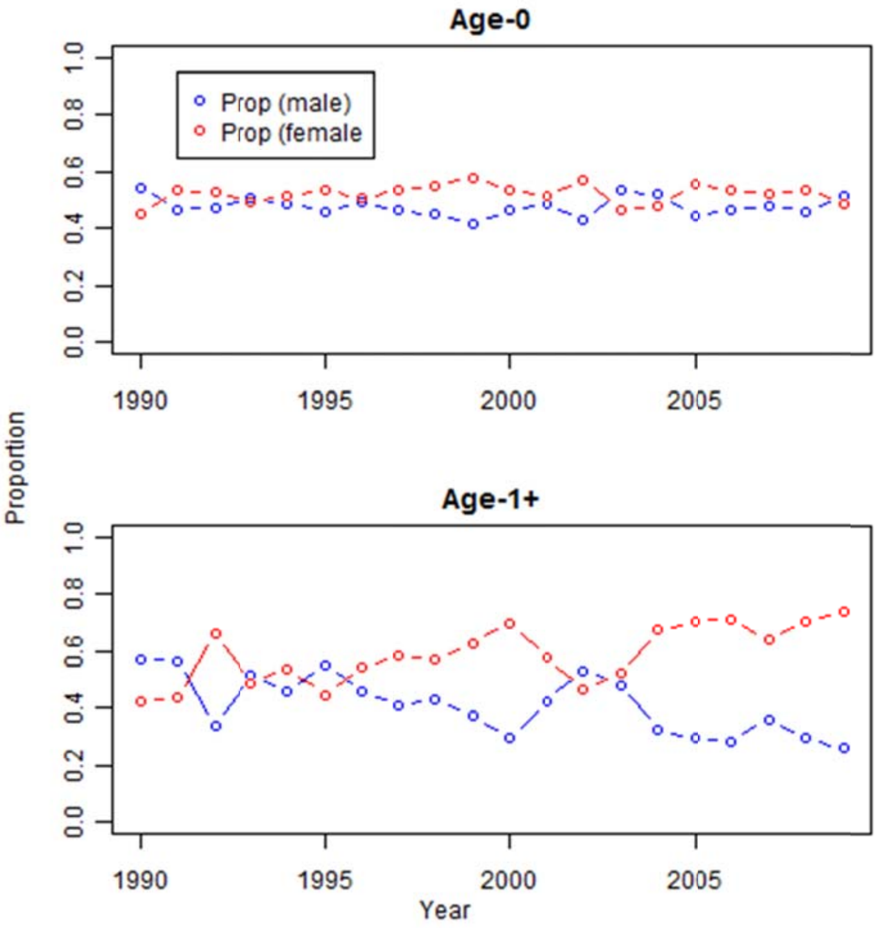

Figure 3.20. Standardized indices for age-0 male, female and combined crabs from the winter dredge survey. Raw observations were standardized using a delta-lognormal model with all design factors (year, stratum, month) and all environmental variables (depth, temperature and salinity). The blue line indicates the standardized index values and the open circles are the annual estimates of stratified means from the survey.

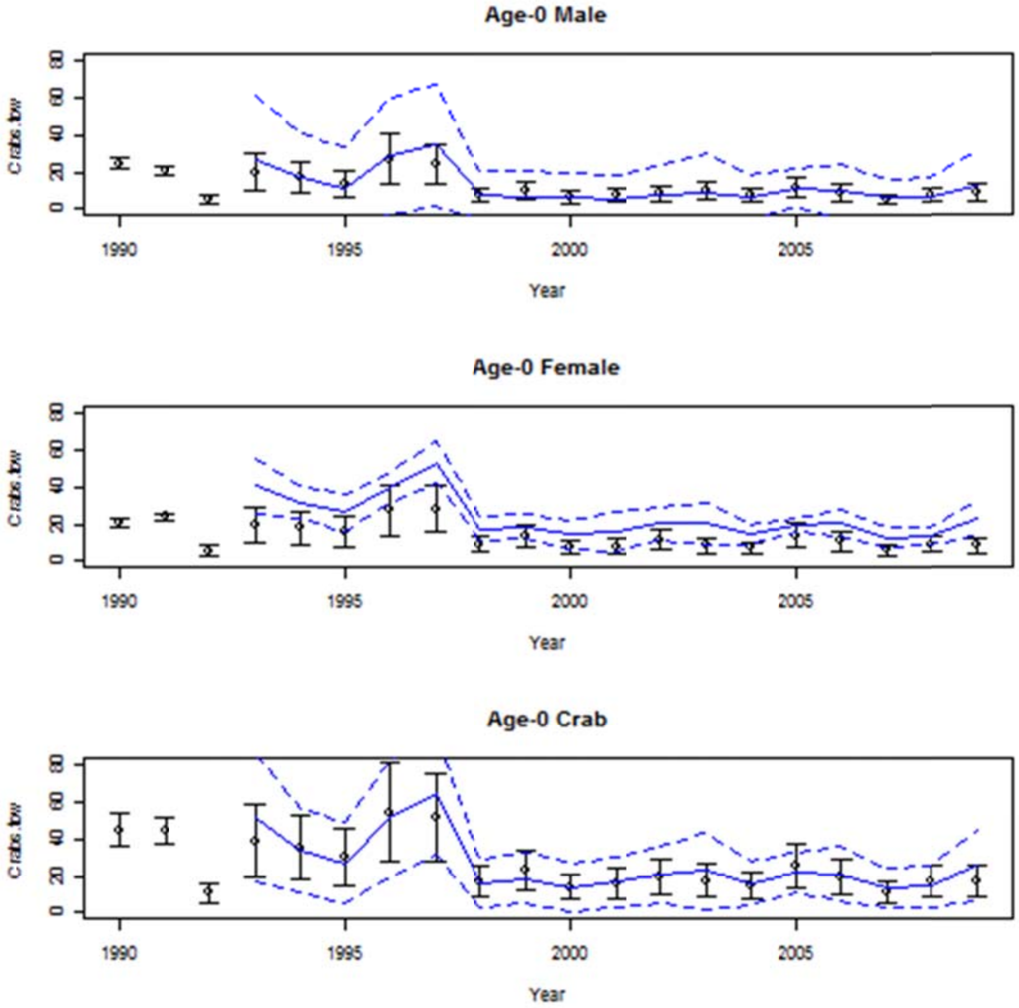

Figure 3.21. Correlations between standardized indices of age-0 crab abundance from the winter dredge survey. The upper panels show the correlation scatter plots. The two lines provide a context for comparing survey indices. The red line on the upper panel plots is the 1:1 line, which is appropriate for comparing sex-specific indices. The blue line is a 1:2 line, which may be more appropriate for comparing the individual sex-specific indices with the aggregate index. The lower panels present the Pearson linear correlation coefficients.

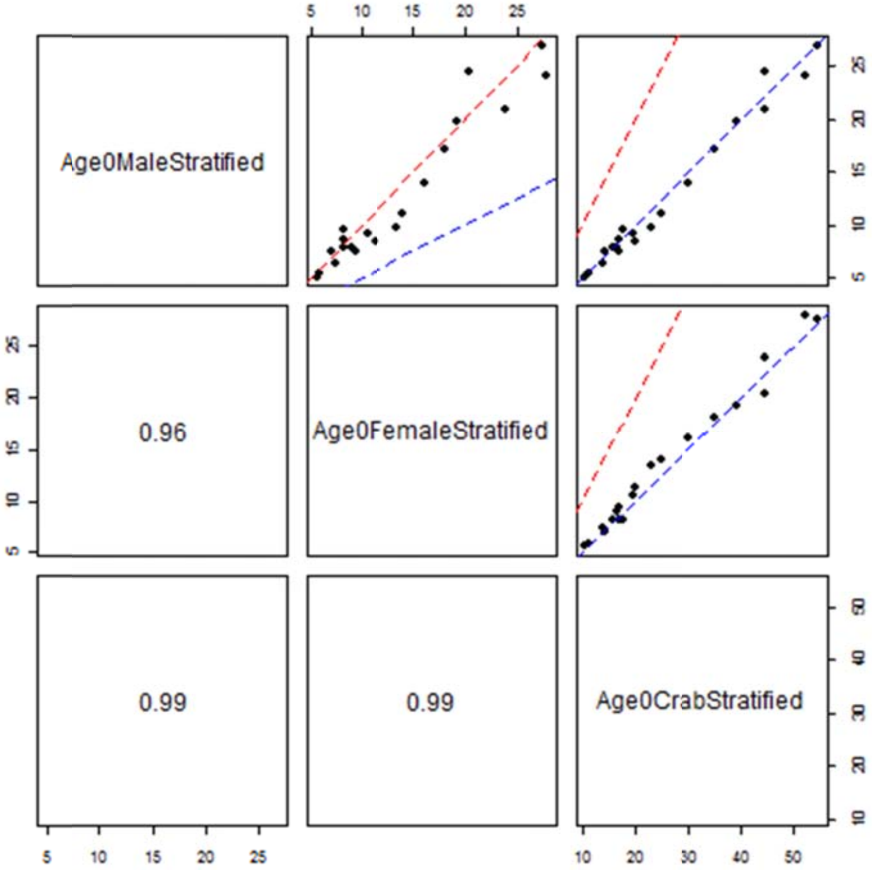

Figure 3.22. Standardized indices for age-1 from the winter dredge survey. Raw observations were standardized using a delta-lognormal model with all design factors (year, stratum, month) and all environmental variables (depth, temperature and salinity). The blue line indicates the standardized index values and the open circles are the annual estimates of stratified means from the survey.

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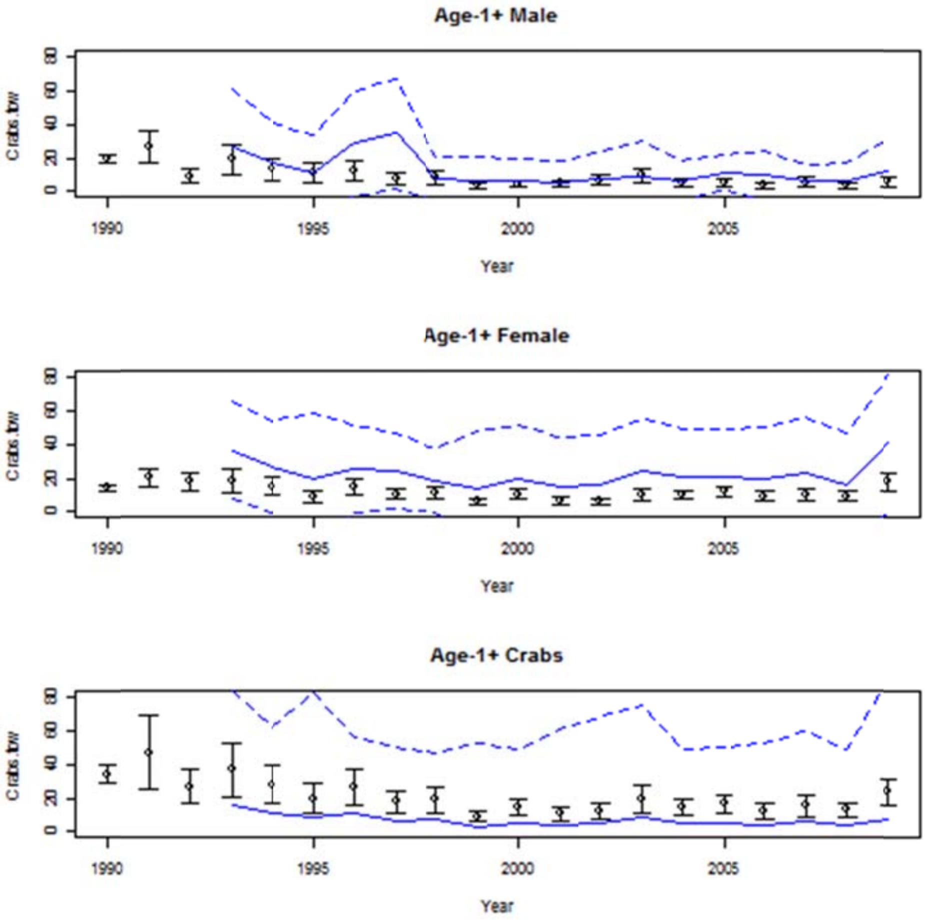


Figure 3.23. Correlations between standardized indices of age-1 crab abundance from the winter dredge survey. The upper panels show the correlation scatter plots. The two lines provide a context for comparing survey indices. The red line on the upper panel plots is the 1:1 line, which is appropriate for comparing sex-specific indices. The blue line is a 1:2 line, which may be more appropriate for comparing the individual sex-specific indices with the aggregate index. The lower panels present the Pearson linear correlation coefficients.

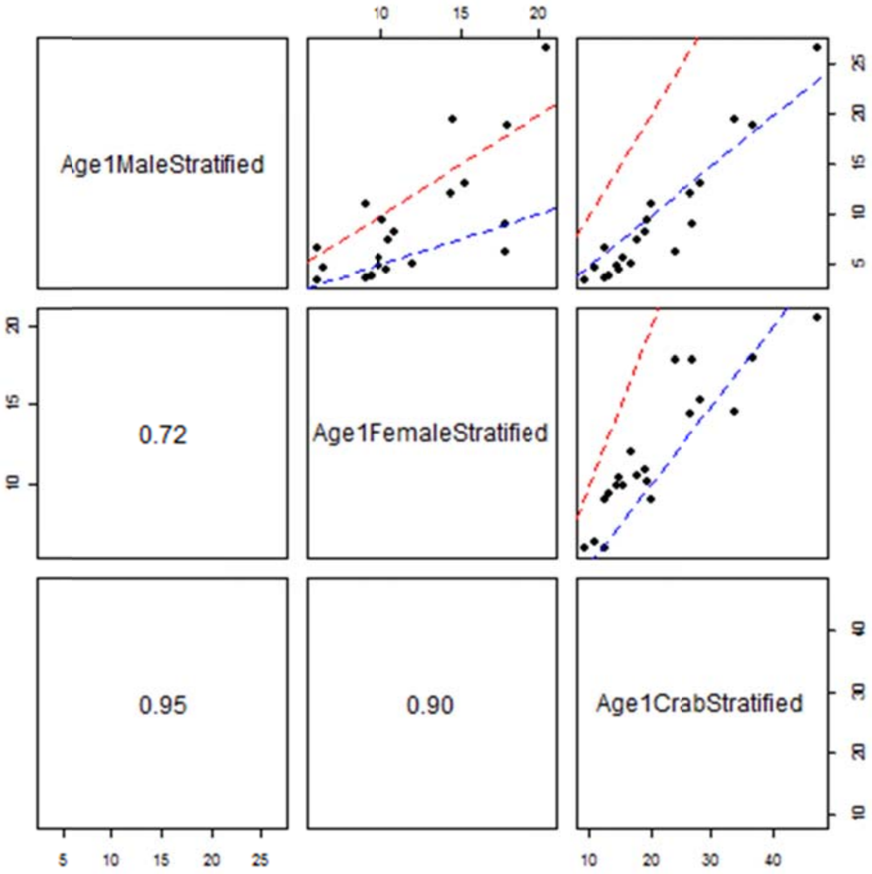


Figure 3.24. Correlation of lagged indices for the winter dredge survey. Plots are for correlation of age-0 indices in year t with age-1 indices in year t+1. The blue line is the least squares linear fit to the data, and the r-statistic is given in each plot

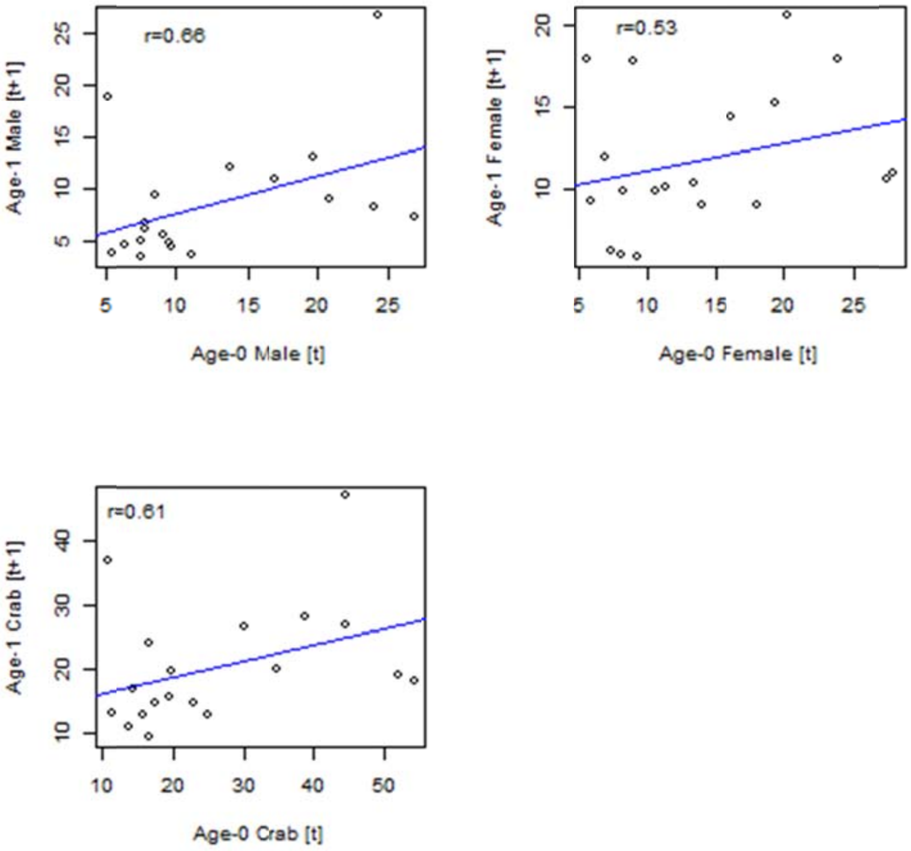


Figure 5.1. Annual reported commercial landings in Virginia for the period 1950-2009.

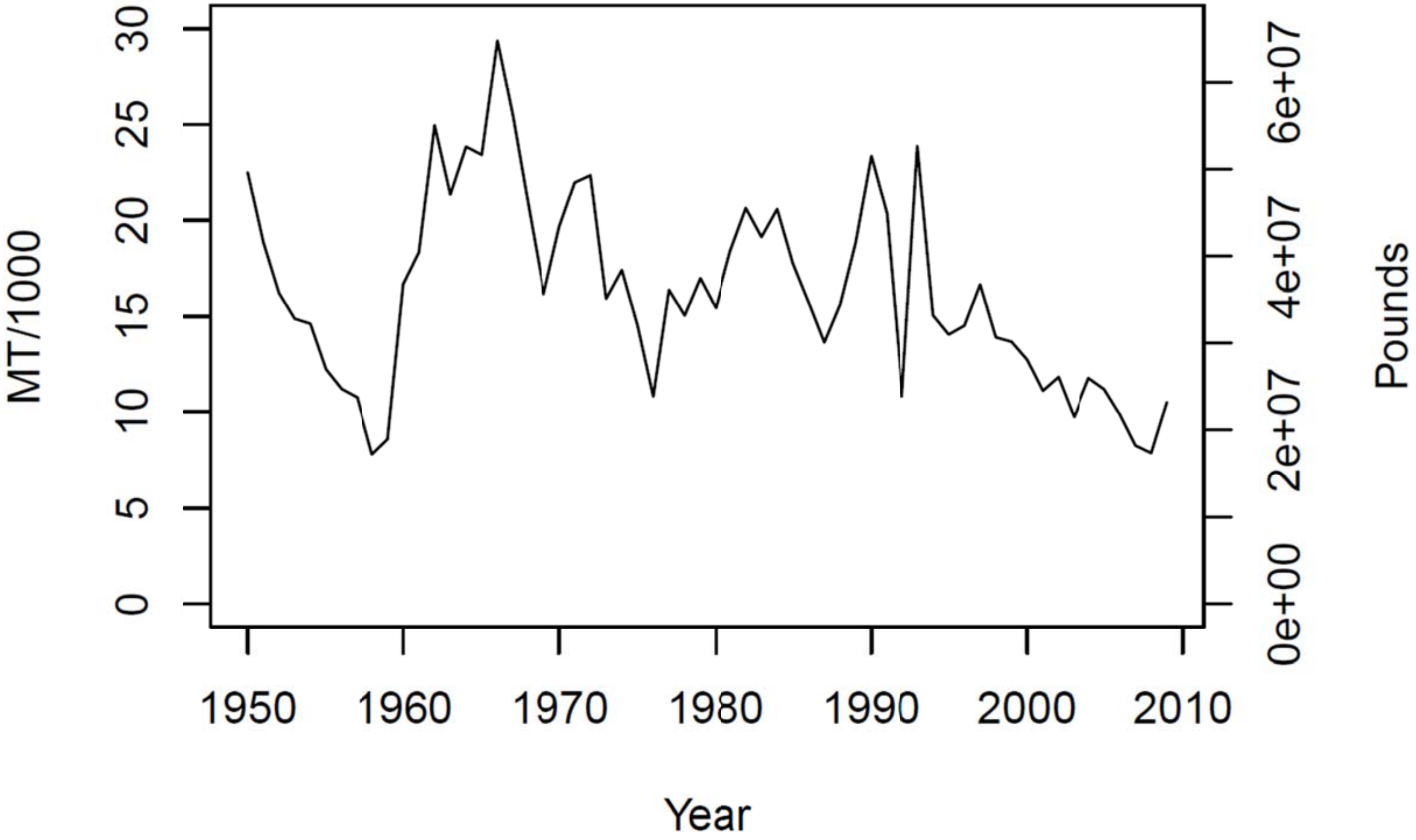


Figure 5.2. First differenced time series of reported commercial landings in Virginia for the period 1950-2009.

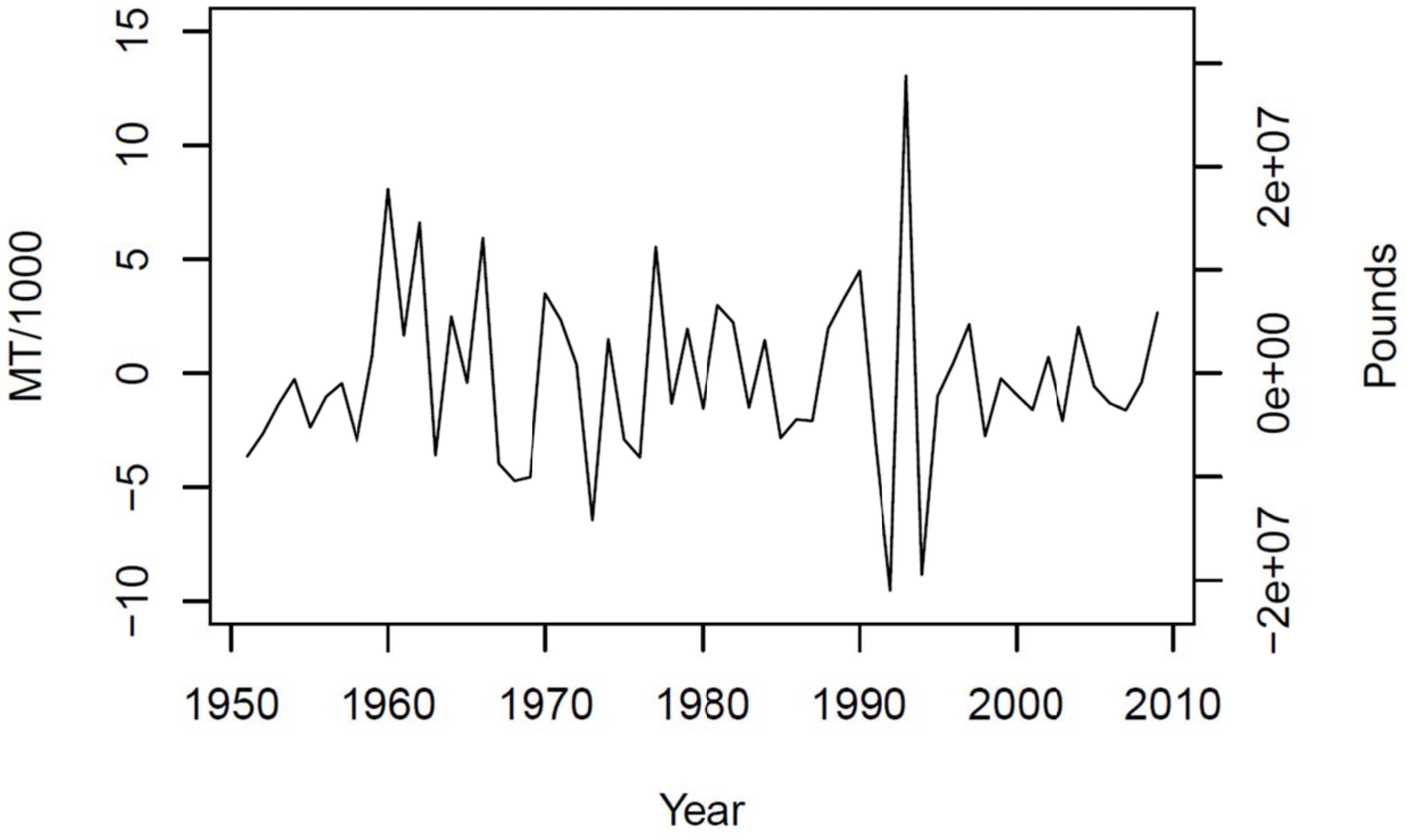


Figure 5.3. Reconstructed Virginia commercial landings. Landings were reconstructed based on the estimated impact of the 1993 reporting change to mandatory reporting. The raw landings are shown in black, and the reconstructed landings are shown in grey.

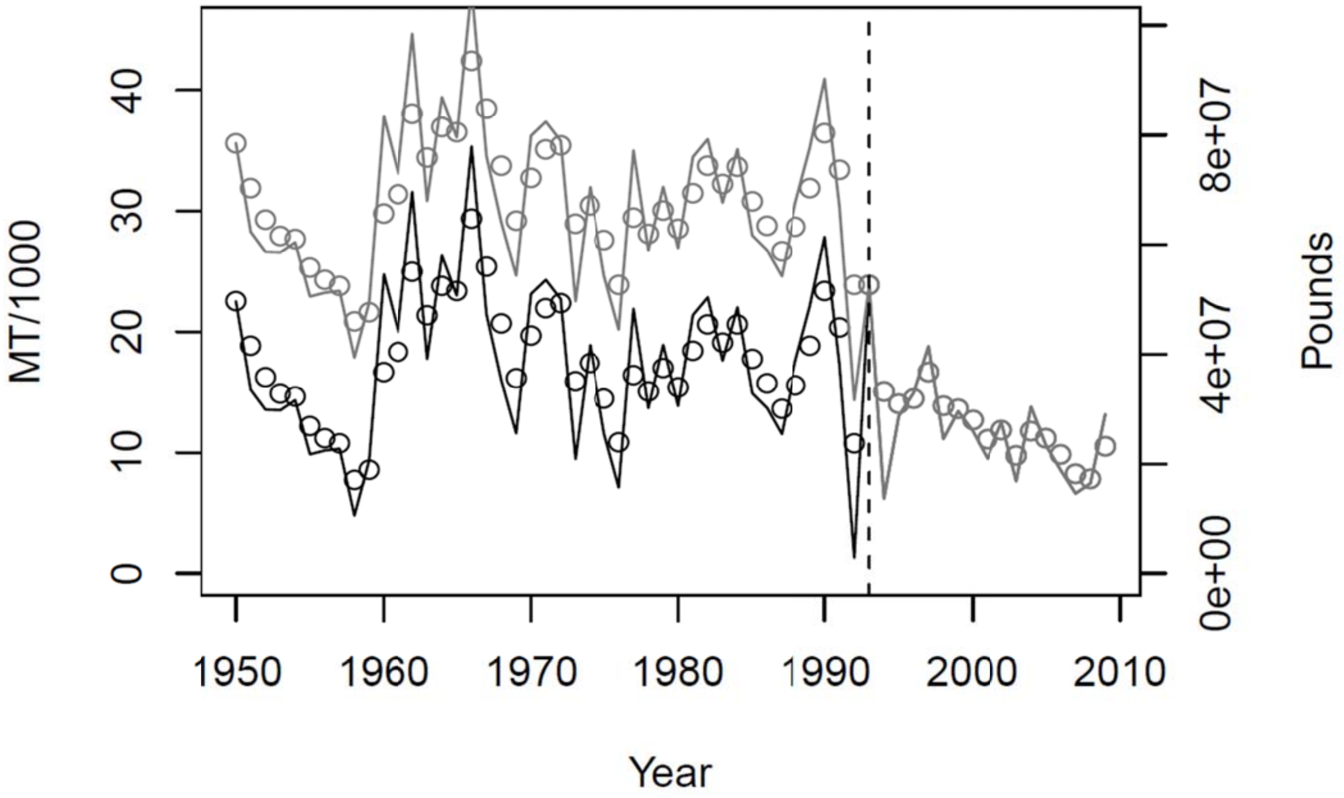


Figure 5.4. Annual reported commercial landings in Maryland for the period 1950-2009.

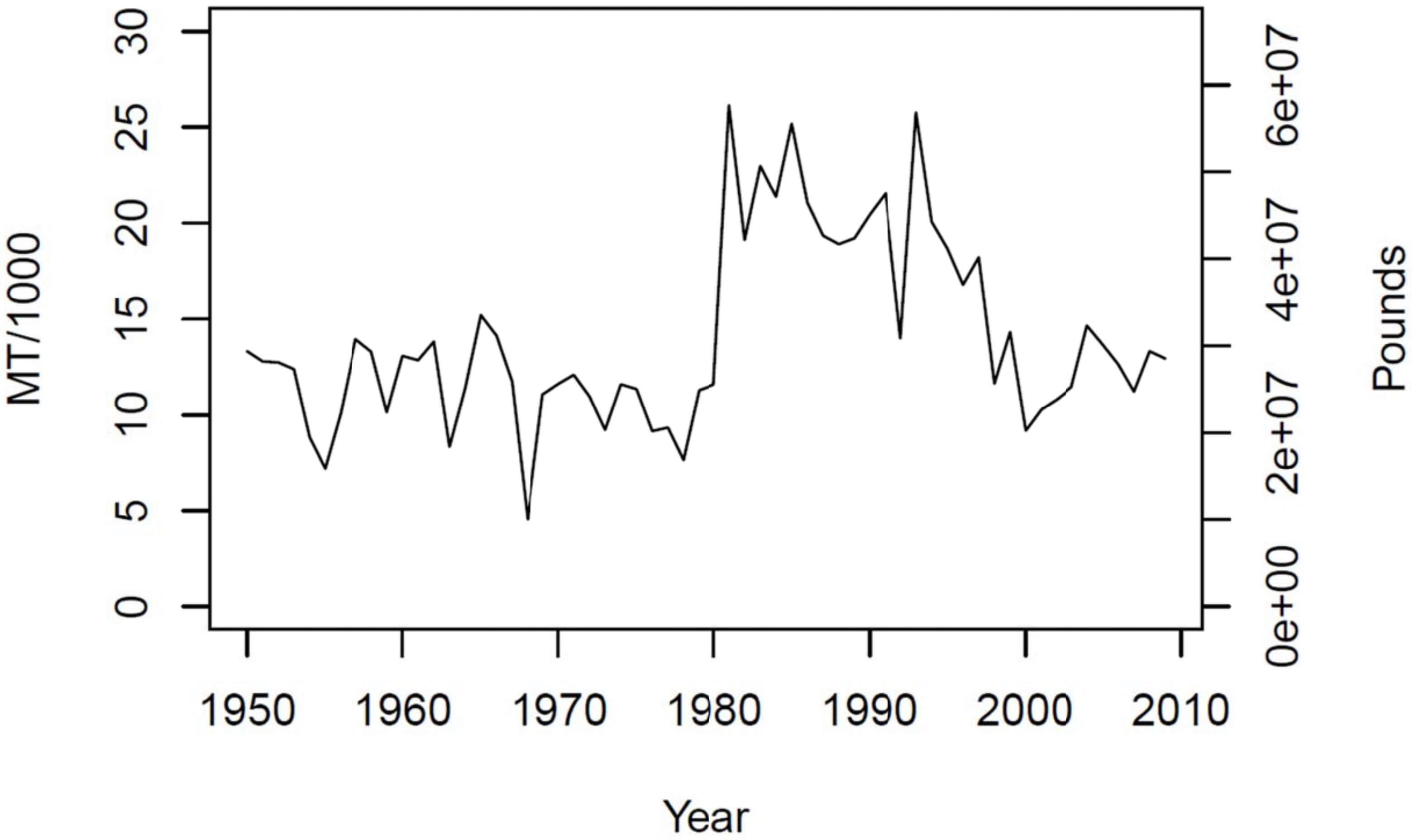


Figure 5.5. First differenced time series of reported commercial landings in Maryland for the period 1950-2009.

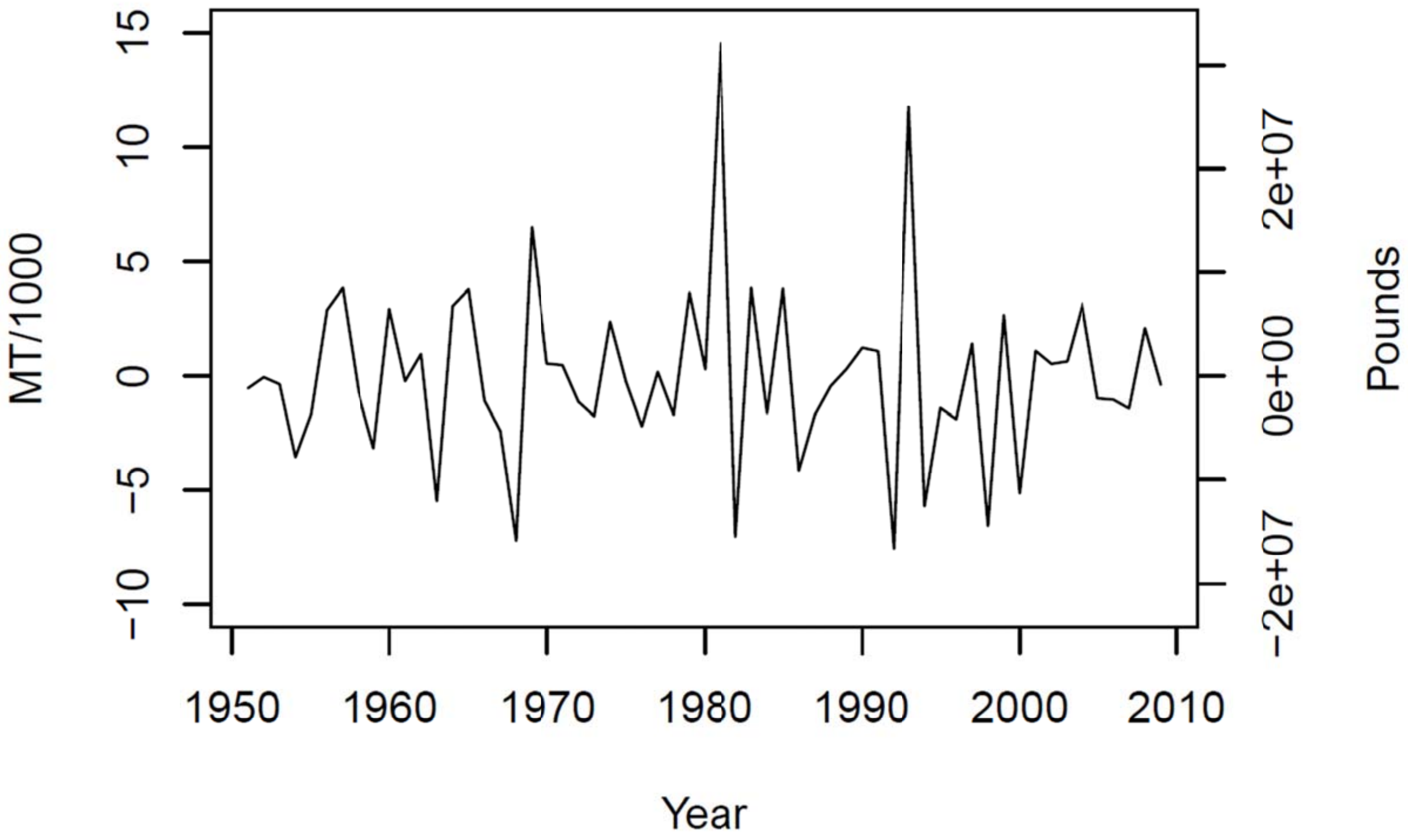


Figure 5.5. Reconstructed Maryland commercial landings. Landings were reconstructed based on the estimated impact of the 1981 reporting change to complete reporting. The raw landings are shown in black, and the reconstructed landings are shown in grey.

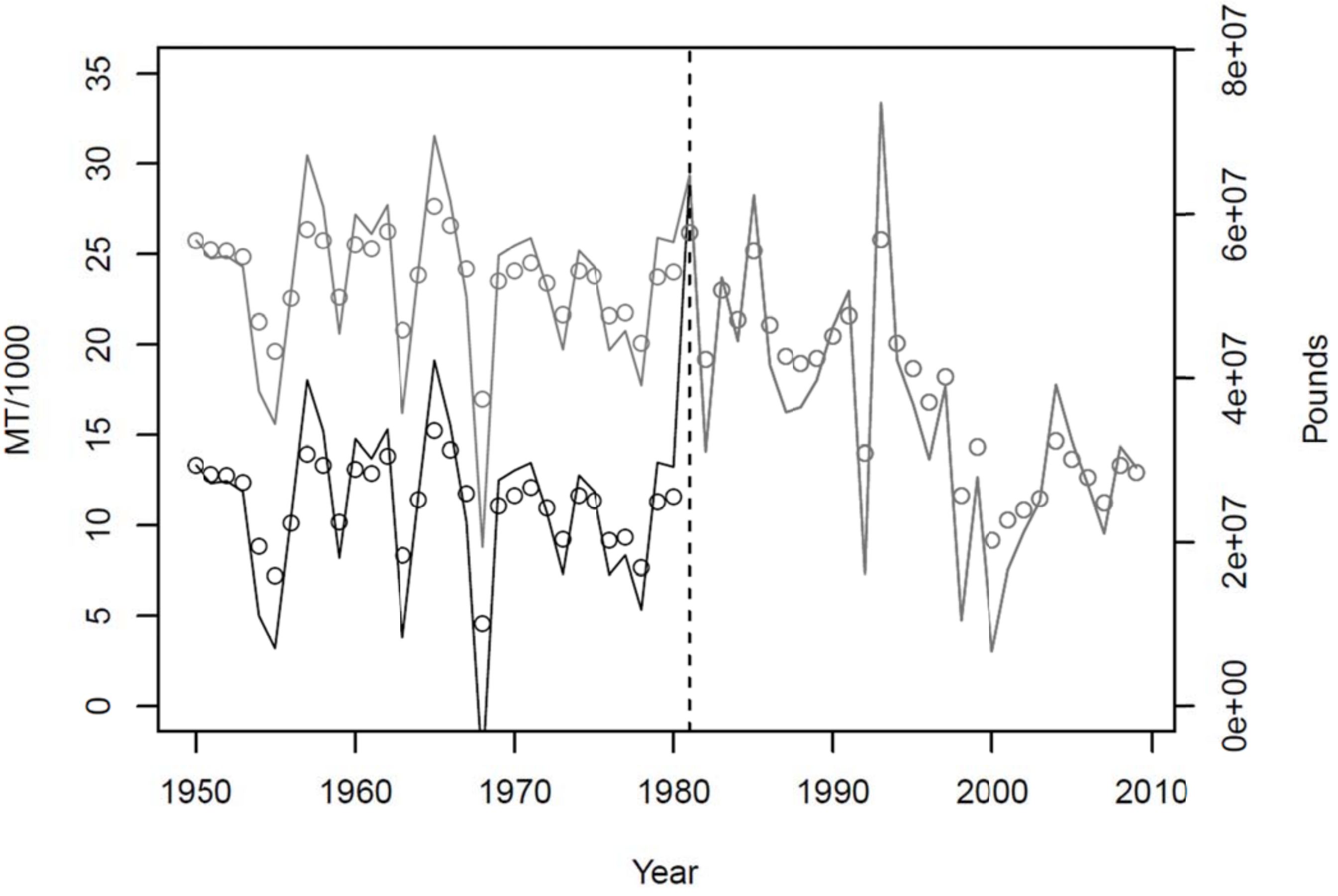


Figure 5.6 Time series of average size of male and female crabs (carapace width, mm) in the Maryland DNR summer trawl survey and the VIMS fall trawl survey for the years 1989 – 2009.

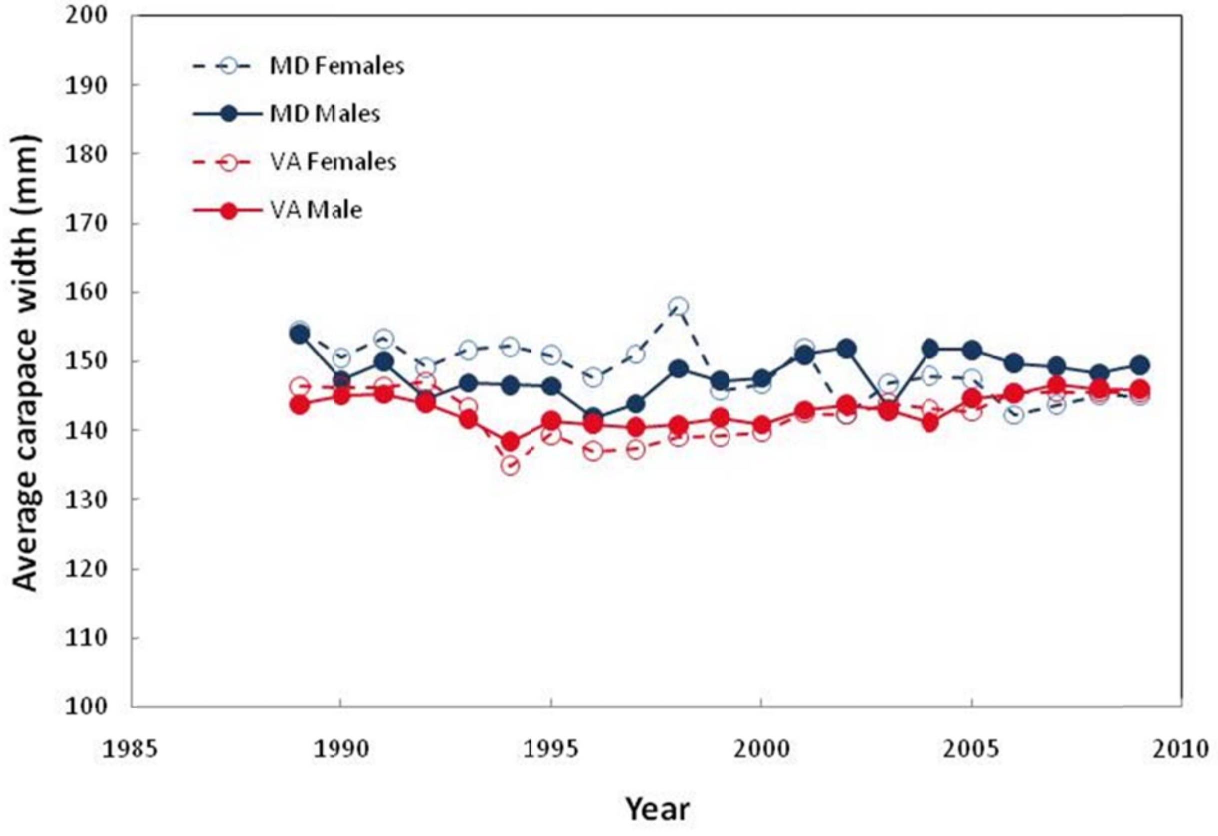


Figure 5.7. The proportion of the total harvest of blue crabs taken from the Chesapeake Bay that is taken as females for the year 1994-2009.

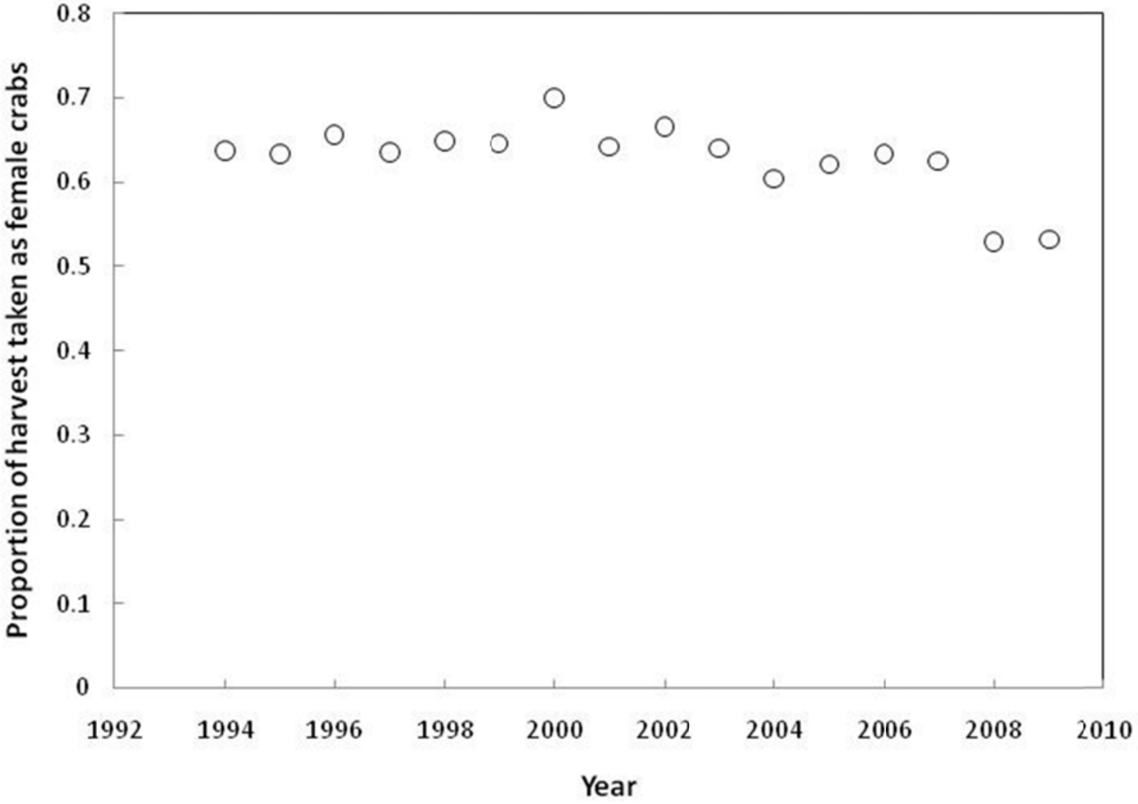


Figure 5.8 Time series of total abundance of blue crabs in the Chesapeake Bay estimate from the winter dredge survey. Shown in the figure are estimates for total abundance (solid symbols and solid line) and estimates for abundance corrected for estimated overwinter mortality (open symbols and dashed line). Data are plotted according to the year in which the survey ended (i.e., the 1989/1990 survey is plotted as 1990).

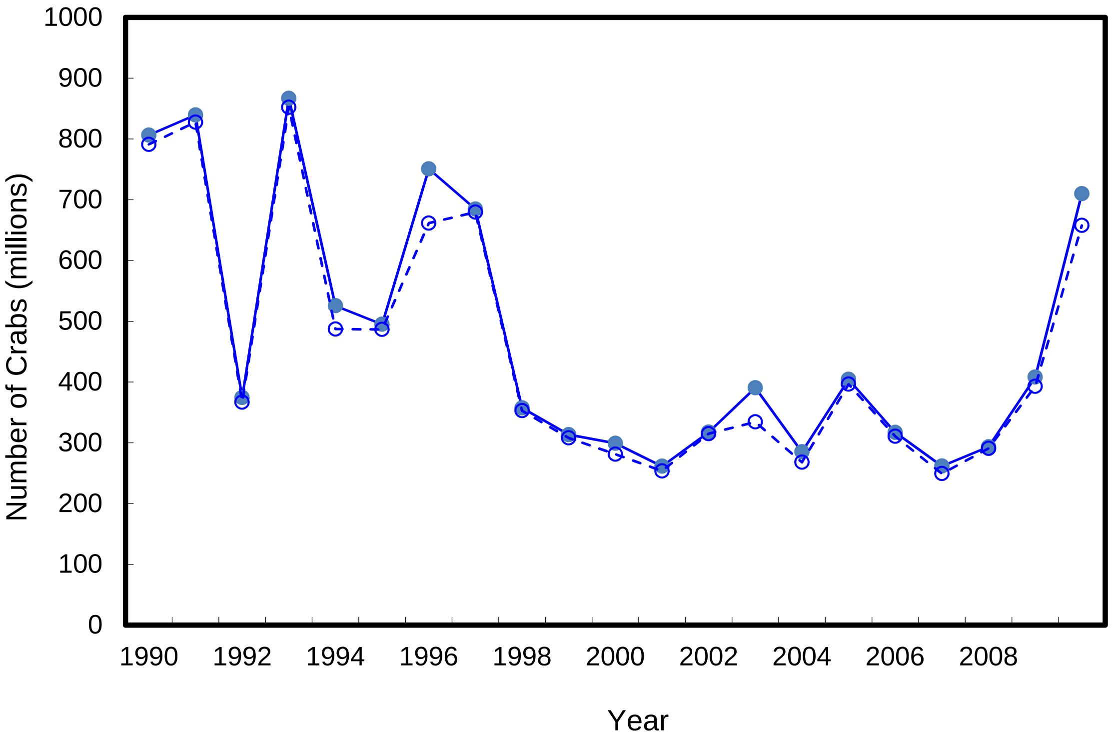


Figure 5.9 Time series of exploitation fraction in the Chesapeake Bay blue crab fishery. Exploitation fraction is calculated according to Eq. using estimates of baywide catches and baywide abundance from the winter dredge survey. Catches have been increased by 8% to include an assumed effect of the recreational fishery.

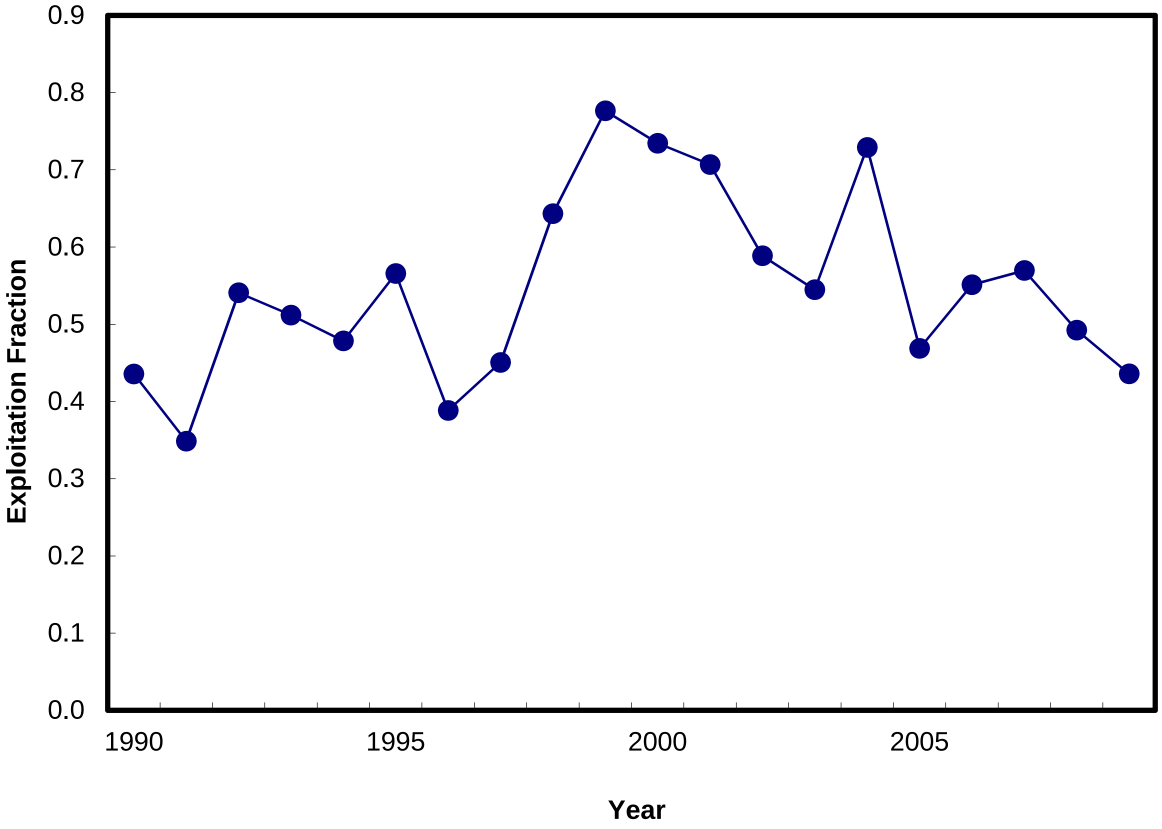


Figure 5.10. Time series of sex-specific exploitation estimated from the ratio of baywide sex-specific catches and baywide abundance from the winter dredge survey. Catches have been increased by 8% to include an assumed effect of the recreational fishery

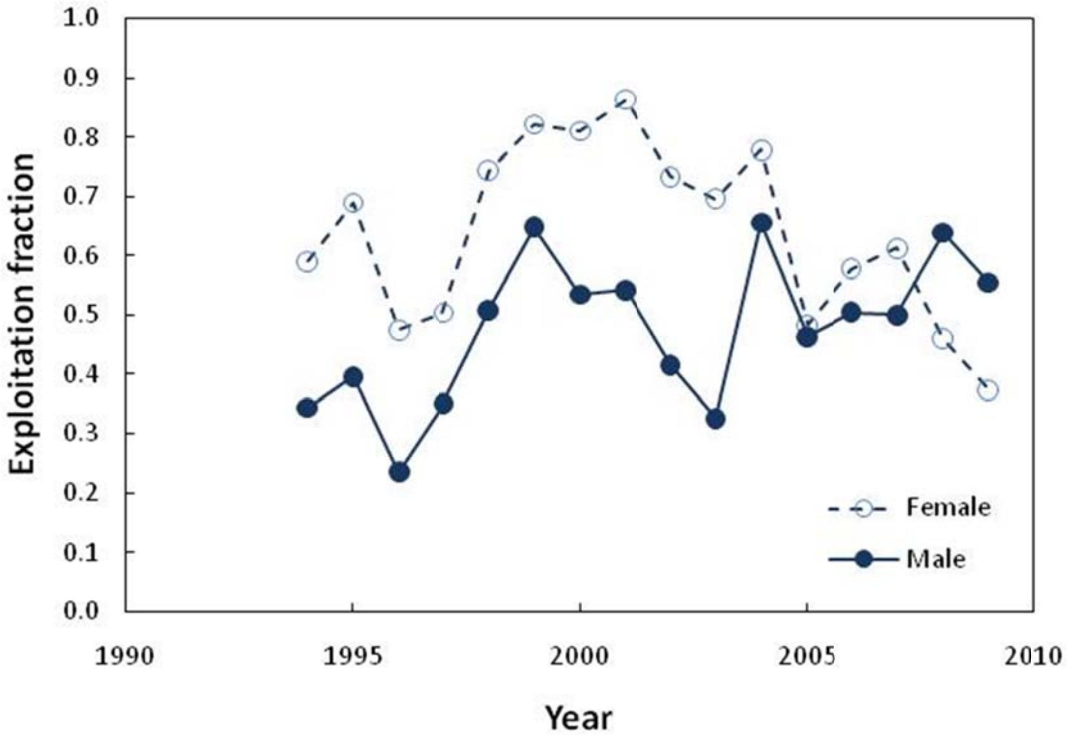


Figure 5.11. (A) Patterns in N and u over time. (B) Relationship between u (C/N) and N. The fit is from nonlinear regression of *u* vs. *N*, whereas predicted *u* are derived from the linear and hyperbolic functions fit to *C vs. N*. (C) Linear and hyperbolic fits to *C vs. N*. Linear fit is from least squares regression, and the hyperbolic fit is from nonlinear least squares regression.

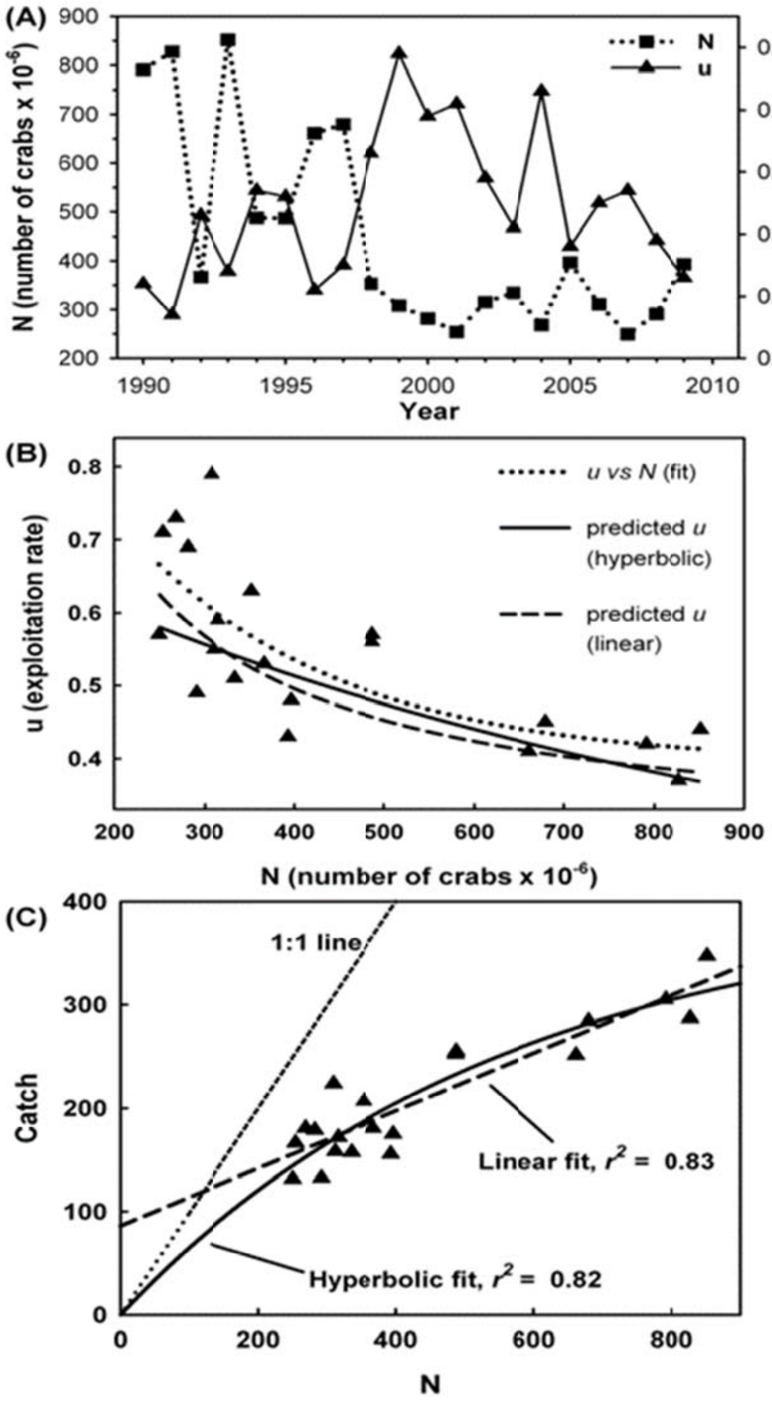


Figure 6.1. The control rule used to manage blue crab in the Chesapeake Bay. Individual data points are calculated from estimates of the abundance in the winter dredge survey (Nt) and the exploitation rate (Ct/Nt). The red horizontal line is the overfishing definition developed from the individual-based yield per recruit analysis (U20%=0.53). The green horizontal line is the exploitation rate target (U10% = 0.46) from the same YPR analysis. The red vertical line is the overfished definition derived from the lowest observed abundance in the winter dredge survey.

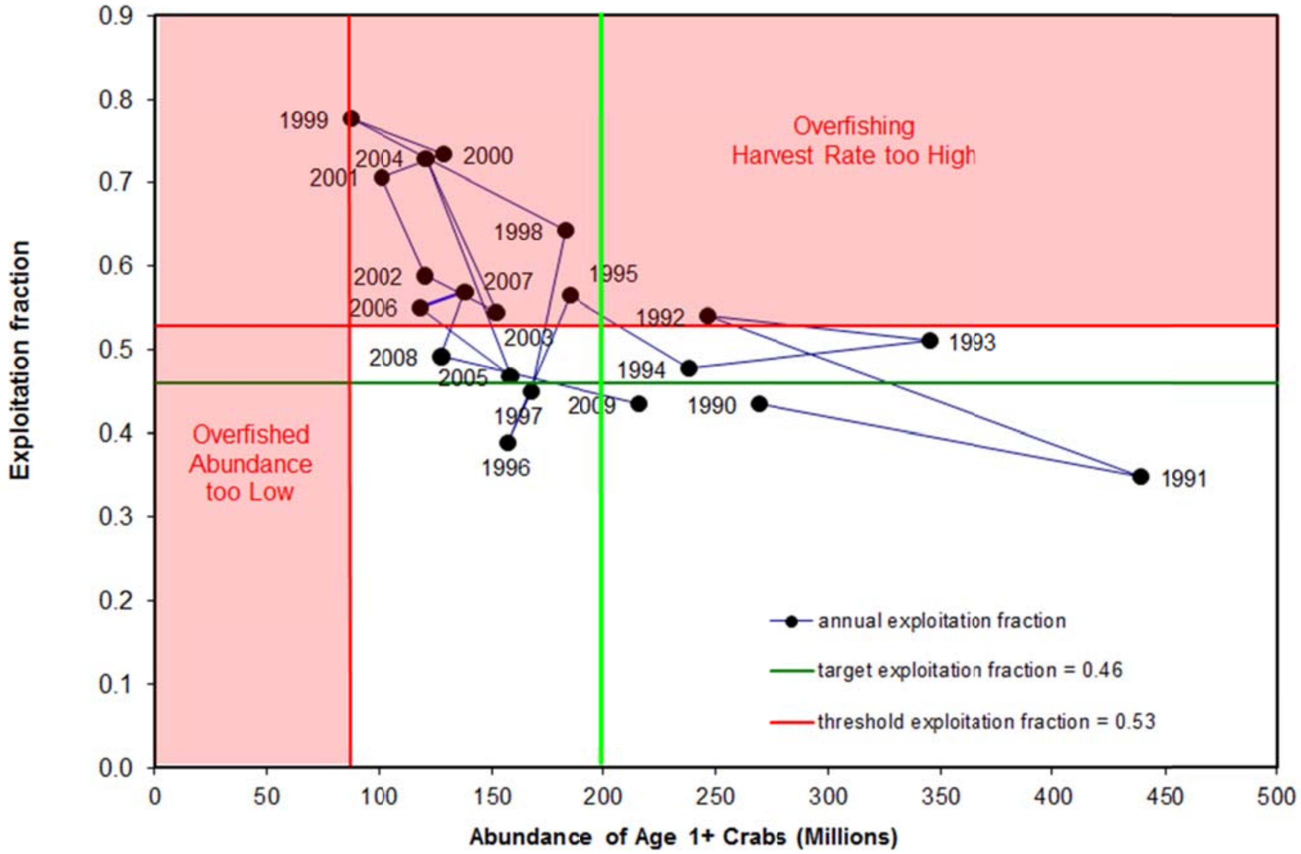


Figure 6.2. A schematic of the SSCMSA assessment model showing the key life history transitions and events.

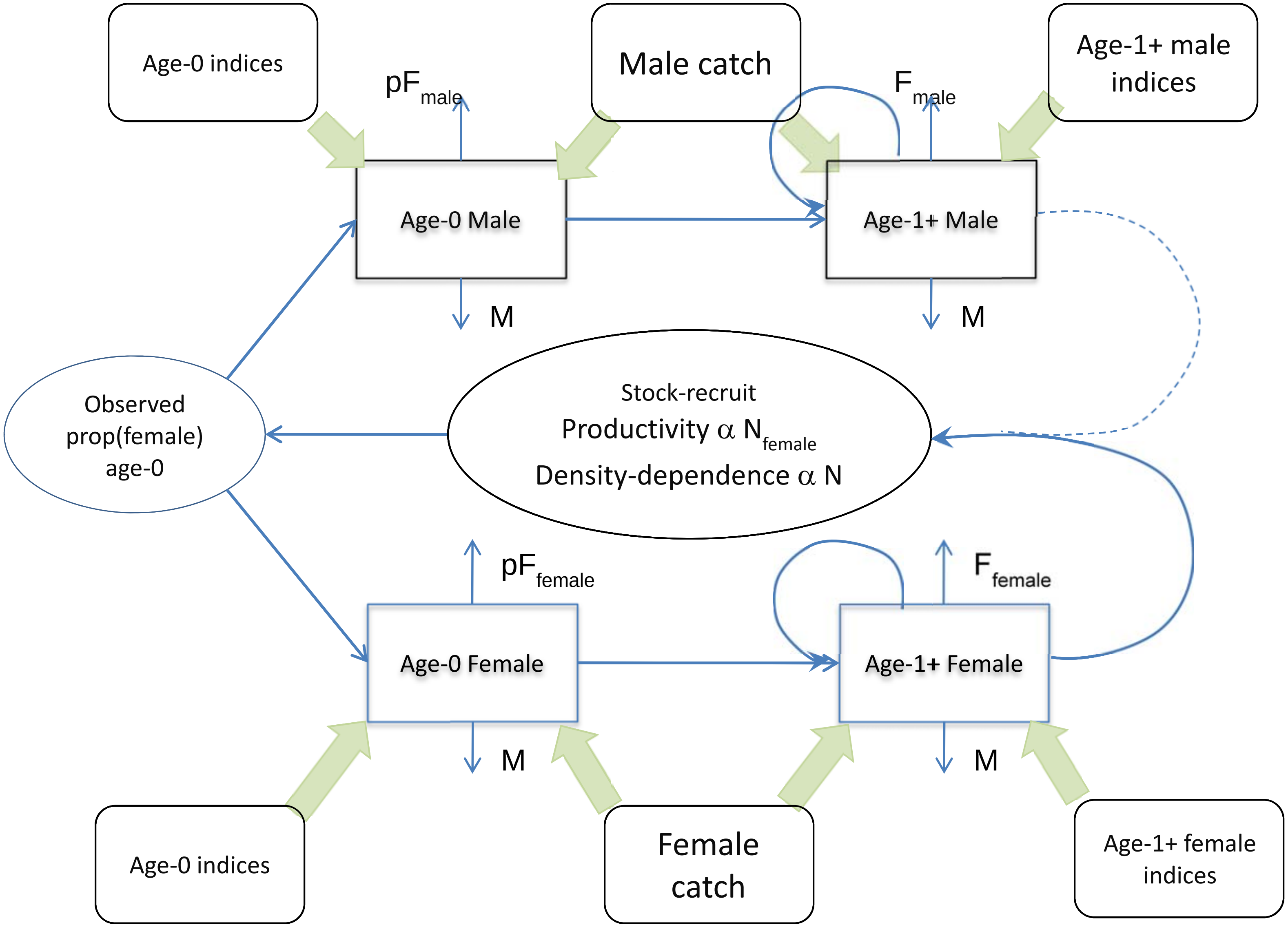


Figure 6.3 Timeline of events in the SSCMSA (upper panel) and cumulative proportional effort in the Maryland pot fishery during 2007-2010.

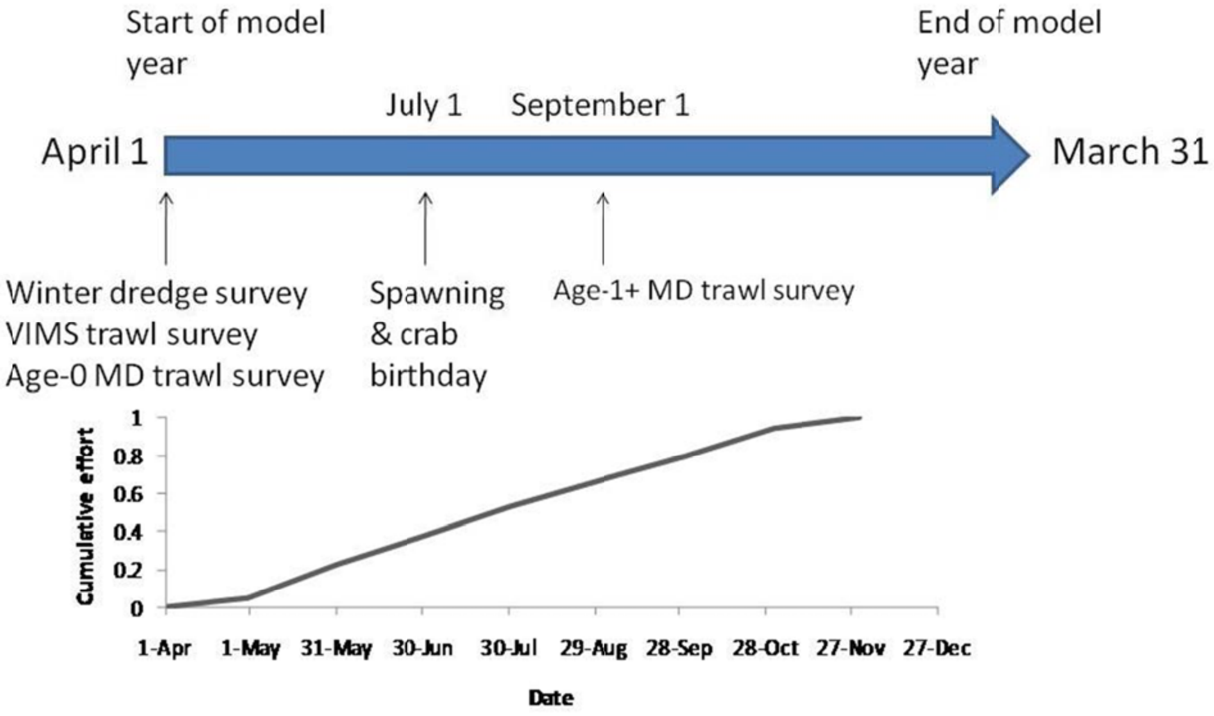


Figure 6.4. Time series of predicted and estimate catch (upper panel), female catch (middle panel) and male catch (bottom panel) resulting from the base run of the SSCMSA. Empirical estimates of catch are shown in solid symbols, the model predictions are shown in the solid line.

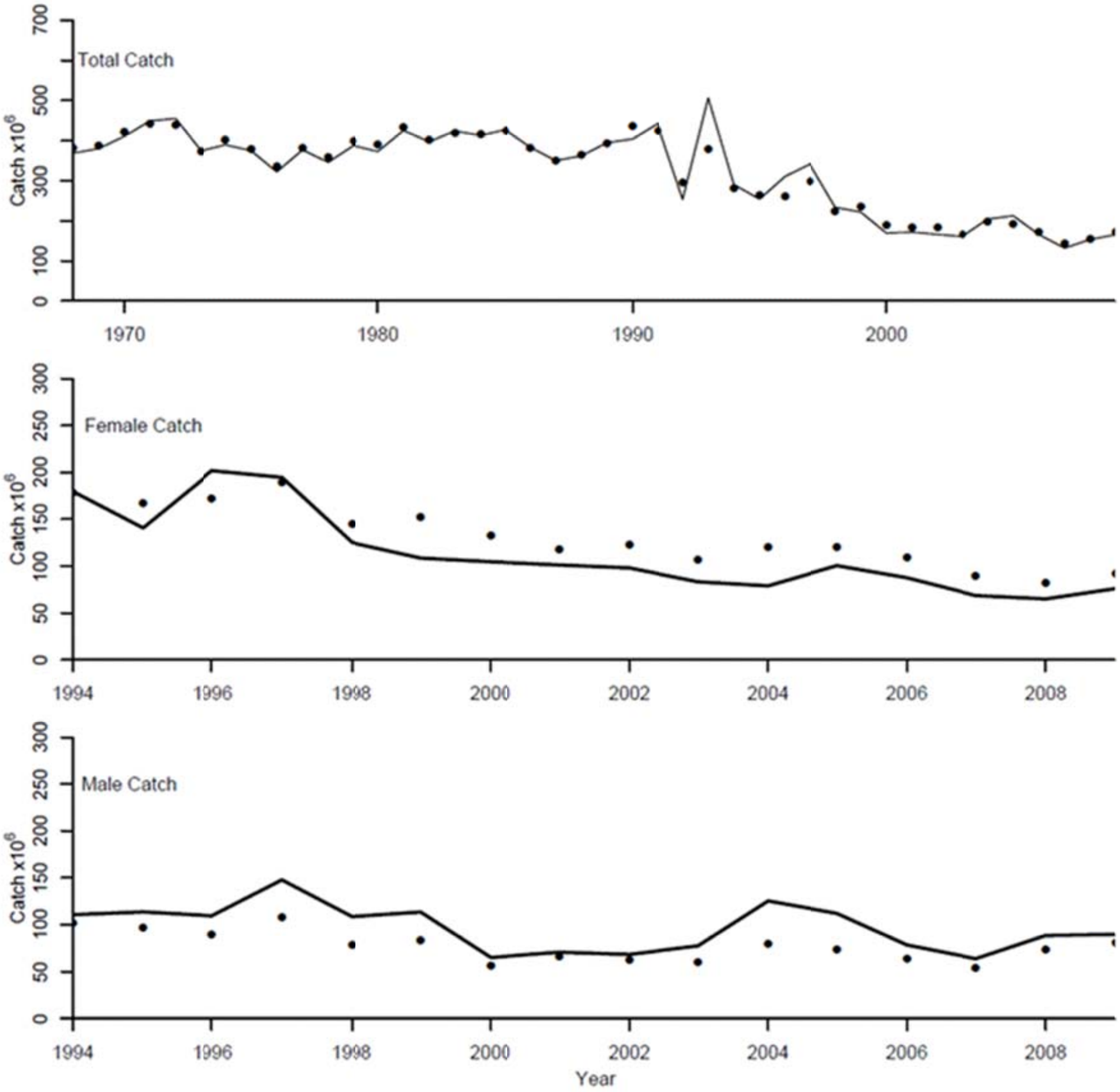


Figure 6.5. Time series of predicted and estimates of survey CPUES in the VIMS spring trawl survey for recruitment (upper panel), age-0+ females (middle panel) and age-1+ males (bottom panel) resulting from the base run of the SSCMSA. Empirical estimates of catch are shown in solid symbols, the model predictions are shown in the solid line.

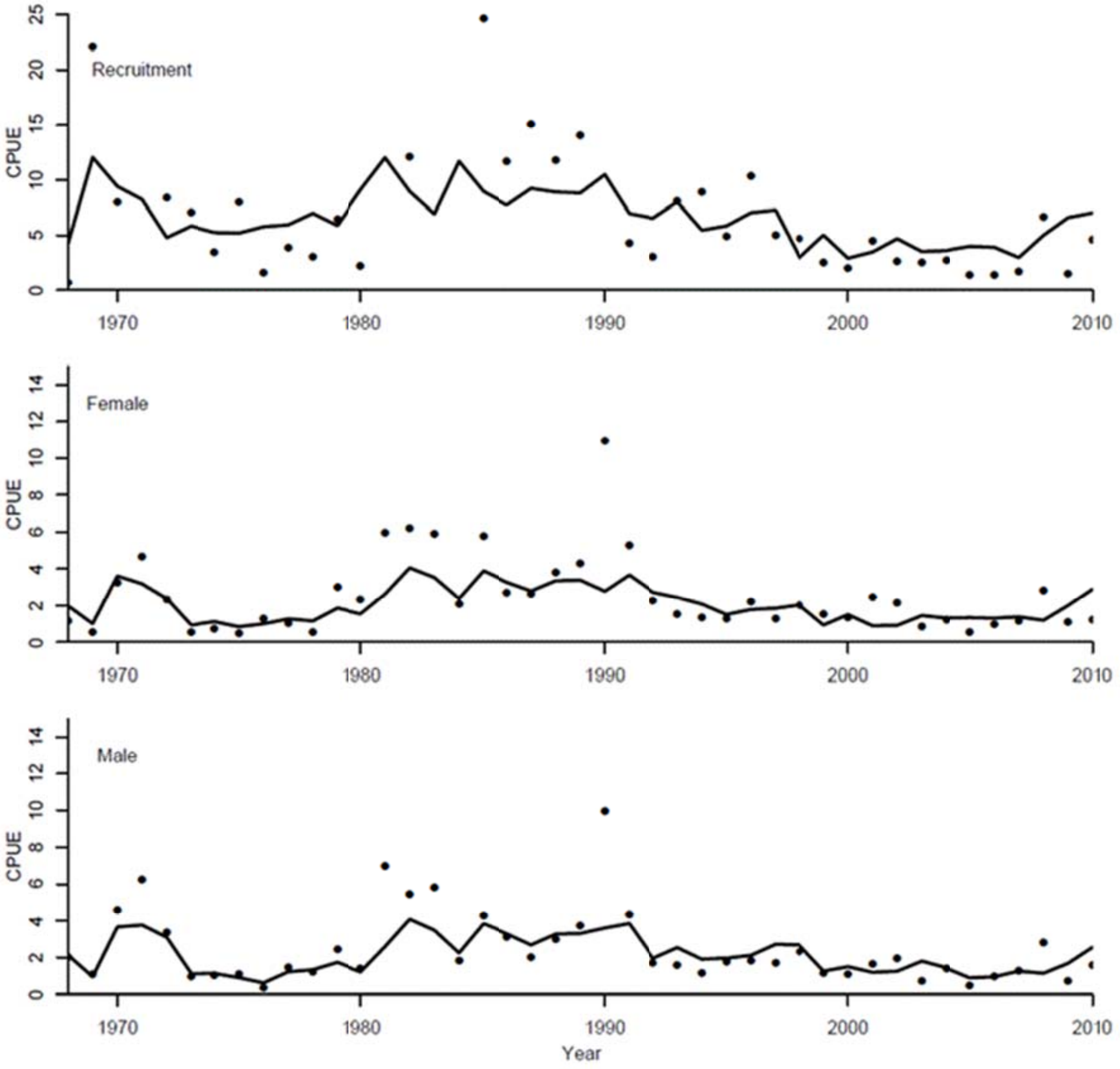


Figure 6.6. Time series of predicted and estimates of survey CPUES in the Maryland DNR Summer trawl survey for recruitment (upper panel), age-0+ females (middle panel) and age-1+ males (bottom panel) resulting from the base run of the SSCMSA. Empirical estimates of catch are shown in solid symbols, the model predictions are shown in the solid line.

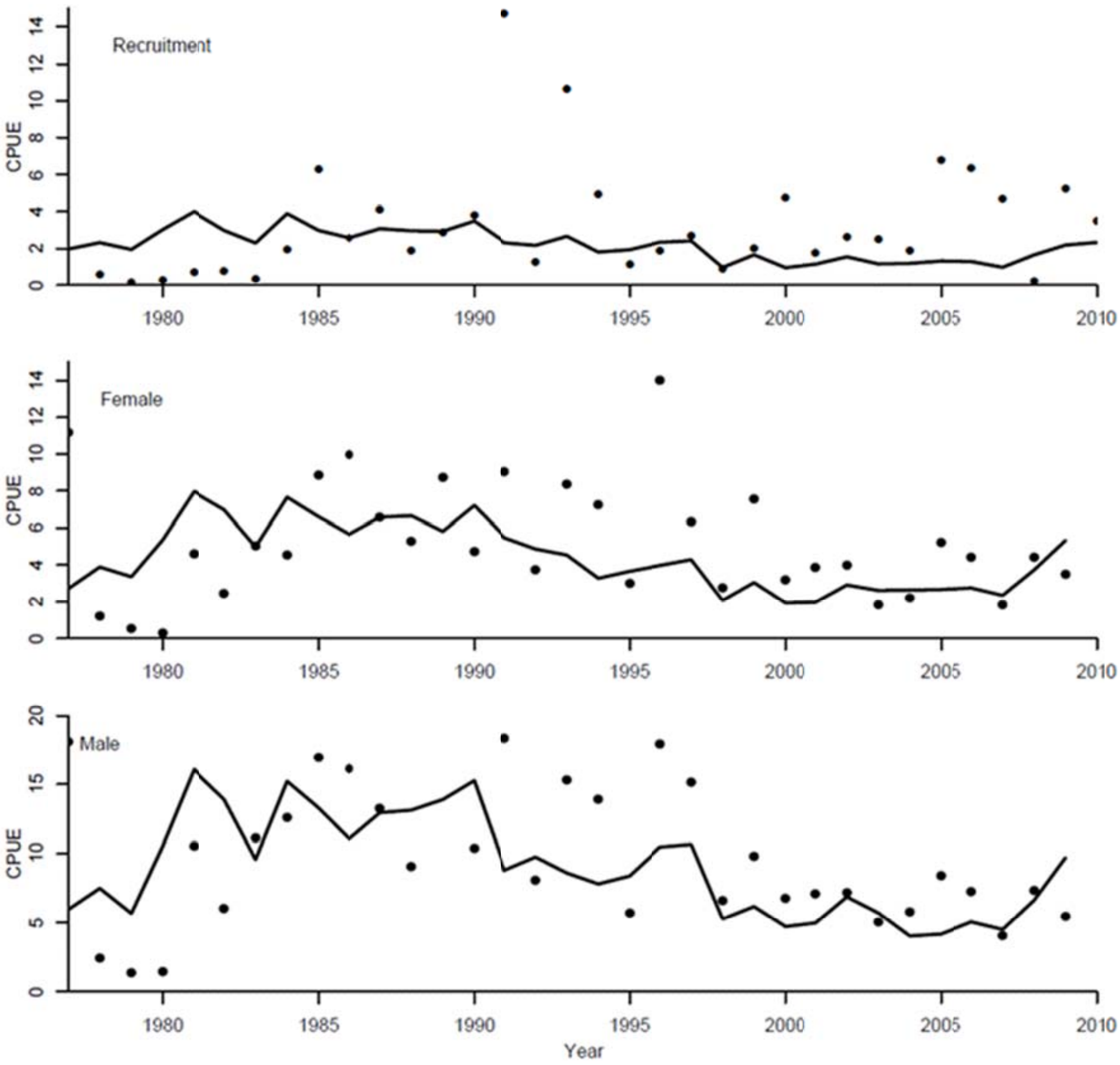


Figure 6.7. Time series of predicted and estimates of survey CPUES in the winter dredge survey for recruitment (upper panel), age-0+ females (middle panel) and age-1+ males (bottom panel) resulting from the base run of the SSCMSA. Empirical estimates of catch are shown in solid symbols, the model predictions are shown in the solid line.

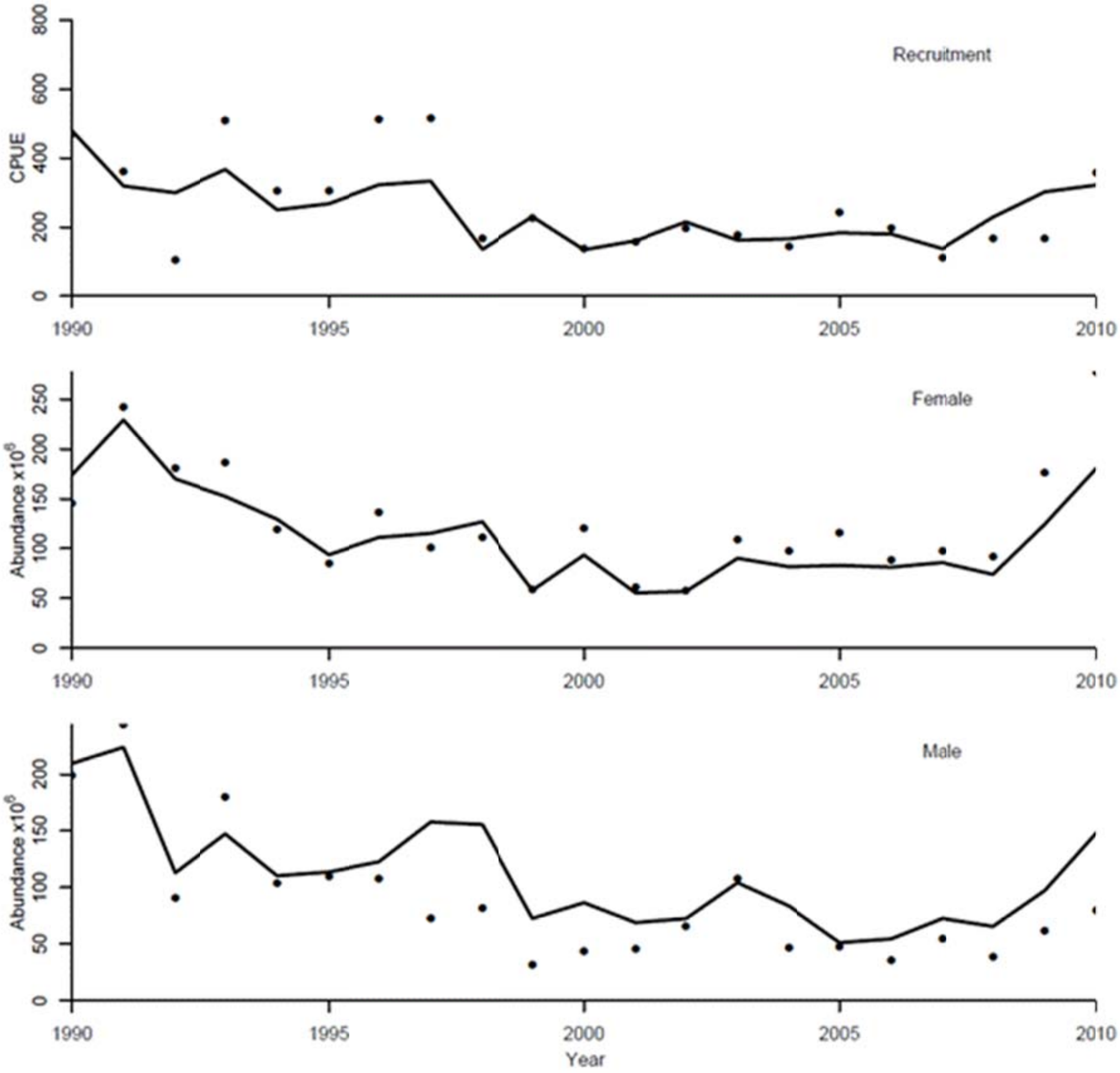


Figure 6.8 Comparison of observed and model predicted values of recruitment for the VIMS trawl survey (upper panel), MD DNR trawl survey (middle panel) and the winter dredge survey (lower panel). Each plotted point is the estimated and predicted recruitment for an individual year. The solid line represents the 1:1 relationship that the data would follow if observed and predicted were in perfect agreement.

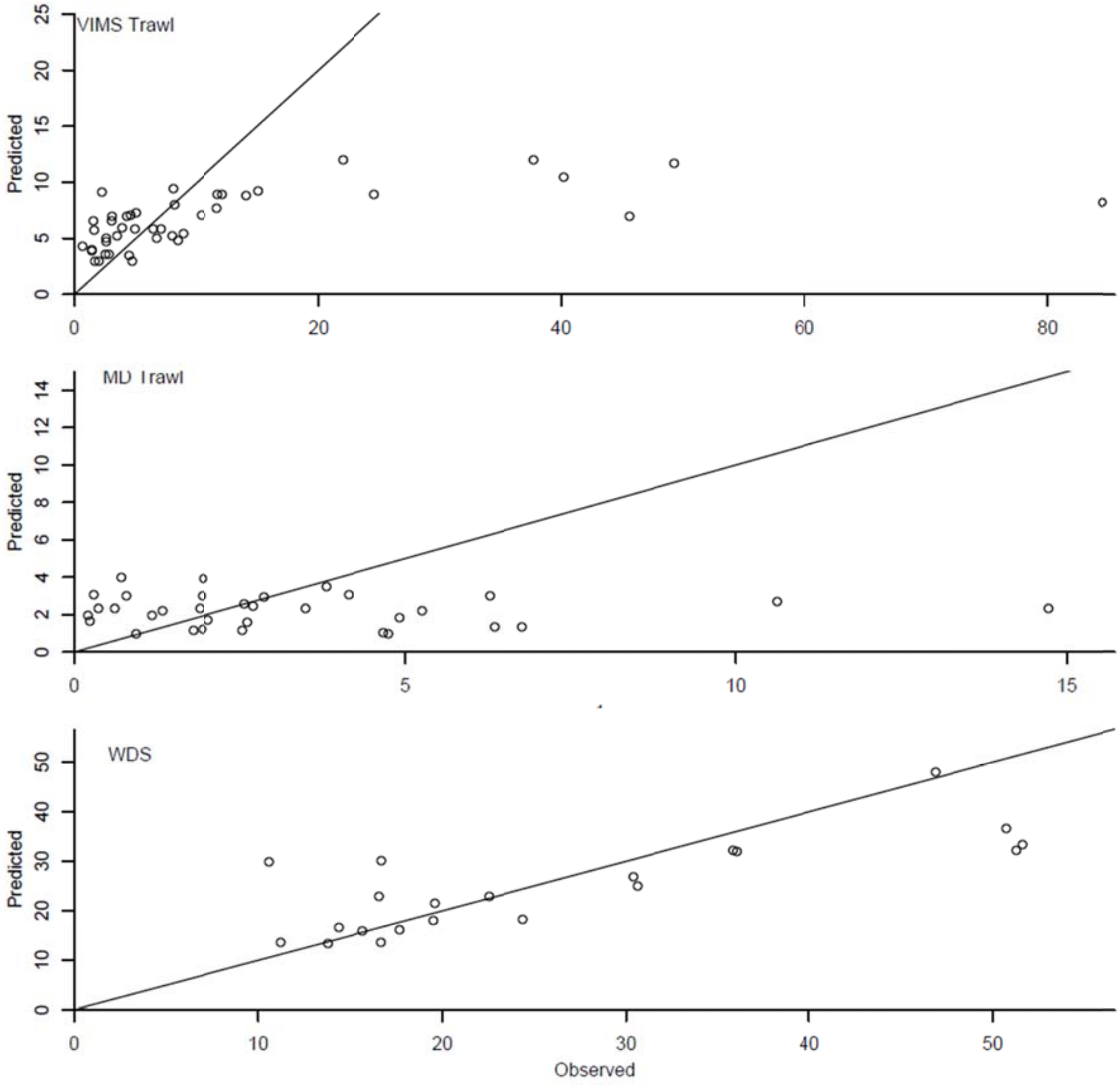


Figure 6.9. Trends in female age-1+ abundance (upper panel) and male age-1+ abundance predicted by the base run of the SSCMSA model. Solid lines indicate maximum likelihood estimates, and dashed lines indicate approximate 95% confidence intervals

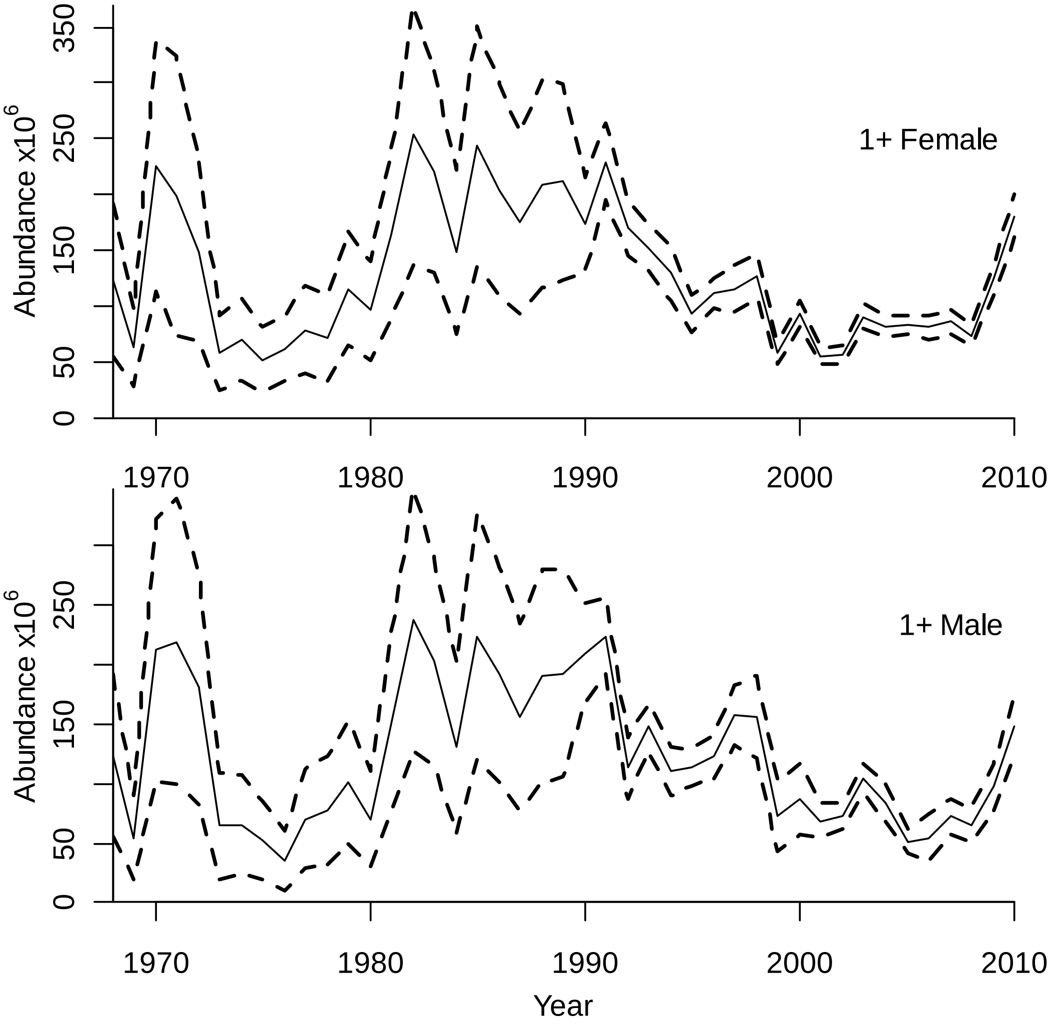


Figure 6.10. The female exploitation rate, male exploitation rate, and the ratio of male-specific exploitation to female specific exploitation estimated from the base run of the SSCMSA. Solid lines indicate maximum likelihood estimates, and dashed lines indicate approximate 95% confidence intervals.

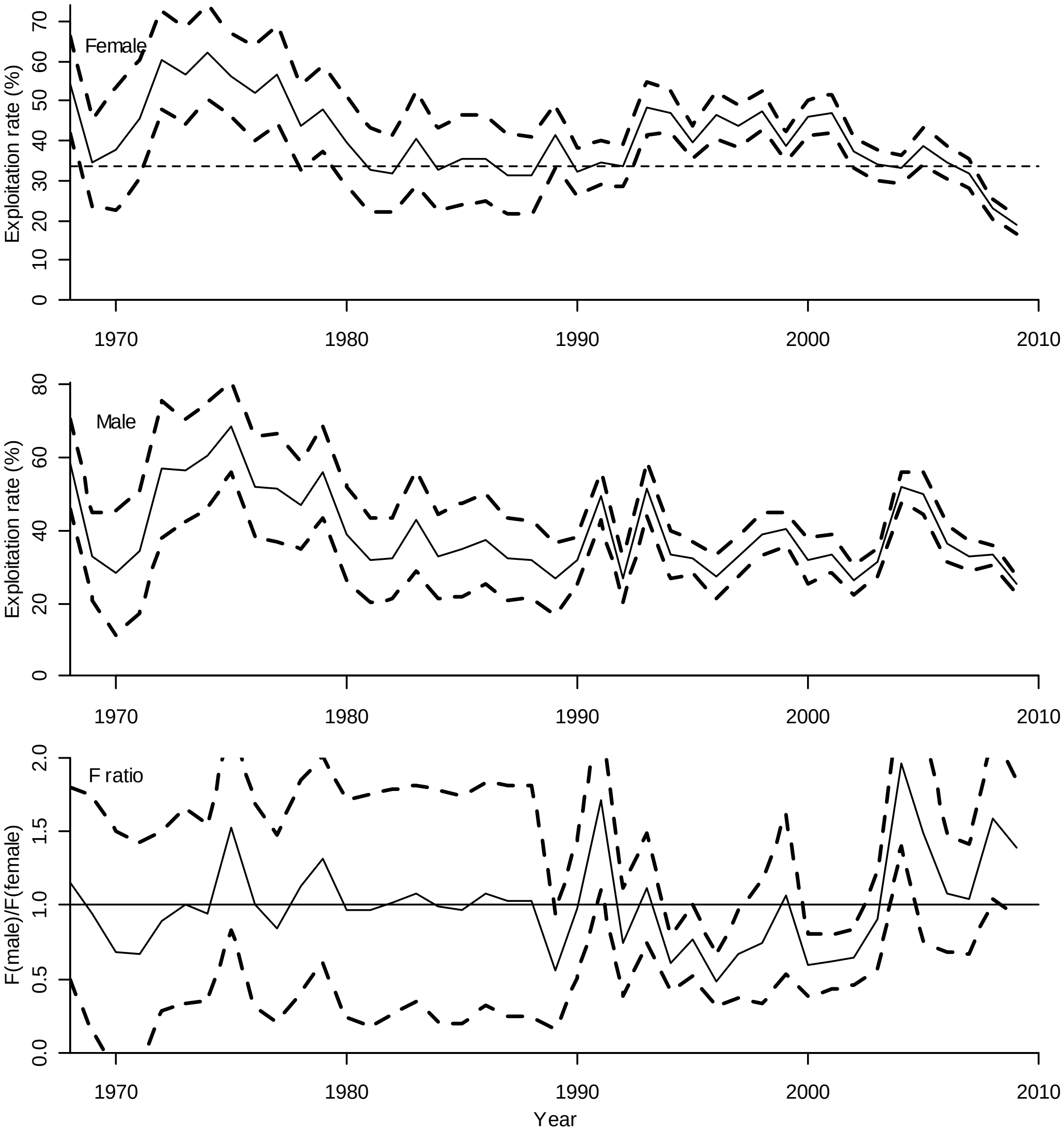


Figure 6.11. Predicted yield curves for the base model as a function of the exploitation rate on age-1+ female crabs. The figure depicts the yield curves for different sex-specifc ratios of exploitation from a F_{male}:F_{female} value of 0.6 (lowest curve), to the maximum ratio of 2.2 (highest curve) in steps of 0.2. The green shaded area encompasses the range of sex-specific exploitation rates generally observed in the population (1968-2009).

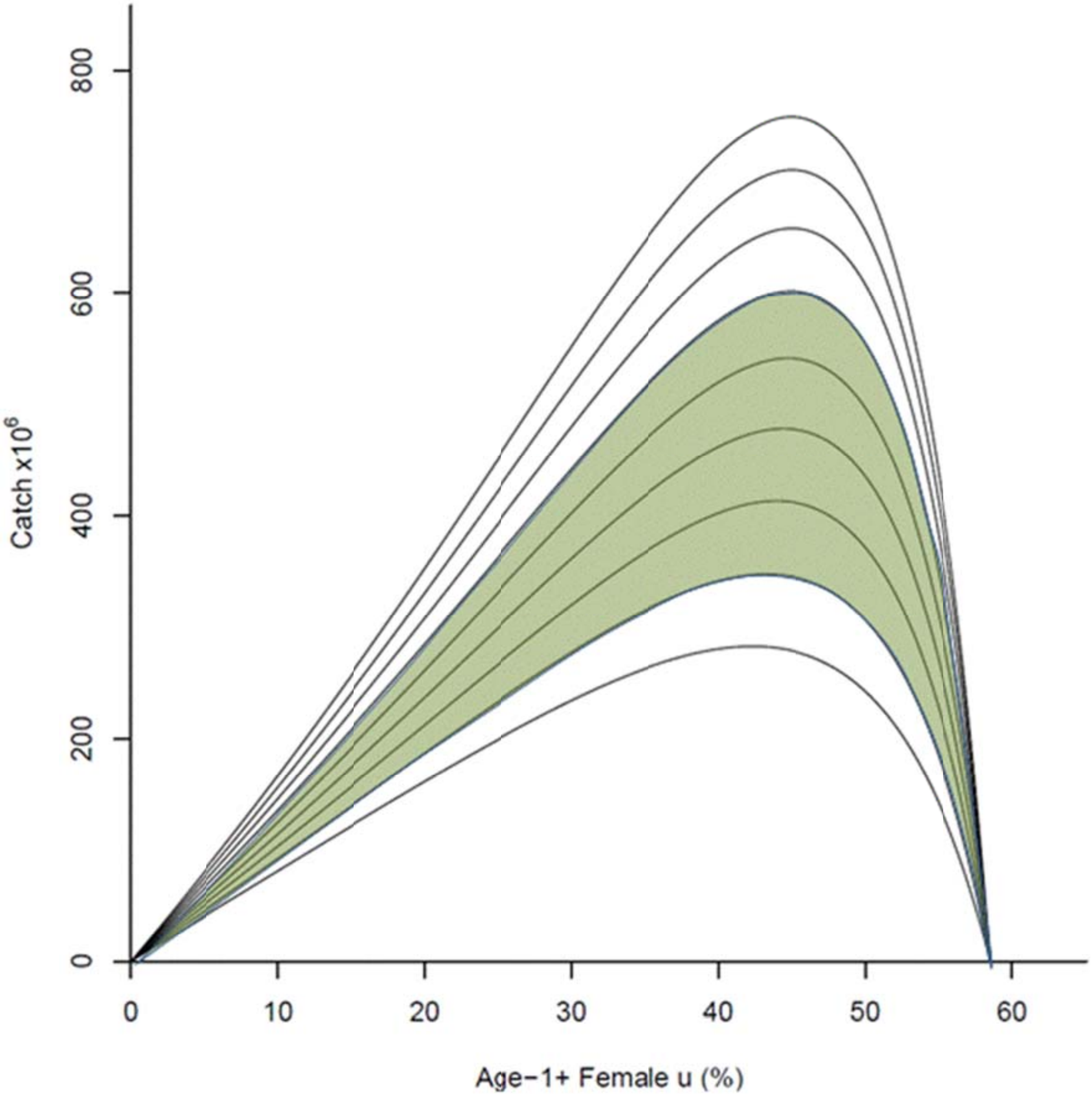


Figure 6.12. Predicted yield curves for the base model as a function of the exploitation rate on age-0+ female crabs. The figure depicts the yield curves for different sex-specifc ratios of exploitation from a F_{male}:F_{female} value of 0.6 (lowest curve), to the maximum ratio of 2.2 (highest curve) in steps of 0.2. The green shaded area encompasses the range of sex-specific exploitation rates generally observed in the population (1968-2009).

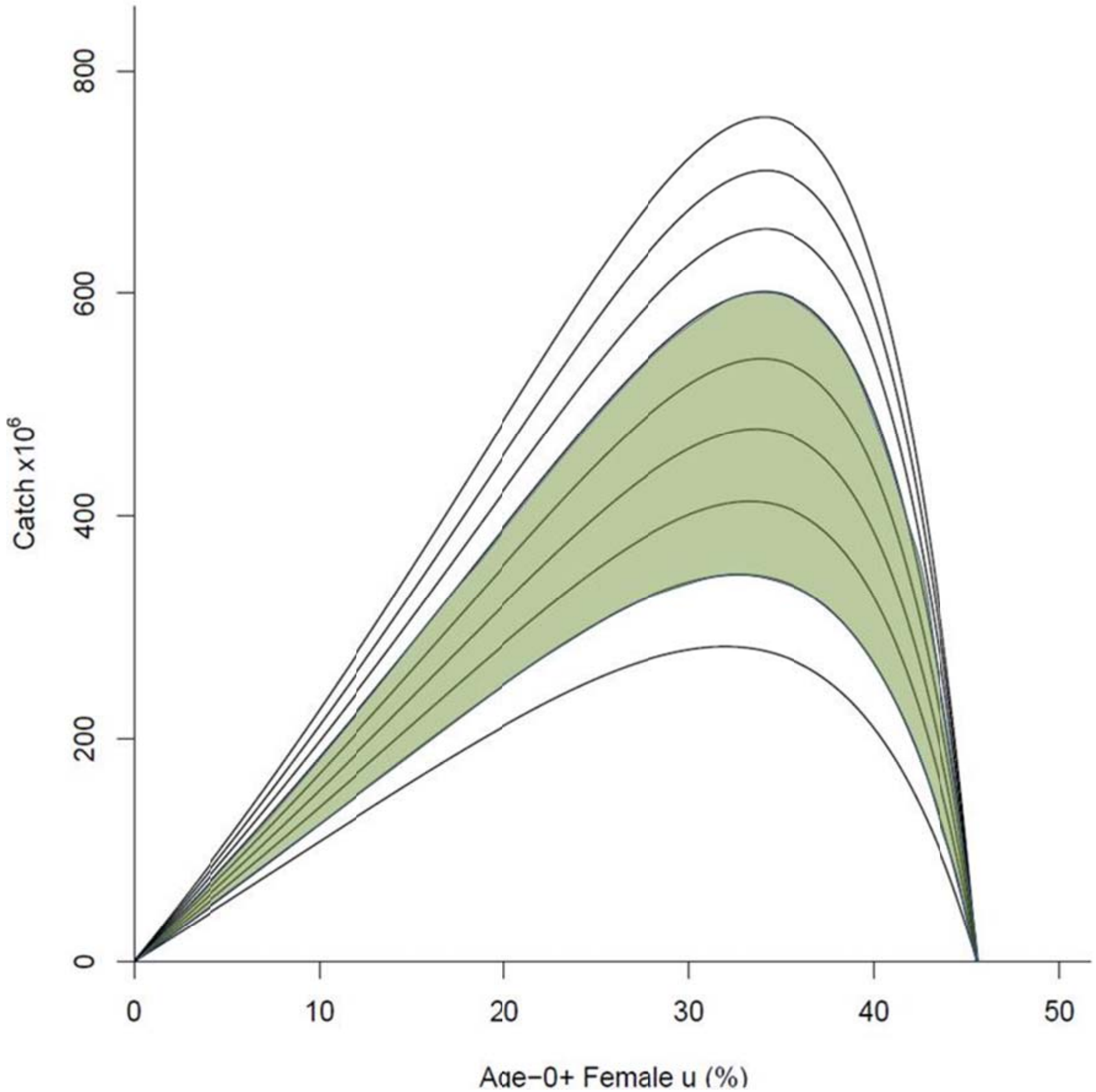


Figure 6.13. Predicted yield curves for the base model as a function of the abundance of age-0+ female crabs. The figure depicts the yield curves for different sex-specifc ratios of exploitation from a F_{male}:F_{female} value of 0.6 (lowest curve), to the maximum ratio of 2.2 (highest curve) in steps of 0.2. The green shaded area encompasses the range of sex-specific exploitation rates generally observed in the population (1968-2009).

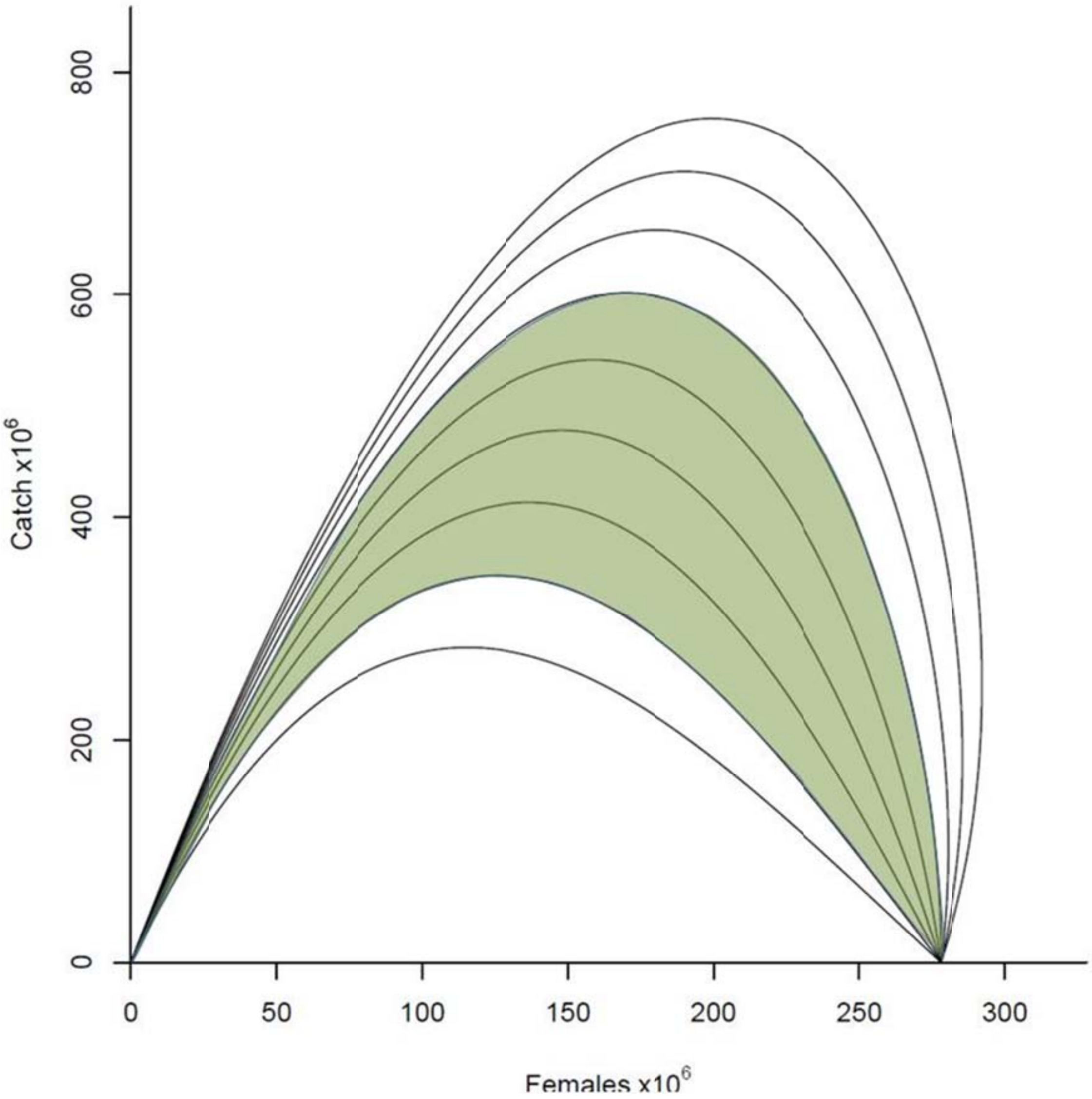


Figure 6. 14. Relationship between the sex-specific ratio of exploitation rates (F_{male}:F_{female})and the equilibrium number of female crabs in the population at MSY.

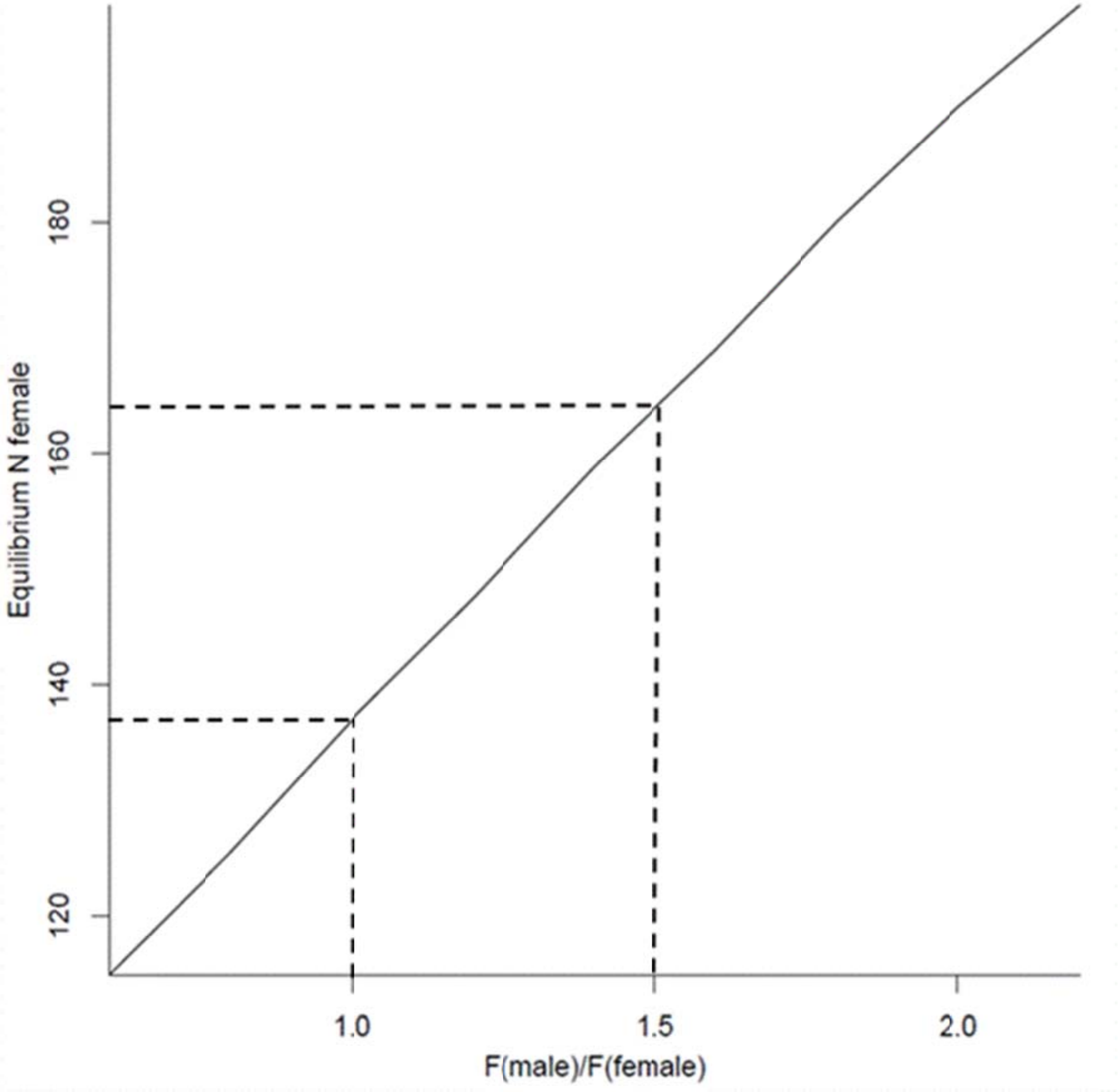


Figure 6.15. Recommended revised control rule for the blue crab fishery in Chesapeake Bay based on revised reference points developed in the SSCMSA and the empirical estimate of stock history estimated from the reported female catch and the estimated female abundance from the winter dredge survey.

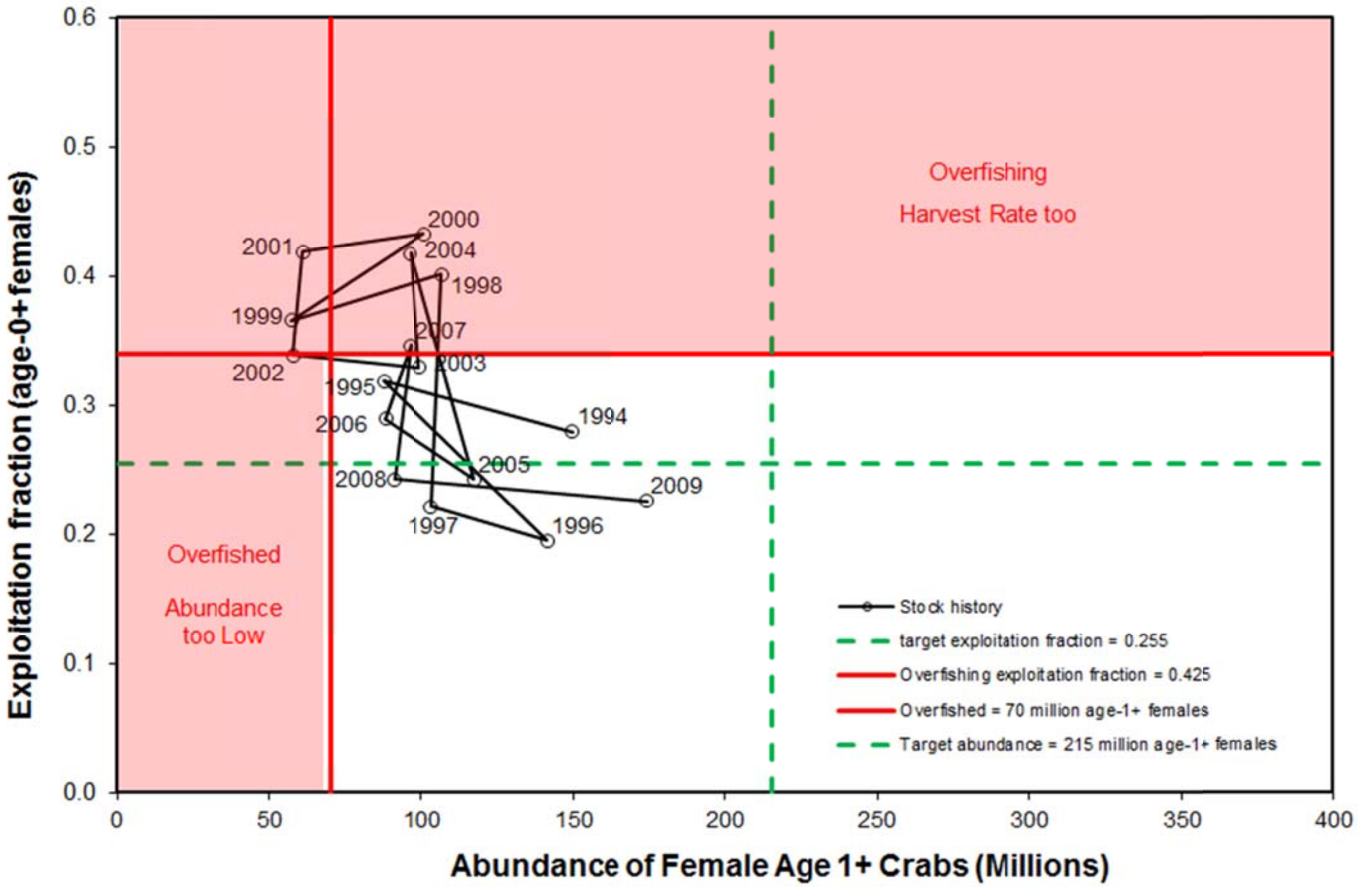


Figure 6.16. A control rule developed from the application of the updated CMSA model (Miller et al. 2005). All parameters in the model fit were as specified in the 2005 assessment.

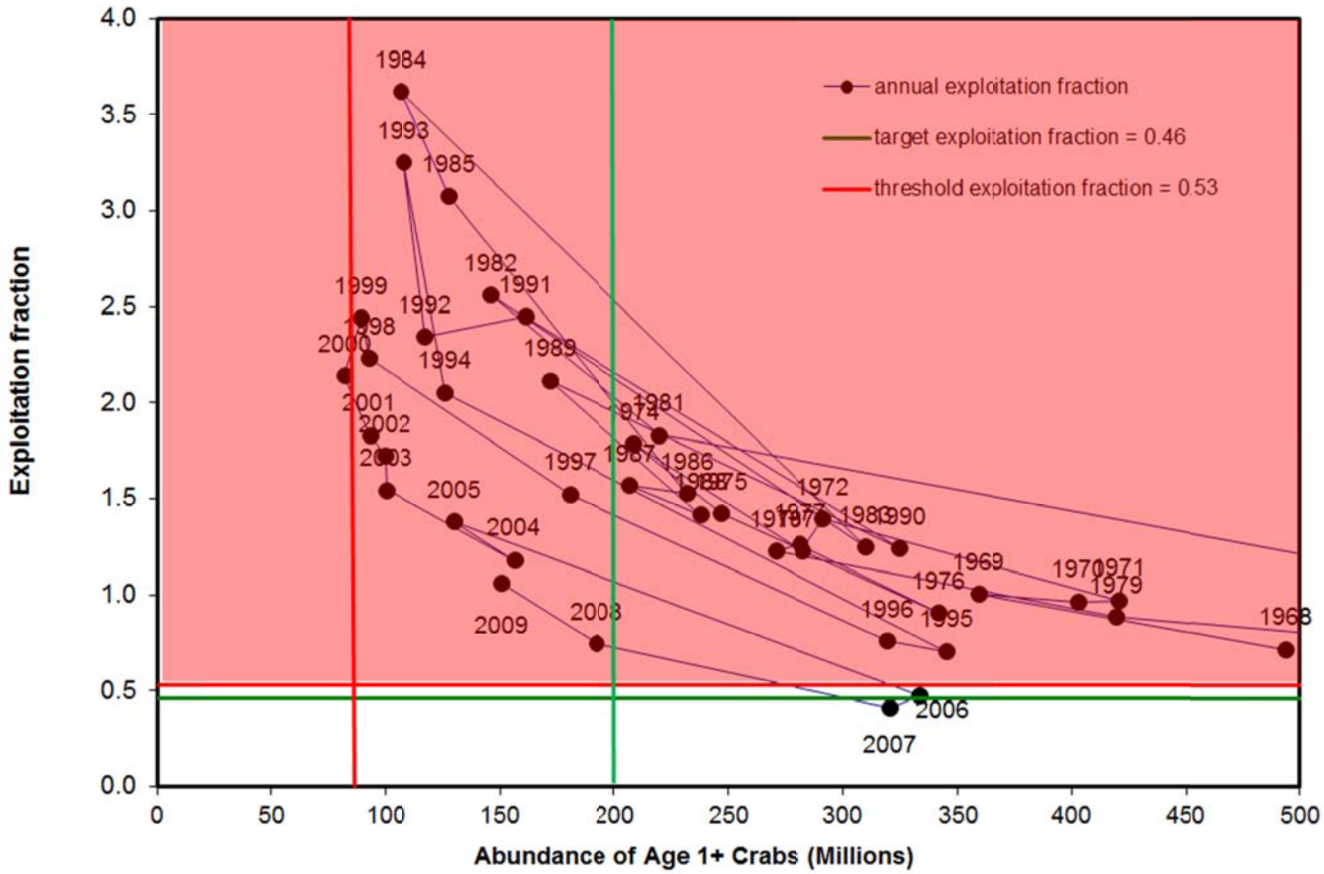
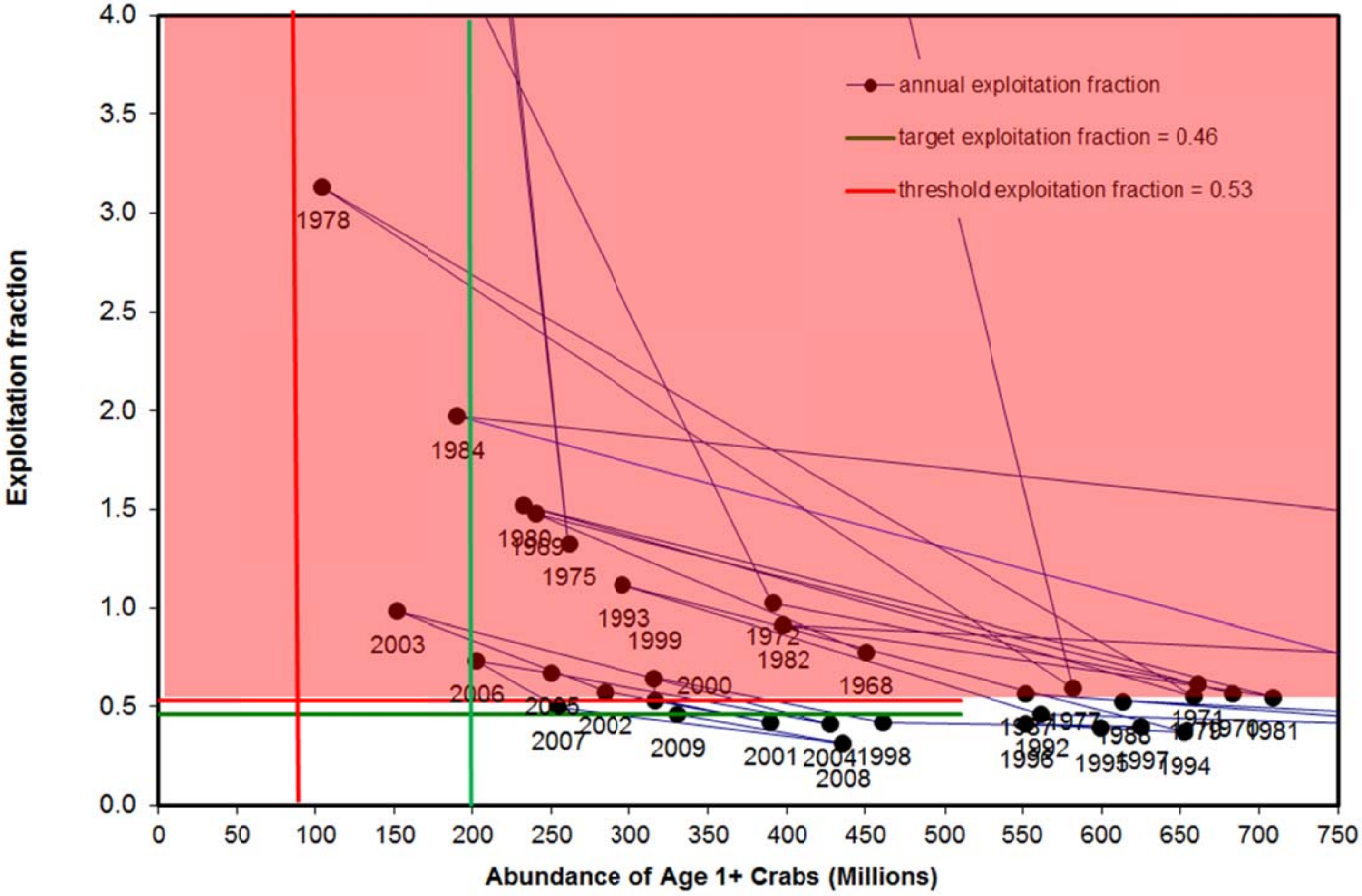


Figure 6.17. A control rule developed from the application of the standardized CMSA model (Miller et al. 2005). All parameters in the model fit were as specified in the 2005 assessment.



Appendix I. Analysis of Fishery-Independent Surveys

Sample R-code used to conduct generalized linear modeling of the fishery-independent surveys. We show sample code used to generate and plot standardized survey indices for the Maryland Trawl Survey.

Appendix I.1 Indexplots.R

```
# Code to produce simply panel plots for indices

# Use two panel functions to create scatter plots with 1:1 and 1:2 lines

#  Tom Miller                    10/1/10

require(grDevices)

# Get MD survey data
indirectory="C:/Users/Tom Miller/My Documents/Research/Crabs/Stock
Assessment/2009/Data/MDBC/"
outdirectoryPlot="c:/Users/Tom Miller/My Documents/research/crabs/Stock
Assessment/2009/Analysis/MDSurvey/1977_2008/Plots/"

mdbc<-read.csv(paste(indirectory,"bc7709Summary.csv",sep=""),header=T)
head(mdbc)

tiff(file=paste(outdirectoryPlot,"age0indices.tif",sep=""))
par(mfrow=c(3,1))

plot(mdbc$year,mdbc$Age0MaleGLM,type="l",col="blue",main="Age-0
Male",xlab="Year",ylab="Crabs.tow")
points(mdbc$year,mdbc$Age0MaleSimple)

plot(mdbc$year,mdbc$Age0FemaleGLM,type="l",col="blue",main="Age-0
Female",xlab="Year",ylab="Crabs.tow")
points(mdbc$year,mdbc$Age0FemaleSimple)

plot(mdbc$year,mdbc$Age0CrabGLM,type="l",col="blue",main="Age-0
Crab",xlab="Year",ylab="Crabs.tow")
points(mdbc$year,mdbc$Age0CrabSimple)

dev.off()
```

```
par(op)
# plot correlations
age0dat<-mdbc[,c(3,6,9)]

panel.cor <- function(x, y, digits=2, prefix="", cex.cor)
    {
        usr <- par("usr"); on.exit(par(usr))
        par(usr = c(0, 1, 0, 1))
        r = (cor(x, y,use="pairwise"))
        txt <- format(c(r, 0.123456789), digits=digits)[1]
        txt <- paste(prefix, txt, sep="")
        if(missing(cex.cor)) cex <- 0.8/strwidth(txt)
        text(0.5, 0.5, txt, cex = 1.5 )
    }

panel.upper <- function(x, y)
    {
              points(x,y, xlim=c(0,max(x,na.rm=TRUE)),ylim=c(0,max(y,na.rm=TRUE)),pch=16,
col='black')
              abline(0,1,col='red',lty=2)
              abline(0,0.5,col='blue',lty=2)
    }


tiff(file=paste(outdirectoryPlot,"age0corr.tif",sep=""))
pairs(age0dat,panel=panel.upper, lower.panel=panel.cor)

dev.off()


# age -1 indices
tiff(file=paste(outdirectoryPlot,"age1indices.tif",sep=""))
par(mfrow=c(3,1))

plot(mdbc$year,mdbc$Age1MaleGLM,type="l",col="blue",main="Age-1+
Male",xlab="Year",ylab="Crabs.tow")
points(mdbc$year,mdbc$Age1MaleSimple)

plot(mdbc$year,mdbc$Age1FemaleGLM,type="l",col="blue",main="Age-1+
Female",xlab="Year",ylab="Crabs.tow")
points(mdbc$year,mdbc$Age1FemaleSimple)

plot(mdbc$year,mdbc$Age1CrabGLM,type="l",col="blue",main="Age-1+
Crab",xlab="Year",ylab="Crabs.tow")
```

```
points(mdbc$year,mdbc$Age1CrabSimple)

dev.off()
par(op)
# plot correlations
age1dat<-mdbc[,c(12,15,18)]

tiff(file=paste(outdirectoryPlot,"age1corr.tif",sep=""))
pairs(age1dat,panel=panel.upper, lower.panel=panel.cor)

dev.off()

# lagged correlations

agecor<-mdbc[,c(3,6,9,12,15,18)]
head(agecor)
nyears<-length(agecor$Age0MaleGLM)

# create a dummy dataframe
agecor2<-agecor[-1,]

for(i in 1:nyears-1)
  {
        agecor2$Age0MaleGLM<agecor$Age0MaleGLM[i]
        agecor2$Age1MaleGLM<agecor$Age01MaleGLM[i+1]
        agecor2$Age0FemaleGLM<agecor$Age0FemaleGLM[i]
        agecor2$Age1FemaleGLM<agecor$Age01FemaleGLM[i+1]
        agecor2$Age0CrabGLM<agecor$Age0CrabGLM[i]
        agecor2$Age1CrabGLM<agecor$Age01CrabGLM[i+1]
        }

#fits

cor1<-sqrt(cor(agecor2$Age1MaleGLM,agecor2$Age0MaleGLM, use="complete.obs"))
cor1<- format(c(cor1, 0.12), digits=2)[1]
cor2<-sqrt(cor(agecor2$Age1FemaleGLM,agecor2$Age0FemaleGLM,
use="complete.obs"))
cor2<- format(c(cor2, 0.12), digits=2)[1]
cor3<-sqrt(cor(agecor2$Age1CrabGLM,agecor2$Age0CrabGLM, use="complete.obs"))
cor3<- format(c(cor3, 0.12), digits=2)[1]

tiff(file=paste(outdirectoryPlot,"agecorr.tif",sep=""))
par(mfrow=c(2,2))
```

```
plot(agecor2$Age0MaleGLM,agecor2$Age1MaleGLM,type="p",xlab="Age-0 Male [t]",ylab="Age-1 Male [t+1]")
abline(lm(agecor2$Age1MaleGLM~agecor2$Age0MaleGLM),col="blue")
text(7,15,paste("r=",cor1,sep=""))
plot(agecor2$Age0FemaleGLM,agecor2$Age1FemaleGLM,type="p",xlab="Age-0 Female [t]",ylab="Age-1 Female [t+1]")
abline(lm(agecor2$Age1FemaleGLM~agecor2$Age0FemaleGLM),col="blue")
text(5,12,paste("r=",cor2,sep=""))
plot(agecor2$Age0CrabGLM,agecor2$Age1CrabGLM,type="p",xlab="Age-0 Crab [t]",ylab="Age-1 Crab [t+1]")
abline(lm(agecor2$Age1CrabGLM~agecor2$Age0CrabGLM),col="blue")
text(10,25,paste("r=",cor3,sep=""))


dev.off()
```

Appendix I.2 Code for apply delta-lognormal GLM model to MD DNR Trawl Survey to generate standardized indices.

```
# code for applying delta lognormal model for MD blue crab survey

library(grDevices)
setwd('c:/files/research/crabs/Stock Assessment/2009/Data/MDBC/')
outdirectoryPlot="c:/files/research/crabs/Stock
Assessment/2009/Analysis/MDSurvey/1977_2008/Plots/"
outdirectoryResults="c:/files/research/crabs/Stock
Assessment/2009/Analysis/MDSurvey/1977_2008/Results/"
#  Name data source
infile="Age1Crab"

dglm<-dget('c:/files/research/crabs/Stock
Assessment/2009/Analysis/MDSurvey/1977_2008/deltaGLM-1-7-2-PBC.r')

mdbccrab<-read.table(paste(infile,".txt.",sep=""), header=T)
head(mdbccrab)

# index for month > -= 9 for age 0 and <=7 for age 1
mdbcdat<-mdbccrab[mdbccrab$MONTH <= 7, ]
head(mdbcdat)

# calculate positive tows
TotN<-length(mdbcdat$Count)
PosTow<-mdbcdat[mdbcdat$Count > 0,]
PosN<-length(PosTow$Count)
Pos<-PosN/TotN
Pos

mdindex<-
dglm(mdbcdat,dist="gamma",types=c('C','F','F','F','C','C','C'),cols.bin=c(2,3,4),cols.pos=c(
2,3,4,5,6),write=F,J=FALSE)
yearvals<-rownames(deltagamma.summary$deltaGLM.index)
deltagamma.summary$aic
deltagamma.results

# get simple index
mdbcmean<-tapply(mdbcdat[,1],mdbcdat[,2],mean)

#write output
write.csv(mdbcmean,file=paste(outdirectoryResults,infile,"SimpleMean.csv",sep=""))
```

```
write.csv(deltagamma.summary$deltaGLM.index,file=paste(outdirectoryResults,infile,"I
ndex.csv",sep=""))

#pdf(file=paste(outdirectory,infile,".pdf",sep=""),onefile=TRUE)
tiff(file=paste(outdirectoryPlot,infile,".tif",sep=""))
plot(rownames(deltagamma.summary$deltaGLM.index),deltagamma.summary$deltaGL
M.index[,1],type='l',col="blue",xlab="Year",ylab=paste("Survey index
(crabs.tow)",sep=""))
points(rownames(deltagamma.summary$deltaGLM.index),mdbcmean)

dev.off()
graphics.off()
```

Appendix II. Reporting Change Methodology

R code used to conduct analysis of the significance of reporting interventions on time series of commercial landings.

```
rm(list=ls())

library(tseries)
library(forecast)

#read data file in
annualMD<-read.csv("C:/Users/Amanda/My Documents/CBL/bc stock assessment/data for interventions/annual landings/MD_landings.csv", header=T, sep=",", dec=".")
year<-annualMD[,1]
pounds<-annualMD[,2]
tons<-annualMD[,3]

#create variables
tspounds<-ts(pounds,start=1950, end=2009, freq=1)
mean(tspounds[1:31])

tstons<-ts(tons,start=1950, end=2009, freq=1)
mean(tstons)
sd(tstons)
mean(tstons[1:31])
sd(tstons[1:31])

x <- year
y1 <- tstons
y2 <- tspounds
par(mar=c(5,4,3,5)+.1)
plot(x,y1,type="l",col="black", ylim=c(0,30), xlab="Year", ylab="MT/1000")
par(new=TRUE)
plot(x, y2,type="l",col="",xaxt="n",yaxt="n",xlab="",ylab="",ylim=c(0,66138678.6))
axis(4)
mtext("Pounds",side=4,line=3)

#Difference Time Series
difpounds<-diff(tspounds)
mean(difpounds)
sd(difpounds)

op<-par(mfrow=c(2,2))
```

```
acf(tspounds, main="MD ACF")
pacf(tspounds, main="MD PACF")
acf(difpounds, main="MD Differenced ACF")
pacf(difpounds, main="MD Differenced PACF")
par(op)

diftons<-diff(tstons)
mean(diftons)
sd(diftons)

op<-par(mfrow=c(2,2))
acf(tstons, main="MD ACF")
pacf(tstons, main="MD PACF")
acf(diftons, main="MD Differenced ACF")
pacf(diftons, main="MD Differenced PACF")
par(op)

par(mar=c(5,4,4,5)+.1)
ts.plot(diftons,type="l",col="black", ylim=c(-10,15), xlab="Year", ylab="MT/1000")
par(new=TRUE)
ts.plot(difpounds,type="l",col="",xaxt="n",yaxt="n",xlab="",ylab="",ylim=c(-
22046226.2,33069339.3))
axis(4)
mtext("Pounds",side=4,line=3)

auto.arima(tspounds,d=1,D=NA)

# fixed intervention at 1981
#create 0,1 vector
X1<-rep(1,60)
X1[32:length(tspounds)]<-0

#run intervention analysis
MDmodelxreg<-arima(tspounds,order=c(0,1,1),xreg=X1,method="ML")
summary(MDmodelxreg)
MDmodelxregt<-arima(tstons,order=c(0,1,1),xreg=X1,method="ML")
summary(MDmodelxregt)

fitt<-tstons+MDmodelxregt$residuals
fit<-tspounds+MDmodelxreg$residuals
adj<-MDmodelxreg$coef[2]*X1
corrected_ts<-tspounds-adj
corrected_tstons<-(corrected_ts*0.00045359237)/1000
mean(corrected_tstons)
```

```
sd(corrected_tstons)
mean(corrected_tstons[1:31])
sd(corrected_tstons[1:31])

#ARIMA model for corrected data
auto.arima(corrected_ts,d=1,D=NA)
MDauto<-arima(corrected_ts,order=c(0,1,1))
AIC(MDauto)
tsdiag(MDauto)
plot(corrected_ts,type='p', ylim=c(0,77161791.7))
fitauto<-corrected_ts+MDauto$residuals
lines(fitauto, col='blue')

#corrected with fit
par(mar=c(5,4,4,5)+.1)
x <- year
y1 <- corrected_tstons
y2 <- fitauto
par(mar=c(5,4,4,5)+.1)
plot(x,y1,type="p",col="black", ylim=c(0,35), xlab="Year", ylab="MT/1000")
par(new=TRUE)
plot(x, y2,type="l",col="black",xaxt="n",yaxt="n",xlab="",ylab="",ylim=c(0,77161791.7))
axis(4)
mtext("Pounds",side=4,line=3)

#raw and corrected with fit
x <- year
y1 <- tstons
y2 <- corrected_ts
par(mar=c(5,4,4,5)+.1)
plot(x,y1,type="p",col="black", ylim=c(0,35), xlab="Year", ylab="MT/1000")
lines(fitt)
par(new=TRUE)
plot(x,
y2,type="p",col="gray47",xaxt="n",yaxt="n",xlab="",ylab="",ylim=c(0,77161791.7))
lines(fitauto,col="gray47")
axis(4)
mtext("Pounds",side=4,line=3)
abline("v"=c(1981),lty=c(2,2))
```

Appendix III. Sex-specific catch, multiple survey analysis model implemented for this assessment.

Appendix III.1 ADMB code

```
//Chesapeake Bay sex-specific catch multiple survye model
//for blue crabs in Chesapeake Bay
//By: M. Wilberg
//Date:10/21/2010
//Last updated: 2/28/2011
//Winter dredge survey and VIMs trawl surveys are end of year surveys
TOP_OF_MAIN_SECTION
  //increase number of estimated parameters
  gradient_structure::set_NUM_DEPENDENT_VARIABLES(1000);
  gradient_structure::set_GRADSTACK_BUFFER_SIZE(200040);
  gradient_structure::set_CMPDIF_BUFFER_SIZE(1000000);
  arrmblsize = 10000000;

  //gradient_structure::set_ARRAY_MEMBLOCK_SIZE(150352);
GLOBALS_SECTION

DATA_SECTION  //Read in data
  init_int fyear   //first year of the model
  init_int lyear   //last year of the model

  //Catch data
  init_int ftcyear  //first year of total catch
  init_int ltcyear  //last year of total catch
  init_vector com_TC_obs(ftcyear,ltcyear)  //total catch
  init_int fscyear  //first year sex-specific catch
  init_int lscyear  //last year sex-specific catch
  init_matrix com_C_obs(1,2,fscyear,lscyear)  //Sex-specific catch
  init_number C_sds

  //Survey data
  init_int nsurveys  //number of surveys
  init_ivector fsyear(1,nsurveys)  //vector of first year of surveys
  init_ivector lsyear(1,nsurveys)  //vector of last survey years
  init_3darray ad_survey_obs(1,nsurveys,1,2,fsyear,lsyear)  //Adult survey CPUE
  init_matrix re_survey_obs(1,nsurveys,fsyear,lsyear)  //Recruit survey CPUE
  init_vector sa_be(1,nsurveys)    //indicate beginning or end of year for surveys
  init_vector sa_time(1,nsurveys)  //Timing of surveys
  init_vector sr_time(1,nsurveys)  //timing of surveys
```

```
init_vector ad_survey_sds(1,nsurveys)  //Survey SDs for adults
init_vector re_survey_sds(1,nsurveys)  //survey SDs for recruits
init_ivector survey_dist(1,nsurveys)   //Distribution for survey likelihoods
init_vector in_M(1,2)     //starting value for M
init_int M_phase     //estimation phase for male M
init_number in_sex_r    //sex ratio of recruits
init_int sex_r_phase //phase for sex ratio estimation
init_number salpha   //starting value for SR alpha
init_number sbeta    //starting value for SR beta
init_number in_rec_sd   //standard deviation for recruitment
init_int rsd_phase   //phase for estimation of recruitment sd
init_number sp_time  //proportion of the year before spawning occurs
init_number p_F_sp   //proportion of female recruits that spawn at age-1

init_number in_rf  //partial recruitment of recruits to the fishery
init_int rf_phase  //phase for estimation of partial recruitment
init_number p_rec  //Proportion of recreational harvest

//number for reference point explorations
init_number Frat_init  //lowest value for ratio of Male to female F
init_number Frat_max   //highest value for ratio of male to female F
init_number Frat_inc   //Increment between values

init_number FSPR_init  //lowest value of female F used in SPR calcs
init_number FSPR_max   //highest value of female F used in SPR calcs
init_number FSPR_inc   //increment for F

int Frat_num
int FSPR_num

!!Frat_num=(Frat_max-Frat_init)/Frat_inc+1;
!!FSPR_num=(FSPR_max-FSPR_init)/FSPR_inc+1;

init_int nspr          //number of values FSPR will be calculated at
init_vector SPR_targ(1,nspr)  //Values of SPR for FSPR reference point calculations
init_int niter         //number of iterations for Newton method of calculating FSPR

init_int test

vector nyrs(1,nsurveys)  //vector for number of years in each survey
ivector fy(1,nsurveys)   //vector of alternative first years for survey

//Total harvest including recreational
init_vector TC_obs(ftcyear,ltcyear)  //total catch
init_matrix C_obs(1,2,fscyear,lscyear)  //Sex-specific catch
```

```
 //Variances for data sets
 number C_var  //variance of catch
 vector ad_survey_var(1,nsurveys)  //variances for adult surveys
 vector re_survey_var(1,nsurveys)  //variances for recruitment surveys

 //Define index varaibles
 int x  //index variable for sex (1 female, 2 male)
 int y  //index variable for year
 int s  //index variable for survey
 int i  //index variable for ratio of male to female F
 int j  //index variable for F in SPR and MSY calculations

 int ispr
 int iter

LOCAL_CALCS
 if(test!=12345)  //check to make sure end of file number is correct
 {
  //if not correct, output the data and exit.
  cout << "Data not reading properly" << endl;
  cout << "fyear, lyear: " << fyear << ", " << lyear << endl;
  cout << "ftcyear, ltcyear: " << ftcyear << ", " << ltcyear << endl;
  cout << "Total catch" << endl << TC_obs << endl;
  cout << "fscyear, lscyear: " << ftcyear << ", " << ltcyear << endl;
  cout << "Sex-specific catch" << endl << C_obs << endl;
  cout << "SD of catch: " << C_sds << endl;
  cout << "number of surveys: " << nsurveys << endl;
  cout << "fsyear, lsyear: " << fsyear << ", " << lsyear << endl;
  cout << "Adult survey indices" << endl << ad_survey_obs << endl;
  cout << "Recruit survey indices" << endl << re_survey_obs << endl;
  cout << "M: " << in_M << endl;
  cout << "sex ratio (proportion female): " << in_sex_r << endl;
  cout << "starting values for alpha, beta: " << salpha << ", " << sbeta << endl;
  cout << "EOF test: " << test << endl;
  exit(1);
 }

 //Calculate SDs from variances
 C_var=square(C_sds);  //variance of catch
 ad_survey_var=square(ad_survey_sds);  //variances for adult surveys
 re_survey_var=square(re_survey_sds);  //variances for recruitment surveys

 TC_obs=com_TC_obs*(1.+p_rec);  //total catch
 C_obs=com_C_obs*(1.+p_rec);    //Sex-specific catch

END_CALCS
```

```
PARAMETER_SECTION
  //initial R and N
  init_bounded_number log_init_N(0.,20.,1)
  init_bounded_number log_init_R(0.,20.,1)

  //Fishing mortality for each year
  init_bounded_vector log_mean_F(1,2,-10.,10.,1)
  init_bounded_dev_vector log_F_dev_1(fyear,lyear-1,-10.,10.,2)
  init_bounded_dev_vector log_F_dev_2(fyear,lyear-1,-10.,10.,2)

  //Stock-recruitment parameters
  init_bounded_number log_alpha(-10.,10.,1)
  init_bounded_number log_beta(-10.,10.,4)
  init_bounded_dev_vector log_rec_devs(fyear,lyear-1,-10,10,1)
  init_bounded_number log_rec_sd(-5,3,rsd_phase)

  //Natural mortality rate
  init_bounded_number log_M(-10.,2.,M_phase)

  //Partial recruitment (i.e., selectivity) of recruits to the fishery
  init_bounded_number log_rf(-10.,0.,rf_phase)

  init_bounded_number log_sex_r(-10,0,sex_r_phase)    //sex ratio of recruits

  //Calculated values
  matrix N(1,2,fyear,lyear)   //sex-specific abundance
  matrix R(1,2,fyear,lyear)   //sex-specific recruitment
  matrix SP(1,2,fyear,lyear)      //number of spawners
  matrix C(1,2,fyear,lyear-1)   //sex-specific catch
  vector TC(fyear,lyear-1)      //total catch
  matrix F(1,2,fyear,lyear-1)   //sex-specific fishing mortality rate
  3darray ad_survey_est(1,nsurveys,1,2,fyear,lyear)  //estimated adult survey indices
  matrix re_survey_est(1,nsurveys,fyear,lyear)  //estimated recruitment survey indices
  sdreport_matrix qa(1,nsurveys,1,2)   //catchability for adult surveys (sex-specific)
  sdreport_vector qr(1,nsurveys)   //catchability for recruitment surveys
  vector M(1,2)                  //Instantaneous natural mortality rate
  number rf               //selectivity (partial recruitment) of recruits to the fishery

  number alpha               //Alpha of the S-R relationship
  number beta               //Beta of the S-R relationship
  number rec_sd               //standard deviation for recruitment
  number rec_var                  //variance for recruitment deviations
  number sex_r    //sex ratio of recruits

  //Variables for reference point calculations
```

```
  number FSPR  //F for SPR calculations
  number Frat  //Ratio of male to female F

  matrix SPRf(1,Frat_num,1,FSPR_num)
  matrix SPRm(1,Frat_num,1,FSPR_num)

  matrix YPRf(1,Frat_num,1,FSPR_num)
  matrix YPRm(1,Frat_num,1,FSPR_num)

  matrix N_eq(1,Frat_num,1,FSPR_num)
  matrix Nf_eq(1,Frat_num,1,FSPR_num)
  matrix Nm_eq(1,Frat_num,1,FSPR_num)
  matrix Nfs_eq(1,Frat_num,1,FSPR_num)
  matrix Nms_eq(1,Frat_num,1,FSPR_num)

  matrix R_eq(1,Frat_num,1,FSPR_num)
  matrix Rf_eq(1,Frat_num,1,FSPR_num)
  matrix Rm_eq(1,Frat_num,1,FSPR_num)

  matrix C_eq(1,Frat_num,1,FSPR_num)
  matrix Cf_eq(1,Frat_num,1,FSPR_num)
  matrix Cm_eq(1,Frat_num,1,FSPR_num)

  matrix uf_eq(1,Frat_num,1,FSPR_num)
  matrix uf0_eq(1,Frat_num,1,FSPR_num)
  matrix um_eq(1,Frat_num,1,FSPR_num)
  matrix urat_eq(1,Frat_num,1,FSPR_num)

  vector FSPR_ref(1,nspr)
  number SPR_temp
  number dSPR


  //variables for likelihood function
  matrix Lsa(1,nsurveys,1,2)  //likelihood components for adult surveys
  vector Lsr(1,nsurveys)  //likelihood components for recruit surveys
  vector Lc(1,3)         //likelihood components for catch time series (1=female, 2-male, 3-
total)
  number Lrdev          //likelihood for recruitment deviations
  number F_pen          //penalty for deviations between male and female F

  number F_pen_mu       //mean for F_pen
  number F_pen_var      //var for F_pen

  //Negative log likelihood
  objective_function_value negLL
```

```
 LOCAL_CALCS
  //specify starting values for parameters
  log_alpha=log(salpha);
  log_beta=log(sbeta);
  log_mean_F=log(0.6);
  log_init_N=log(73.7);
  log_init_R=log(150.);
  log_M=log(in_M(2));
  log_rf=log(in_rf);
  log_rec_sd=log(in_rec_sd);
  log_sex_r=log(in_sex_r);

  //calculate number of years in each survey (needs to be here because
  //functions are not visible in the DATA_SECTION LOCAL_CALCS)
  for(s=1;s<=nsurveys;s++)
  {
    if(fsyear(s)>fyear)
    {
      fy(s)=fsyear(s);
    }
    else
    {
      fy(s)=fyear;
    }
    nyrs(s)=double(lyear-fy(s)+1);
  }

 END_CALCS

PROCEDURE_SECTION
  //Put in values for the first year and convert parameters to the arithmetic scale
  set_initial_conditions();
  //calculate abundance for each year
  calculate_abundance_and_catch();
  calculate_predicted_indices();
  calculate_objective_function();

FUNCTION set_initial_conditions
  //convert parameters from the log scale
  alpha=exp(log_alpha);
  beta=exp(log_beta);
  rec_sd=exp(log_rec_sd);
  rec_var=square(rec_sd);
  sex_r=exp(log_sex_r);
  M(1)=in_M(1);
```

```
 M(2)=exp(log_M);
 rf=exp(log_rf);

 //Calculate F for each year
 for(y=fyear;y<lyear;y++)
 {
  F(1,y)=exp(log_mean_F(1)+log_F_dev_1(y));
  F(2,y)=exp(log_mean_F(2)+log_F_dev_2(y));
 }

 //assign starting abundance and recruitment
 for(x=1;x<=2;x++)
 {
  N(x,fyear)=exp(log_init_N);
  R(x,fyear)=exp(log_init_R);
 }

FUNCTION calculate_abundance_and_catch
 for(y=fyear;y<lyear;y++)
 {
  for(x=1;x<=2;x++)  //loop over sexes
  {
   //abundance for the next year
   N(x,y+1)=R(x,y)*exp(-(M(x)+rf*F(x,y)))+N(x,y)*exp(-(M(x)+F(x,y)));
   //spawners also include some animals that were recruits in the beginning of the year
   SP(x,y)=nspawn(F(x,y),M(x),N(x,y),R(x,y));

   //Baranov catch equation
   C(x,y)=baranov(F(x,y),M(x),N(x,y))+baranov(rf*F(x,y),M(x),R(x,y));
  }

  //Calculate next year's recruitment
  //Ricker S-R function uses only females for egg production but total abundance for
density dependence
  R(1,y+1)=sex_r*alpha*SP(1,y)*exp(-beta*(SP(1,y)+SP(2,y)))*exp(log_rec_devs(y));
  R(2,y+1)=R(1,y+1)*(1.-sex_r)/sex_r;
 }

 //Total catch
 for(y=fyear;y<lyear;y++)
 {
  TC(y)=C(1,y)+C(2,y);
 }

FUNCTION calculate_predicted_indices
 for(s=1;s<=nsurveys;s++)
```

```
{
  re_survey_est(s)=0.0;
  qr(s)=0.0;
  double missy=0.0;
  for(y=fy(s);y<=lyear;y++)
  {
    if(re_survey_obs(s,y)!=-99.)  //check to make sure year is not missing
    {
      if(!last_phase())
      {
       //small constant added to recruitment in earlier stages to
       //increase numerical stability
       qr(s)+=log(re_survey_obs(s,y))-log((R(1,y)+.01)/sex_r);
      }
      else
      {
        //small constant not included in last estimation stage
        qr(s)+=log(re_survey_obs(s,y))-log(R(1,y)/sex_r);
      }
   }
    else
    {
      //survey index missed a year
      missy+=1.;
    }
  }
  //calculate geometric mean
  qr(s)=exp(qr(s)/(nyrs(s)-missy));

  for(x=1;x<=2;x++)
  {
    //calculate catchability for each sex-index combination
    double missy=0.0;
    qa(s,x)=0.;
    for(y=fy(s);y<=lyear;y++)
    {
    if(s<nsurveys)
    {
      if(ad_survey_obs(s,x,y)!=-99.)  //check to make sure year is not missing
      {
        if(sa_be(s)==0) //beginning of year survey
        {
          qa(s,x)+=log(ad_survey_obs(s,x,y))-log(N(x,y));
        }
        else
        {
```

```
      qa(s,x)+=log(ad_survey_obs(s,x,y))-log(N(x,y)*exp(-
sa_time(s)*(M(x)+F(x,y)))+R(x,y)*exp(-sa_time(s)*(M(x)+rf*F(x,y))));
      }
    }
    else
    {
     //survey index missed a year
     missy+=1.;
    }
   }
   else  //last adult survey is the winter dredge survey
   {
    qa(s,x)=1.0;  //Set adult q for winter dredge survey to 1.
   }
   }
   //calculate geometric mean
   if(s<nsurveys) qa(s,x)=exp(qa(s,x)/(nyrs(s)-missy));

   //Calculate each predicted index of abundance
    if(sa_be(s)==0) //beginning of year survey
    {
     ad_survey_est(s,x)=qa(s,x)*N(x);
    }
    else
    {
     ad_survey_est(s,x)(fy(s),lyear-1)=qa(s,x)*(elem_prod(N(x)(fy(s),lyear-1),exp(-
sa_time(s)*(M(x)+F(x)(fy(s),lyear-1))))+
                  elem_prod(R(x)(fy(s),lyear-1),exp(-
sa_time(s)*(M(x)+rf*F(x)(fy(s),lyear-1)))));
    }
  }
   re_survey_est(s)=qr(s)*R(1)/sex_r;
 }

FUNCTION calculate_objective_function
 //Calculate survey likelihood components
 for(s=1;s<=nsurveys;s++)
 {
  for(x=1;x<=2;x++)
  {
   //Adult survey
   if(survey_dist(s)==1)
   {

Lsa(s,x)=lognorm(ad_survey_obs(s,x)(fy(s),lyear),ad_survey_est(s,x)(fy(s),lyear),ad_sur
vey_var(s));
```

```
     }
     if(survey_dist(s)==0)
     {
Lsa(s,x)=normal(ad_survey_obs(s,x)(fy(s),lyear),ad_survey_est(s,x)(fy(s),lyear),ad_surv
ey_sds(s));
     }
   }
   //Recruit survey
   if(survey_dist(s)==1)
   {
Lsr(s)=lognorm(re_survey_obs(s)(fy(s),lyear),re_survey_est(s)(fy(s),lyear),re_survey_var
(s));
   }
   if(survey_dist(s)==0)
   {
Lsr(s)=normal(re_survey_obs(s)(fy(s),lyear),re_survey_est(s)(fy(s),lyear),re_survey_sds(
s));
   }
  }

  //calculate sex-specific catch likelihood components
  for(x=1;x<=2;x++)
  {
   Lc(x)=lognorm(C_obs(x)(fscyear,lyear-1),C(x)(fscyear,lyear-1),C_var);
  }

  //calculate total catch likelihood components
  if(fscyear>fyear)  //not all catch is sex-specific
  {
   Lc(3)=lognorm(TC_obs(fyear,fscyear-1),TC(fyear,fscyear-1),C_var);
  }
  else
  {
   Lc(3)=0.0;
  }

  //calculate likelihood component for recruitment deviations
  Lrdev=0.5*size(log_rec_devs)*log(rec_var)+0.5*norm2(log_rec_devs)/rec_var;

  //Calculate penalty for differences between male and female F for years
  //before sex-specific catch
  //Calculate mean F ratio
```

```
  F_pen_mu=sum(elem_div(F(2)(fscyear,2006),F(1)(fscyear,2006)))/double(2006-
fscyear+1);
  //calculate variance of F_ratio
  F_pen_var=norm2(elem_div(F(2)(fscyear,2006),F(1)(fscyear,2006))-
F_pen_mu)/double(2006-fscyear-1);
  //calculate penalty based on normal distribution of F ratio
  F_pen=0.5*norm2(elem_div(F(2)(fyear,fscyear-1),F(1)(fyear,fscyear-1))-
F_pen_mu)/(F_pen_var+.0001);  //small constant added so quotient is defined

  negLL=sum(Lsa)+sum(Lsr)+sum(Lc)+Lrdev+F_pen;

FUNCTION calculate_reference_points
  //Calculate equilibrium abundance and catch under each of the Fs
  //Modified for a two-sex model following Shepherd (1982)

  Frat=Frat_init;
  i=0;
  j=0;

  for(i=1;i<=Frat_num;i++)
  {
    //i++;  //counter to keep track of results
    FSPR=FSPR_init;
    for(j=1;j<=FSPR_num;j++)
    {
      //calculate SPR
      SPRf(i,j)=calc_SPR(FSPR,M(1),sex_r);
      SPRm(i,j)=calc_SPR(FSPR*Frat,M(2),1.-sex_r);

      //calculate YPR
      YPRf(i,j)=calc_YPR(FSPR,M(1),sex_r);   //female
      YPRm(i,j)=calc_YPR(FSPR*Frat,M(2),1.-sex_r);  //male

      //calculate equilibrium total N
      N_eq(i,j)=(log(SPRf(i,j))+log_alpha+0.5*rec_var)/beta;

      //calculate equilibrium female N
      Nf_eq(i,j)=N_eq(i,j)*SPRf(i,j)/(SPRf(i,j)+SPRm(i,j));
      Nfs_eq(i,j)=Nf_eq(i,j)*exp(sp_time*(M(1)+FSPR));

      //calculate equilibrium male N
      Nm_eq(i,j)=N_eq(i,j)-Nf_eq(i,j);
      Nms_eq(i,j)=Nm_eq(i,j)*exp(sp_time*(M(2)+FSPR*Frat));

      //calculate equilibrium recruitment
      R_eq(i,j)=Nf_eq(i,j)/SPRf(i,j);
```

```
    //calculate female equilibrium recruitment
    Rf_eq(i,j)=sex_r*R_eq(i,j);

    //calculate male equilibrium recruitment
    Rm_eq(i,j)=R_eq(i,j)-Rf_eq(i,j);

    //calculate equilibrium catch in numbers
    C_eq(i,j)=R_eq(i,j)*(YPRf(i,j)+YPRm(i,j));

    //calculate female equilibrium catch
    Cf_eq(i,j)=R_eq(i,j)*YPRf(i,j);

    //calculate male equilibrium catch
    Cm_eq(i,j)=R_eq(i,j)*YPRm(i,j);

    //calculate female exploitation rate
    uf_eq(i,j)=FSPR/(FSPR+M(1))*(1.-exp(-(FSPR+M(1))));
    uf0_eq(i,j)=Cf_eq(i,j)/(Nfs_eq(i,j)+Rf_eq(i,j));

    //calculate male exploitation rate
    um_eq(i,j)=FSPR*Frat/(FSPR*Frat+M(2))*(1.-exp(-(FSPR*Frat+M(2))));

    //calculate ratio of male to female exploitation rate
    urat_eq(i,j)=Frat;

    //increment the female F for the SPR
    FSPR+=FSPR_inc;
   }

   //increment for ratio of female to male F
   Frat+=Frat_inc;
  }

   //Find F that produces specific %SPR
   for(ispr=1;ispr<=nspr;ispr++)
   {
    FSPR_ref(ispr)=0.5;
    for(iter=1;iter<=niter;iter++)
    {
     SPR_temp=(exp(M(1))-1.)/(exp(M(1)+FSPR_ref(ispr))-1.)-SPR_targ(ispr);
     dSPR=-(exp(2.*M(1)+FSPR_ref(ispr))-
exp(M(1)+FSPR_ref(ispr)))/(exp(2.*(M(1)+FSPR_ref(ispr)))-
2.*exp(M(1)+FSPR_ref(ispr))+1.);
     FSPR_ref(ispr)-=SPR_temp/dSPR;
    }
```

```
  }


FUNCTION dvariable lognorm(dvector obs, dvar_vector est, double var)
 //Function to calculate a lognormal log likelihood
 dvariable L;
 //need to make sure not to include missing data (coded as -99)
 L=0.0;
 double missy=0.0;
 for(y=obs.indexmin();y<=obs.indexmax();y++)
 {
  if(obs(y)!=-99)
  {
   //calculate sum of squares
   L+=square(log(obs(y))-log(est(y)));
  }
  else
  {
   //ass one to the number of missing data points
   missy+=1.0;
  }
 }
 L=0.5*(size(obs)-missy)*log(var)+0.5*L/var;
 return(L);

FUNCTION dvariable normal(dvector obs, dvar_vector est, double cv)
 //Function to calculate a lognormal log likelihood
 dvariable L;
 //need to make sure not to include missing data (coded as -99)
 L=0.0;
 double missy=0.0;
 for(y=obs.indexmin();y<=obs.indexmax();y++)
 {
  if(obs(y)!=-99)
  {
   //calculate sum of squares
   L+=log(cv*est(y))+0.5*square((obs(y)-est(y))/(cv*est(y)));
  }
 }
 return(L);

FUNCTION dvariable calc_SD(dvector obs, dvar_vector est)
 //Function to calculate a standard deviation
 dvariable V;
 //need to make sure not to include missing data (coded as -99)
 V=0.0;
```

```
  double missy=0.0;
  for(y=obs.indexmin();y<=obs.indexmax();y++)
  {
    if(obs(y)!=-99)
    {
      //calculate sum of squares
      V+=square(log(obs(y))-log(est(y)));
    }
    else
    {
      //ass one to the number of missing data points
      missy+=1.0;
    }
  }
  V/=(size(obs)-missy);
  return(sqrt(V));

//Overload Baranov catch equation function
FUNCTION dvariable baranov(dvariable F, dvariable M, dvariable N)
  //Baranov catch equation
  return(F/(F+M)*(1.-exp(-(F+M)))*N);

FUNCTION dvariable baranov(prevariable F, dvariable M, dvariable N)
  //Baranov catch equation
  return(F/(F+M)*(1.-exp(-(F+M)))*N);

FUNCTION dvariable baranov(prevariable F, dvariable M, data_number N)
  //Baranov catch equation
  return(F/(F+M)*(1.-exp(-(F+M)))*N);

//Overload SPR and YPR functions so they can take a variable from the
DATA_SECTION
FUNCTION dvariable calc_SPR(dvariable F, dvariable M, dvariable srat)
  //SPR based on infinite series solution
  return(srat*(p_F_sp*exp(-sp_time*(M+rf*F))+exp(-
((1.+sp_time)*M+rf*F+sp_time*F))/(1.-exp(-(M+F)))));

FUNCTION dvariable calc_SPR(dvariable F, dvariable M, data_number srat)
  //SPR based on infinite series solution
  return(srat*(p_F_sp*exp(-sp_time*(M+rf*F))+exp(-
((1.+sp_time)*M+rf*F+sp_time*F))/(1.-exp(-(M+F)))));

FUNCTION dvariable calc_YPR(dvariable F, dvariable M, dvariable srat)
  //YPR based on infinite series solution
  dvariable NPR=srat*exp(-(M+rf*F))/(1.-exp(-(M+F)));
  return(baranov(rf*F,M,srat)+baranov(F,M,NPR));
```

```
FUNCTION dvariable calc_YPR(dvariable F, dvariable M, data_number srat)
  //YPR based on infinite series solution
  dvariable NPR=srat*exp(-(M+rf*F))/(1.-exp(-(M+F)));
  return(baranov(rf*F,M,srat)+baranov(F,M,NPR));

FUNCTION dvariable nspawn(dvariable F, dvariable M, dvariable N, dvariable R)
  return (N*exp(-sp_time*(M+F))+p_F_sp*R*exp(-sp_time*(M+rf*F)));

FUNCTION double size(dvector obs)
  return(double(obs.indexmax()-obs.indexmin()+1));

FUNCTION double size(param_init_bounded_dev_vector obs)  //overload size function
  return(double(obs.indexmax()-obs.indexmin()+1));

//*******************************************************************
********
//Functions to write report files
//*******************************************************************
********

FUNCTION general_report
  ofstream ofs_gen("gen_results.dat");
  {
    ofs_gen << "Name Value" << endl;
    ofs_gen << "negLL " << negLL <<endl;
    ofs_gen << "Lsa_1f " << Lsa(1,1) <<endl;
    ofs_gen << "Lsa_1m " << Lsa(1,2) <<endl;
    ofs_gen << "Lsa_2f " << Lsa(2,1) <<endl;
    ofs_gen << "Lsa_2m " << Lsa(2,2) <<endl;
    ofs_gen << "Lsa_3f " << Lsa(3,1) <<endl;
    ofs_gen << "Lsa_3m " << Lsa(3,2) <<endl;
    ofs_gen << "Lsr_1 " << Lsr(1) << endl;
    ofs_gen << "Lsr_2 " << Lsr(2) << endl;
    ofs_gen << "Lsr_3 " << Lsr(3) << endl;
    ofs_gen << "Lc_f " <<  Lc(1) << endl;
    ofs_gen << "Lc_m " <<  Lc(2) << endl;
    ofs_gen << "Lc_t " <<  Lc(3) << endl;
    ofs_gen << "Lrdev " << Lrdev << endl;
    ofs_gen << "F_pen " << F_pen << endl;
    ofs_gen << "sa_be_1 " << sa_be(1) << endl;
    ofs_gen << "sa_be_2 " << sa_be(2) << endl;
    ofs_gen << "sa_be_3 " << sa_be(3) << endl;
    ofs_gen << "sa_time_1 " << sa_time(1) << endl;
    ofs_gen << "sa_time_2 " << sa_time(2) << endl;
    ofs_gen << "sa_time_3 " << sa_time(3) << endl;
```

```
   ofs_gen << "ads_sds_1 " << ad_survey_sds(1) << endl;
   ofs_gen << "ads_sds_2 " << ad_survey_sds(2) << endl;
   ofs_gen << "ads_sds_3 " << ad_survey_sds(3) << endl;
   s=1;
   x=1;
   ofs_gen << "adsf_sds_1 " <<
calc_SD(ad_survey_obs(s,x)(fy(s),lyear),ad_survey_est(s,x)(fy(s),lyear)) << endl;
   x=2;
   ofs_gen << "adsm_sds_1 " <<
calc_SD(ad_survey_obs(s,x)(fy(s),lyear),ad_survey_est(s,x)(fy(s),lyear)) << endl;
   s=2;
   x=1;
   ofs_gen << "adsf_sds_2 " <<
calc_SD(ad_survey_obs(s,x)(fy(s),lyear),ad_survey_est(s,x)(fy(s),lyear)) << endl;
   x=2;
   ofs_gen << "adsm_sds_2 " <<
calc_SD(ad_survey_obs(s,x)(fy(s),lyear),ad_survey_est(s,x)(fy(s),lyear)) << endl;
   s=3;
   x=1;
   ofs_gen << "adsf_sds_3 " <<
calc_SD(ad_survey_obs(s,x)(fy(s),lyear),ad_survey_est(s,x)(fy(s),lyear)) << endl;
   x=2;
   ofs_gen << "adsm_sds_3 " <<
calc_SD(ad_survey_obs(s,x)(fy(s),lyear),ad_survey_est(s,x)(fy(s),lyear)) << endl;
   ofs_gen << "res_sds_1 " << re_survey_sds(1) << endl;
   ofs_gen << "res_sds_2 " << re_survey_sds(2) << endl;
   ofs_gen << "res_sds_3 " << re_survey_sds(3) << endl;
   s=1;
   ofs_gen << "adsf_sds_1 " <<
calc_SD(re_survey_obs(s)(fy(s),lyear),re_survey_est(s)(fy(s),lyear)) << endl;
   s=2;
   ofs_gen << "adsf_sds_2 " <<
calc_SD(re_survey_obs(s)(fy(s),lyear),re_survey_est(s)(fy(s),lyear)) << endl;
   s=3;
   ofs_gen << "adsf_sds_3 " <<
calc_SD(re_survey_obs(s)(fy(s),lyear),re_survey_est(s)(fy(s),lyear)) << endl;
   ofs_gen << "p_rec " << p_rec << endl;
   ofs_gen << "Mf " << M(1) << endl;
   ofs_gen << "Mm " << M(2) << endl;
   ofs_gen << "rec_sd " << rec_sd << endl;
   ofs_gen << "sp_time " << sp_time <<endl;
   ofs_gen << "rf " << rf <<endl;
   ofs_gen << "lyear " << lyear <<endl;
   //catchability
   ofs_gen << "qa_1f " << qa(1,1) << endl;
   ofs_gen << "qa_1m " << qa(1,2) << endl;
```

```
  ofs_gen << "qa_2f " << qa(2,1) << endl;
  ofs_gen << "qa_2m " << qa(2,2) << endl;
  ofs_gen << "qa_3f " << qa(3,1) << endl;
  ofs_gen << "qa_3m " << qa(3,2) << endl;
  ofs_gen << "qr_1 " << qr(1) << endl;
  ofs_gen << "qr_2 " << qr(2) << endl;
  ofs_gen << "qr_3 " << qr(3) << endl;
  //SR parameters
  ofs_gen << "alpha " << alpha << endl;
  ofs_gen << "beta " << beta << endl;
  //sex ratio
  ofs_gen << "sex_r " << sex_r << endl;
 }

FUNCTION obs_pred
 ofstream ofs_op("obs_pred_results.dat");
 {
  ofs_op << "year sex a_r s_c snum obs pred" << endl;
  for(y=fyear;y<=lyear-1;y++)
  {
   //total observed and predicted catch
   ofs_op << y << " t a c 0 " << TC_obs(y) << " " << TC(y) <<  endl;
  }

  //sex-specific catch
  for(y=fscyear;y<=lyear-1;y++)
  {
   for(x=1;x<=2;x++)
   {
    ofs_op << y << " " << x << " a c 0 " << C_obs(x,y) << " " << C(x,y) << endl;
   }
  }

  //sex-specific survey CPUE
  for(s=1;s<=nsurveys;s++)
  {
   for(y=fy(s);y<=lyear;y++)
   {
    for(x=1;x<=2;x++)
    {
     //adult surveys
     ofs_op << y << " " << x << " a s " << s << " " << ad_survey_obs(s,x,y) << " " <<
ad_survey_est(s,x,y) << endl;
    }
    //recruit surveys
```

```
     ofs_op << y << " 0 r s " << s << " " << re_survey_obs(s,y) << " " <<
re_survey_est(s,y) << endl;
   }
  }
  //recruitment deviations
  for(y=fyear;y<=lyear-1;y++)
  {
     ofs_op << y+1 << " r r r 0 " << alpha*SP(1,y)*exp(-beta*(SP(1,y)+SP(2,y)))  << "
" << R(1,y+1)/sex_r  <<  endl;
  }
 }

FUNCTION HPD_estimates
 ofstream ofs_hpd("HPD_results.dat");
 {
  ofs_hpd << "Year Adult_F Adult_M Rec u_F u_M Frat N_SP_F N_SP_T u_Ft" <<
endl;
  for(y=fyear;y<=lyear;y++)
  {
   if(y<lyear)
   {
   ofs_hpd << y << " " << N(1,y) << " " << N(2,y) << " " << R(1,y)/sex_r << " " <<
F(1,y)/(F(1,y)+M(1))*(1.-exp(-(F(1,y)+M(1)))) << " " << F(2,y)/(F(2,y)+M(2))*(1.-exp(-
(F(2,y)+M(2)))) << " " << F(2,y)/F(1,y) << " " << SP(1,y)<< " " <<SP(1,y)+SP(2,y) << "
" << C(1,y)/(R(1,y)+N(1,y)) << endl;
   }
   else
   {
    ofs_hpd << y << " " << N(1,y) << " " << N(2,y) << " " << R(1,y)/sex_r << " " <<
"NA" << " " << "NA" << " " << "NA" << " " << "NA"<< " " << "NA" << " NA" <<
endl;
   }
  }
 }

FUNCTION MSY_estimates
 ofstream ofs_msy("MSY_results.dat");
 {
  //Column headings
  ofs_msy << "n u_fem F_rat SY SYf SYm Nf Nm R SPRf u_fem0" << endl;

  Frat=Frat_init;
  for(i=1;i<=Frat_num;i++)
  {
   FSPR=FSPR_init;
   for(j=1;j<=FSPR_num;j++)
```

```
      {
        ofs_msy << j << " " << uf_eq(i,j) << " " << urat_eq(i,j) << " " << C_eq(i,j) << " "
<< Cf_eq(i,j) << " " << Cm_eq(i,j) << " " << Nfs_eq(i,j) << " " << Nms_eq(i,j) << " " <<
R_eq(i,j) << " " << SPRf(i,j)/SPRf(1,1) << " " << uf0_eq(i,j) << endl;
      }

      //increment for ratio of female to male F
      Frat+=Frat_inc;
    }
  }

REPORT_SECTION
  //Call reporting functions
  //cout << "Starting report section" << endl;
  general_report();
  obs_pred();
  //cout << "wrote model fit" << endl;
  //write out results to file
  calculate_reference_points();
  //cout << "reference point calculations" << endl;
  MSY_estimates();
  //cout << "output reference points" << endl;
  HPD_estimates();
  //cout << "output HPD estimates" << endl;

  report << "Beginning of report section" << endl;
  report << "Likelihood components" << endl;
  report << "Lsa" << endl;
  report << Lsa << endl;
  report << "Lsr" << endl << Lsr <<endl;
  report << "Lc" << endl << Lc << endl;
  report << "Lrdev" << endl << Lrdev << endl;
  report << "F_pen" << endl << F_pen << endl;
  report << endl;
  report << "Variables that define scenarios" << endl;
  report << "VIMS_s_time MDT_s_time WDS_time" << endl;
  report <<  sa_time << endl;
  report << "CVs for indices of abundance" << endl;
  report << "VIMS_a MDT_a WDS_a VIMS_r MDT_r WDS_r" << endl;
  report << ad_survey_sds << " " << re_survey_sds << endl;
  report << "Mf Mm R_sd SP_m prf lyear" << endl;
  report << M << " " << rec_sd << " " << sp_time << " " << rf << " " << lyear  << endl;
  report << "Adult catchability" << endl;
  report << qa << endl;
  report << "recruit catchability" << endl;
  report << qr << endl;
```

```
RUNTIME_SECTION
  maximum_function_evaluations 5000, 25000, 20000, 20000, 20000, 20000
//Leave space below this line
```

Appendix IV. Sample input file for sex-specific catch, multiple survey analysis model

```
#Data file
#simulated data file for model testing
#uses 3 surveys and catch time series to mimic actual inputs
#first year last year for the model
1968 2010

#first year for total catch time series
1968

#last year for each catch time series
2009

#Total Commercial Catch (in 10 millions of crabs)
35.32649993
35.99548462
38.9573118
40.94467322
40.60101668
34.6970454
37.24924462
35.09267686
31.04507618
35.48006154
33.2690882
37.08803657
36.28139262
40.23281932
37.31398442
38.74893563
38.57836057
39.38614898
35.35517168
32.50414361
33.71333044
36.38055438
40.39210756
39.38681015
27.4801405
35.09034322
25.92563982
24.4290027
24.25932991
```

```
27.52581305
20.72059382
21.79344792
17.50880675
17.0220234
17.13021589
15.50371594
18.4702237
17.9032453
15.89912147
13.31260409
14.31395714
15.98375029
#first year for sex-specific catch time series
1994

#last year for sex-specific catch time series
2009

#Sex-specific Catch (female) (10 millions)
16.52259496
15.47166477
15.93201778
17.50448858
13.43921231
14.07901012
12.26559245
10.9263303
11.39459958
9.924485716
11.15646747
11.12213582
10.06711685
8.317427213
7.573100214
8.509033803
#Sex-specific Catch (male) (10 millions)
9.403044864
8.957337925
8.327312134
10.02132447
7.281381518
7.714437797
5.243214304
6.095693094
5.735616315
```

```
5.579230227
7.313756229
6.781109479
5.832004621
4.995176877
6.740856928
7.474716489
#log-scale SDs of each catch time series
.1

#number of surveys
3

#first year in surveys
1968 1977 1990

#last year in survey
2010 2010 2010

#Adult surveys (first row female, second male)
#Spring VIMS Trawl survey adult females
1.13
0.56
3.23
4.67
2.31
0.56
0.72
0.47
1.25
1.03
0.56
3.01
2.31
5.95
6.23
5.92
2.07
5.78
2.7
2.64
3.78
4.32
10.97
5.27
2.29
```

```
1.52
1.32
1.26
2.19
1.3
2.03
1.5
1.36
2.47
2.17
0.87
1.2
0.54
0.96
1.17
2.81
1.08
1.23
#Spring VIMS Trawl survey adult males
1.99
1.09
4.62
6.24
3.39
0.98
1.05
1.08
0.36
1.46
1.23
2.46
1.37
6.98
5.47
5.81
1.83
4.31
3.11
2.03
3.01
3.75
9.93
4.35
1.68
1.58
1.17
```

1.77
1.81
1.68
2.32
1.12
1.1
1.65
1.93
0.74
1.41
0.49
0.97
1.25
2.83
0.69
1.56
#MD DNR Trawl survey adult female
11.21185886
1.217667936
0.569077232
0.302754137
4.590413484
2.462508308
5.021874254
4.513029416
8.872372179
9.953465897
6.56860043
5.262238715
8.730553399
4.735010649
9.058373572
3.717542358
8.364266145
7.232744121
3.018044156
14.04553484
6.346350104
2.743458677
7.559346737
3.203314656
3.868050528
3.989930447
1.80299741
2.216738223
5.198504287

```
4.434616001
1.839390325
4.389631385
3.488863409
-99
#MD DNR Trawl survey adult males
18.14389386
2.470389765
1.398510918
1.441037763
10.56310072
6.051862132
11.11846433
12.6038085
16.96619445
16.14276231
13.28813264
9.099119288
20.60134902
10.35552016
18.36396003
8.085180594
15.36163271
13.90215378
5.744600768
17.94545567
15.11869667
6.629876618
9.825551356
6.799590957
7.116969865
7.213467236
5.068661591
5.812775271
8.441390134
7.312799093
4.093030749
7.3754235
5.479330607
-99
#Winter dredge survey adult females
14.576808
24.175928
18.070096
18.663856
11.964264
```

```
8.530352
13.616896
10.123608
11.133
5.878224
12.053328
6.13552
5.808952
10.925184
9.717872
11.5730577
8.896504
9.716156232
9.173592
17.575296
27.738488
#Winter dredge survey adult males
19.881064
24.413432
9.084528
18.000824
10.410592
10.98456
10.806432
7.283456
8.203784
3.186512
4.364136
4.532368
6.600632
10.756952
4.710496
4.790771461
3.552664
5.474360917
3.829752
6.125624
8.005864
#recruitment surveys (first row female, second male)
#Spring VIMS Trawl survey recruits
0.67
22.01
8.04
84.52
8.42
7.03
```

```
3.49
7.96
1.61
3.9
3.07
6.42
2.26
37.77
12.15
45.6
49.35
24.66
11.72
15.09
11.78
14.1
40.24
4.26
3.04
8.14
8.88
4.94
10.35
5.04
4.72
2.6
2
4.46
2.61
2.54
2.8
1.43
1.43
1.69
6.69
1.54
4.58
#MD DNR Trawl survey recruits
-99
0.604258123
0.205177703
0.292404479
0.7044564
0.777209771
0.359273906
1.938398197
```

6.266824438
2.56504475
4.133753965
1.92470902
2.859065106
3.793421191
14.72900208
1.31718273
10.61766184
4.918298035
1.160673623
1.882773123
2.699867916
0.925440176
2.022395537
4.746893857
1.77990413
2.615024881
2.534162624
1.926020926
6.771638877
6.336419423
4.669765912
0.235491182
5.250469017
3.484760731
#Winter dredge survey recruits
46.847664
36.051128
10.578824
50.736792
30.618224
30.390616
51.281072
51.617536
16.694552
22.523296
13.75544
15.695056
19.603976
17.694048
14.329408
24.41617923
19.514912
11.19368564
16.585696

```
16.704448
35.833416
#adult survey nubers beginning or end of year survey (0 beginning 1 end)
0 1 0
#adult survey time (0=beginning of the year, 1=end of the year)
0. 0.67 0.  #Timing of MD trawl based on proportion of effort in MD 2007-2010

#recruitment survey time (0=beginning of the year, 1=end of the year)
0.0 0.0 0.

#adult survey log-scale SD for lognormal dist or CV for normal dist
0.4 0.7 0.1

#recruitment survey log-scale SD for lognormal dist or CV for normal dist
0.8 1.1 0.1

#Distribution for survey likelihood (0: normal, 1: lognormal)
1 1 0

#M
#0.9 Base
0.9 0.9

#M_phase for male M (negative indicates not estimated)
-6

#sex ratio of recruitment (proportion female)
0.52
#phase of estimation for sex ratio
-5

#starting values for alpha and beta
10  .002

#sd for recruitment deviations
0.6
#phase for recruitment sd (negative not estimated)
4
#proportion of the year before spawning occurs
0.37    #Proportion of pot effort in MD before July 1 during 2007-2010

#Proportion of age-1 females that spawn at age-1
0.

#initial value for partial recruitment of recruits to the fishery
#0.6 primary value used
```

```
.6
#Phase for estimation of partial recruitment parameter (negative phase is not estimated)
-4

#Proportion of recreational harvest
.08

#Variables to control ratio of male to female F for reference point calculations
#Frat_init Frat_max Frat_inc
0.6 2.4 0.2

#variables to control F for females used in reference point calculations
#FSPR_init FSPR_max FSPR_inc
0 2.0 0.01

#SPR targets for calculating F reference points
#number of SPR targets
4
#targets
0.1 0.2 0.3 0.4
#max number of iterations for calculating SPR-based reference points
7

#EOF number
12345
```

Appendix V. Parameter and model estimates and asymptotic standard errors for sex-specific catch, multiple survey analysis model under the base configuration

```
 index   name         value               std dev
   1   log_init_N   2.5144e+000 2.7726e-001
   2   log_init_R   3.3316e+000 2.0753e-001
   3   log_mean_F   -1.5547e-001 4.2119e-002
   4   log_mean_F   -2.0443e-001 5.8167e-002
   5   log_F_dev_1  4.6926e-001 1.9903e-001
   6   log_F_dev_1  -2.2045e-001 2.6431e-001
   7   log_F_dev_1  -8.7734e-002 3.2741e-001
   8   log_F_dev_1  1.7620e-001 2.8511e-001
   9   log_F_dev_1  6.7805e-001 2.0044e-001
  10   log_F_dev_1  5.4606e-001 2.0151e-001
  11   log_F_dev_1  7.4496e-001 1.8767e-001
  12   log_F_dev_1  5.4373e-001 1.7366e-001
  13   log_F_dev_1  3.9657e-001 2.0508e-001
  14   log_F_dev_1  5.5696e-001 2.0615e-001
  15   log_F_dev_1  1.1859e-001 2.0867e-001
  16   log_F_dev_1  2.6402e-001 1.8972e-001
  17   log_F_dev_1  -1.9764e-002 2.3250e-001
  18   log_F_dev_1  -2.8875e-001 2.5797e-001
  19   log_F_dev_1  -3.2445e-001 2.3437e-001
  20   log_F_dev_1  3.6753e-003 2.2821e-001
  21   log_F_dev_1  -2.8071e-001 2.4746e-001
  22   log_F_dev_1  -1.8314e-001 2.4818e-001
  23   log_F_dev_1  -1.7529e-001 2.3423e-001
  24   log_F_dev_1  -3.3751e-001 2.4412e-001
  25   log_F_dev_1  -3.4261e-001 2.3540e-001
  26   log_F_dev_1  3.6866e-002 1.6801e-001
  27   log_F_dev_1  -3.0376e-001 1.5510e-001
  28   log_F_dev_1  -2.1828e-001 1.3187e-001
  29   log_F_dev_1  -2.4706e-001 1.3199e-001
  30   log_F_dev_1  2.6959e-001 1.2836e-001
  31   log_F_dev_1  2.3735e-001 1.0629e-001
  32   log_F_dev_1  -2.4646e-002 9.3271e-002
  33   log_F_dev_1  2.1285e-001 1.1793e-001
  34   log_F_dev_1  1.1833e-001 1.1236e-001
  35   log_F_dev_1  2.5014e-001 9.7383e-002
  36   log_F_dev_1  -6.4369e-002 9.2257e-002
  37   log_F_dev_1  1.9460e-001 9.0466e-002
  38   log_F_dev_1  2.2388e-001 9.5887e-002
  39   log_F_dev_1  -1.1806e-001 9.5465e-002
  40   log_F_dev_1  -2.3717e-001 9.8691e-002
  41   log_F_dev_1  -2.7875e-001 9.1895e-002
```

```
42  log_F_dev_1  -6.6279e-002 1.0531e-001
43  log_F_dev_1  -2.1523e-001 1.0244e-001
44  log_F_dev_1  -3.2611e-001 9.5963e-002
45  log_F_dev_1  -7.3519e-001 9.8588e-002
46  log_F_dev_1  -9.4637e-001 9.9875e-002
47  log_F_dev_2  6.5637e-001 2.1523e-001
48  log_F_dev_2  -2.3200e-001 2.9724e-001
49  log_F_dev_2  -4.1755e-001 3.8531e-001
50  log_F_dev_2  -1.8326e-001 3.7748e-001
51  log_F_dev_2  6.0990e-001 2.5549e-001
52  log_F_dev_2  5.9470e-001 2.4960e-001
53  log_F_dev_2  7.3163e-001 2.3076e-001
54  log_F_dev_2  1.0171e+000 1.9635e-001
55  log_F_dev_2  4.4431e-001 2.5320e-001
56  log_F_dev_2  4.3514e-001 2.6681e-001
57  log_F_dev_2  2.8330e-001 2.3185e-001
58  log_F_dev_2  5.8345e-001 2.0889e-001
59  log_F_dev_2  -1.6631e-003 2.6272e-001
60  log_F_dev_2  -2.7649e-001 2.7248e-001
61  log_F_dev_2  -2.5492e-001 2.5211e-001
62  log_F_dev_2  1.3145e-001 2.5005e-001
63  log_F_dev_2  -2.3691e-001 2.6891e-001
64  log_F_dev_2  -1.6349e-001 2.6756e-001
65  log_F_dev_2  -5.4072e-002 2.5356e-001
66  log_F_dev_2  -2.6149e-001 2.6617e-001
67  log_F_dev_2  -2.6566e-001 2.6298e-001
68  log_F_dev_2  -5.0255e-001 2.4556e-001
69  log_F_dev_2  -2.7262e-001 1.5547e-001
70  log_F_dev_2  3.6585e-001 1.3677e-001
71  log_F_dev_2  -4.8965e-001 1.8197e-001
72  log_F_dev_2  4.2956e-001 1.2483e-001
73  log_F_dev_2  -2.0860e-001 1.2147e-001
74  log_F_dev_2  -2.4425e-001 1.2987e-001
75  log_F_dev_2  -4.7007e-001 1.4567e-001
76  log_F_dev_2  -2.3559e-001 1.7420e-001
77  log_F_dev_2  4.2064e-003 2.3571e-001
78  log_F_dev_2  5.2799e-002 2.0965e-001
79  log_F_dev_2  -2.7802e-001 1.4822e-001
80  log_F_dev_2  -2.0440e-001 1.2264e-001
81  log_F_dev_2  -5.0743e-001 1.2336e-001
82  log_F_dev_2  -2.9048e-001 1.5957e-001
83  log_F_dev_2  4.4532e-001 1.1946e-001
84  log_F_dev_2  3.8267e-001 1.9822e-001
85  log_F_dev_2  -9.3164e-002 1.4878e-001
86  log_F_dev_2  -2.3199e-001 1.5196e-001
87  log_F_dev_2  -2.2250e-001 1.5191e-001
```

```
 88   log_F_dev_2  -5.6897e-001 1.4248e-001
 89   log_alpha    3.2837e+000 1.7946e-001
 90   log_beta     -2.9641e+000 2.4775e-001
 91   log_rec_devs 5.9669e-001 2.0485e-001
 92   log_rec_devs 5.8437e-001 2.5979e-001
 93   log_rec_devs 1.3846e-001 2.1448e-001
 94   log_rec_devs -3.2544e-001 2.1756e-001
 95   log_rec_devs -4.5448e-002 2.1445e-001
 96   log_rec_devs 3.0099e-001 2.3952e-001
 97   log_rec_devs 2.2236e-001 2.2758e-001
 98   log_rec_devs 4.2644e-001 2.3852e-001
 99   log_rec_devs 2.3715e-001 2.1855e-001
100   log_rec_devs 3.4718e-001 2.2163e-001
101   log_rec_devs 1.1704e-001 2.2427e-001
102   log_rec_devs 2.5850e-001 1.9138e-001
103   log_rec_devs 5.7265e-001 2.0902e-001
104   log_rec_devs 1.4043e-001 1.9589e-001
105   log_rec_devs -4.1710e-002 2.2762e-001
106   log_rec_devs 3.9312e-001 1.8949e-001
107   log_rec_devs 1.3181e-001 1.9888e-001
108   log_rec_devs 3.3732e-002 2.1311e-001
109   log_rec_devs 1.6857e-001 1.9657e-001
110   log_rec_devs 1.1072e-001 1.8963e-001
111   log_rec_devs 1.2247e-001 1.6885e-001
112   log_rec_devs 3.6841e-001 1.3822e-001
113   log_rec_devs 3.0739e-002 1.3823e-001
114   log_rec_devs -2.2017e-001 1.4163e-001
115   log_rec_devs -8.0295e-002 7.8772e-002
116   log_rec_devs -3.1040e-001 8.2298e-002
117   log_rec_devs -1.6737e-001 9.5980e-002
118   log_rec_devs 1.9445e-001 8.6830e-002
119   log_rec_devs 2.0753e-001 7.7344e-002
120   log_rec_devs -6.5791e-001 1.0383e-001
121   log_rec_devs -1.9573e-001 1.0341e-001
122   log_rec_devs -4.4488e-001 1.3422e-001
123   log_rec_devs -5.2175e-001 9.7470e-002
124   log_rec_devs 1.5273e-001 1.2012e-001
125   log_rec_devs -2.2576e-001 1.1929e-001
126   log_rec_devs -5.0761e-001 8.8015e-002
127   log_rec_devs -4.5656e-001 9.8606e-002
128   log_rec_devs -5.1613e-001 1.1567e-001
129   log_rec_devs -7.7116e-001 1.2847e-001
130   log_rec_devs -2.6308e-001 1.0194e-001
131   log_rec_devs 4.7316e-002 1.0575e-001
132   log_rec_devs -1.5244e-001 9.3217e-002
133   log_rec_sd   -1.0828e+000 1.5470e-001
```

134	N	1.2360e+001	3.4268e+000
135	N	6.2837e+000	1.7283e+000
136	N	2.2578e+001	5.6230e+000
137	N	1.9908e+001	6.2505e+000
138	N	1.4841e+001	4.0101e+000
139	N	5.7734e+000	1.6628e+000
140	N	6.9652e+000	1.8306e+000
141	N	5.2292e+000	1.4513e+000
142	N	6.2233e+000	1.4707e+000
143	N	7.9007e+000	1.9854e+000
144	N	7.2051e+000	1.9167e+000
145	N	1.1582e+001	2.5718e+000
146	N	9.5947e+000	2.1856e+000
147	N	1.6393e+001	3.7786e+000
148	N	2.5353e+001	5.8332e+000
149	N	2.2069e+001	4.4952e+000
150	N	1.4850e+001	3.6684e+000
151	N	2.4338e+001	5.4022e+000
152	N	2.0453e+001	4.6930e+000
153	N	1.7460e+001	4.0358e+000
154	N	2.0959e+001	4.6511e+000
155	N	2.1165e+001	4.3989e+000
156	N	1.7369e+001	2.0919e+000
157	N	2.2925e+001	1.7210e+000
158	N	1.6999e+001	1.2153e+000
159	N	1.5238e+001	1.0376e+000
160	N	1.2947e+001	1.2183e+000
161	N	9.3842e+000	8.2446e-001
162	N	1.1119e+001	6.5550e-001
163	N	1.1531e+001	1.0482e+000
164	N	1.2692e+001	1.0350e+000
165	N	5.8107e+000	4.7739e-001
166	N	9.3552e+000	5.6250e-001
167	N	5.5462e+000	3.8865e-001
168	N	5.6935e+000	4.3989e-001
169	N	9.0262e+000	5.4027e-001
170	N	8.1735e+000	5.0565e-001
171	N	8.3115e+000	4.3015e-001
172	N	8.1344e+000	5.3251e-001
173	N	8.5986e+000	5.4370e-001
174	N	7.4097e+000	4.6638e-001
175	N	1.2441e+001	6.9812e-001
176	N	1.8062e+001	9.5810e-001
177	N	1.2360e+001	3.4268e+000
178	N	5.4758e+000	1.7395e+000
179	N	2.1302e+001	5.4829e+000

180	N	2.1891e+001	5.9901e+000
181	N	1.8033e+001	4.8896e+000
182	N	6.4423e+000	2.2029e+000
183	N	6.5346e+000	2.0850e+000
184	N	5.1812e+000	1.6445e+000
185	N	3.5384e+000	1.2410e+000
186	N	7.0485e+000	2.0608e+000
187	N	7.7031e+000	2.2706e+000
188	N	1.0060e+001	2.5844e+000
189	N	6.9860e+000	1.9950e+000
190	N	1.5045e+001	3.6332e+000
191	N	2.3741e+001	5.4749e+000
192	N	2.0262e+001	4.3501e+000
193	N	1.3029e+001	3.5577e+000
194	N	2.2370e+001	5.1533e+000
195	N	1.9132e+001	4.4867e+000
196	N	1.5575e+001	3.9075e+000
197	N	1.9012e+001	4.4752e+000
198	N	1.9233e+001	4.3543e+000
199	N	2.0956e+001	2.0804e+000
200	N	2.2396e+001	1.6227e+000
201	N	1.1299e+001	1.3252e+000
202	N	1.4738e+001	1.0066e+000
203	N	1.1034e+001	1.0467e+000
204	N	1.1368e+001	8.0810e-001
205	N	1.2272e+001	9.1488e-001
206	N	1.5788e+001	1.2426e+000
207	N	1.5563e+001	1.7260e+000
208	N	7.2608e+000	1.4906e+000
209	N	8.6524e+000	1.4812e+000
210	N	6.8955e+000	7.8239e-001
211	N	7.2390e+000	5.5687e-001
212	N	1.0424e+001	6.3249e-001
213	N	8.3581e+000	7.9187e-001
214	N	5.1230e+000	5.1377e-001
215	N	5.4530e+000	9.6150e-001
216	N	7.2633e+000	7.5238e-001
217	N	6.5607e+000	7.0883e-001
218	N	9.7245e+000	9.5132e-001
219	N	1.4822e+001	1.1896e+000
220	Rt	5.5967e+001	1.1615e+001
221	Rt	1.5206e+002	2.6719e+001
222	Rt	1.1901e+002	2.8545e+001
223	Rt	1.0408e+002	1.9075e+001
224	Rt	6.0577e+001	1.0936e+001
225	Rt	7.3816e+001	9.9799e+000

226	Rt	6.6457e+001	8.6815e+000
227	Rt	6.5723e+001	8.1813e+000
228	Rt	7.3002e+001	1.0110e+001
229	Rt	7.5167e+001	1.0353e+001
230	Rt	8.8257e+001	1.2817e+001
231	Rt	7.4321e+001	1.1193e+001
232	Rt	1.1511e+002	1.7735e+001
233	Rt	1.5181e+002	2.6804e+001
234	Rt	1.1326e+002	2.0736e+001
235	Rt	8.7519e+001	1.7042e+001
236	Rt	1.4763e+002	2.4794e+001
237	Rt	1.1318e+002	2.0607e+001
238	Rt	9.7576e+001	1.8722e+001
239	Rt	1.1672e+002	2.1208e+001
240	Rt	1.1254e+002	2.0125e+001
241	Rt	1.1145e+002	1.1682e+001
242	Rt	1.3247e+002	7.7792e+000
243	Rt	8.8030e+001	5.6304e+000
244	Rt	8.2635e+001	5.7173e+000
245	Rt	1.0126e+002	5.1982e+000
246	Rt	6.8998e+001	3.6075e+000
247	Rt	7.3889e+001	3.6898e+000
248	Rt	8.8966e+001	4.2934e+000
249	Rt	9.1939e+001	4.5453e+000
250	Rt	3.7431e+001	2.5107e+000
251	Rt	6.3520e+001	3.7076e+000
252	Rt	3.7091e+001	2.4468e+000
253	Rt	4.4250e+001	2.5027e+000
254	Rt	5.9311e+001	2.9981e+000
255	Rt	4.4725e+001	2.7185e+000
256	Rt	4.5857e+001	2.5264e+000
257	Rt	5.0620e+001	2.5591e+000
258	Rt	4.9670e+001	2.7746e+000
259	Rt	3.7860e+001	2.7637e+000
260	Rt	6.3181e+001	3.7936e+000
261	Rt	8.3332e+001	5.2660e+000
262	Rt	8.8771e+001	7.6478e+000
263	C	1.7648e+001	2.3919e+000
264	C	2.0307e+001	3.8818e+000
265	C	2.4409e+001	5.4970e+000
266	C	2.6120e+001	5.6660e+000
267	C	2.3155e+001	3.8375e+000
268	C	1.9114e+001	2.8911e+000
269	C	2.0599e+001	2.8393e+000
270	C	1.7042e+001	2.2013e+000
271	C	1.7353e+001	2.5500e+000

272	C	2.0750e+001	3.1632e+000
273	C	1.7007e+001	2.7262e+000
274	C	1.8597e+001	2.5782e+000
275	C	2.0014e+001	3.4055e+000
276	C	2.2461e+001	4.2496e+000
277	C	2.0444e+001	3.7105e+000
278	C	2.1472e+001	3.4979e+000
279	C	2.1629e+001	3.9896e+000
280	C	2.2544e+001	4.1066e+000
281	C	1.9369e+001	3.3539e+000
282	C	1.8114e+001	3.3048e+000
283	C	1.8687e+001	3.3885e+000
284	C	2.5165e+001	3.5486e+000
285	C	2.0349e+001	2.8799e+000
286	C	1.8427e+001	2.2203e+000
287	C	1.5379e+001	1.8541e+000
288	C	2.5179e+001	2.6805e+000
289	C	1.7975e+001	1.4940e+000
290	C	1.4077e+001	1.1637e+000
291	C	2.0186e+001	1.8168e+000
292	C	1.9471e+001	1.7533e+000
293	C	1.2535e+001	1.0346e+000
294	C	1.0862e+001	9.7726e-001
295	C	1.0471e+001	8.1408e-001
296	C	1.0128e+001	8.1699e-001
297	C	9.8171e+000	8.2038e-001
298	C	8.3307e+000	7.1131e-001
299	C	7.9026e+000	6.6462e-001
300	C	1.0060e+001	9.2411e-001
301	C	8.7635e+000	7.7161e-001
302	C	6.8642e+000	5.9628e-001
303	C	6.5092e+000	5.8852e-001
304	C	7.6167e+000	7.0949e-001
305	C	1.9244e+001	2.5211e+000
306	C	1.7717e+001	3.7879e+000
307	C	1.6688e+001	5.1853e+000
308	C	1.8820e+001	5.3839e+000
309	C	2.2383e+001	3.7160e+000
310	C	1.8267e+001	2.8135e+000
311	C	1.8379e+001	2.6763e+000
312	C	2.0494e+001	2.3876e+000
313	C	1.4861e+001	2.4519e+000
314	C	1.6960e+001	2.9826e+000
315	C	1.7608e+001	2.7610e+000
316	C	2.0260e+001	2.7038e+000
317	C	1.7303e+001	3.3117e+000

318	C	2.0084e+001	4.1755e+000
319	C	1.9301e+001	3.6896e+000
320	C	2.0975e+001	3.5235e+000
321	C	1.9658e+001	3.9369e+000
322	C	2.0295e+001	4.0224e+000
323	C	1.9021e+001	3.3874e+000
324	C	1.6924e+001	3.2924e+000
325	C	1.7544e+001	3.3843e+000
326	C	1.4351e+001	3.2670e+000
327	C	2.0079e+001	2.7945e+000
328	C	2.5924e+001	2.6561e+000
329	C	9.9618e+000	1.7101e+000
330	C	2.5456e+001	2.4750e+000
331	C	1.1060e+001	1.0561e+000
332	C	1.1359e+001	1.1624e+000
333	C	1.0935e+001	1.2642e+000
334	C	1.4773e+001	2.0118e+000
335	C	1.0848e+001	1.6427e+000
336	C	1.1345e+001	1.5883e+000
337	C	6.4814e+000	6.8515e-001
338	C	7.0567e+000	6.8020e-001
339	C	6.8109e+000	6.8069e-001
340	C	7.7334e+000	9.1988e-001
341	C	1.2526e+001	1.1171e+000
342	C	1.1199e+001	1.5767e+000
343	C	7.8273e+000	8.7449e-001
344	C	6.3519e+000	6.9158e-001
345	C	8.8400e+000	9.8573e-001
346	C	8.9608e+000	9.5655e-001
347	u	4.3744e-001	6.0768e-002
348	u	2.3791e-001	5.4700e-002
349	u	2.8900e-001	7.7130e-002
350	u	3.5283e-001	7.4140e-002
351	u	4.9967e-001	6.2672e-002
352	u	4.3286e-001	6.0612e-002
353	u	4.9610e-001	5.8701e-002
354	u	4.3249e-001	5.2583e-002
355	u	3.9275e-001	5.9462e-002
356	u	4.4160e-001	6.2469e-002
357	u	3.2029e-001	5.3965e-002
358	u	3.7025e-001	5.3874e-002
359	u	2.8818e-001	5.5771e-002
360	u	2.3561e-001	5.2967e-002
361	u	2.4267e-001	4.9077e-002
362	u	3.1774e-001	5.9095e-002
363	u	2.3608e-001	5.1131e-002

364	u	2.7099e-001	5.6520e-002
365	u	2.7207e-001	5.4270e-002
366	u	2.3178e-001	4.9888e-002
367	u	2.3511e-001	4.8326e-002
368	u	3.1805e-001	4.0144e-002
369	u	2.3592e-001	2.9858e-002
370	u	2.6822e-001	2.7715e-002
371	u	2.5644e-001	2.6150e-002
372	u	3.7084e-001	3.3175e-002
373	u	3.6814e-001	2.6911e-002
374	u	2.9446e-001	1.9882e-002
375	u	3.5178e-001	2.9153e-002
376	u	3.2814e-001	2.6356e-002
377	u	3.8981e-001	2.4349e-002
378	u	2.7965e-001	1.8795e-002
379	u	3.6556e-001	2.1540e-002
380	u	3.5468e-001	2.3345e-002
381	u	2.6870e-001	1.9097e-002
382	u	2.5805e-001	1.9126e-002
383	u	2.4681e-001	1.7355e-002
384	u	2.9047e-001	2.3148e-002
385	u	2.5803e-001	2.0201e-002
386	u	2.4267e-001	1.7674e-002
387	u	1.6166e-001	1.3172e-002
388	u	1.3657e-001	1.1446e-002
389	u	4.3744e-001	6.0768e-002
390	u	2.5880e-001	6.0050e-002
391	u	3.1124e-001	8.5243e-002
392	u	3.6354e-001	8.3888e-002
393	u	4.9152e-001	9.3759e-002
394	u	4.5646e-001	7.0756e-002
395	u	5.3597e-001	7.1802e-002
396	u	4.6401e-001	6.1704e-002
397	u	4.4981e-001	7.0989e-002
398	u	4.8111e-001	7.3294e-002
399	u	3.3969e-001	6.0559e-002
400	u	4.0665e-001	6.2998e-002
401	u	3.2158e-001	6.3695e-002
402	u	2.5549e-001	5.8586e-002
403	u	2.6176e-001	5.5253e-002
404	u	3.4482e-001	6.7937e-002
405	u	2.5782e-001	5.7008e-002
406	u	2.9394e-001	6.3542e-002
407	u	2.9361e-001	6.1710e-002
408	u	2.5299e-001	5.5870e-002
409	u	2.5587e-001	5.4260e-002

410	u	3.4600e-001	4.9113e-002
411	u	2.4070e-001	3.3131e-002
412	u	2.8503e-001	3.2205e-002
413	u	3.0175e-001	3.3559e-002
414	u	3.9749e-001	3.7284e-002
415	u	4.0711e-001	3.2700e-002
416	u	3.0057e-001	2.1467e-002
417	u	3.6718e-001	3.1061e-002
418	u	3.2497e-001	2.6852e-002
419	u	3.7385e-001	2.9476e-002
420	u	2.8773e-001	2.1743e-002
421	u	3.9577e-001	3.1177e-002
422	u	3.5998e-001	2.5831e-002
423	u	2.7492e-001	2.0095e-002
424	u	2.6121e-001	1.9953e-002
425	u	2.6022e-001	1.9502e-002
426	u	3.4194e-001	2.9251e-002
427	u	2.9915e-001	2.5684e-002
428	u	2.6986e-001	2.1119e-002
429	u	1.7646e-001	1.4656e-002
430	u	1.5318e-001	1.3042e-002
431	Fratsd	1.1481e+000	3.2741e-001
432	Fratsd	9.4128e-001	3.9739e-001
433	Fratsd	6.8469e-001	4.0895e-001
434	Fratsd	6.6470e-001	3.7837e-001
435	Fratsd	8.8948e-001	3.0347e-001
436	Fratsd	9.9967e-001	3.3335e-001
437	Fratsd	9.3960e-001	2.9708e-001
438	Fratsd	1.5287e+000	3.4974e-001
439	Fratsd	9.9877e-001	3.4329e-001
440	Fratsd	8.4300e-001	3.1571e-001
441	Fratsd	1.1227e+000	3.6013e-001
442	Fratsd	1.3106e+000	3.5050e-001
443	Fratsd	9.6960e-001	3.6966e-001
444	Fratsd	9.6396e-001	3.9469e-001
445	Fratsd	1.0208e+000	3.8401e-001
446	Fratsd	1.0820e+000	3.6772e-001
447	Fratsd	9.9485e-001	3.9194e-001
448	Fratsd	9.7111e-001	3.8497e-001
449	Fratsd	1.0749e+000	3.7992e-001
450	Fratsd	1.0274e+000	3.9226e-001
451	Fratsd	1.0284e+000	3.9050e-001
452	Fratsd	5.5522e-001	1.9521e-001
453	Fratsd	9.8233e-001	2.3680e-001
454	Fratsd	1.7077e+000	3.0210e-001
455	Fratsd	7.4710e-001	1.8219e-001

456	Fratsd	1.1174e+000	1.8418e-001
457	Fratsd	6.0962e-001	9.3390e-002
458	Fratsd	7.6447e-001	1.1982e-001
459	Fratsd	4.8100e-001	8.9243e-002
460	Fratsd	6.6839e-001	1.4638e-001
461	Fratsd	7.4460e-001	2.0794e-001
462	Fratsd	1.0706e+000	2.7187e-001
463	Fratsd	5.9358e-001	1.0545e-001
464	Fratsd	6.2049e-001	9.2075e-002
465	Fratsd	6.4511e-001	9.4789e-002
466	Fratsd	9.0278e-001	1.6732e-001
467	Fratsd	1.9642e+000	2.8382e-001
468	Fratsd	1.4918e+000	3.6778e-001
469	Fratsd	1.0758e+000	1.9848e-001
470	Fratsd	1.0462e+000	1.8628e-001
471	Fratsd	1.5900e+000	2.7699e-001
472	Fratsd	1.3888e+000	2.2938e-001
473	qa	1.5981e-001	7.5953e-003
474	qa	1.7197e-001	1.0045e-002
475	qa	2.0347e-001	6.7826e-003
476	qa	4.4049e-001	1.8732e-002
477	qa	1.0000e+000	0.0000e+000
478	qa	1.0000e+000	0.0000e+000
479	qr	7.9185e-002	1.5975e-003
480	qr	2.6437e-002	5.1813e-004
481	qr	3.6246e-001	5.3830e-003