G D A R

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Gulf of Mexico Blue Crab

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Gulf States Marine Fisheries Commission

Blue Crab Assessment Workshop (GDAR01)

GDAR01-AW Terms of Reference

1. Evaluate precision and accuracy of fishery-dependent and fishery-independent data used in the assessment:
    a. Discuss data strengths and weaknesses (e.g. temporal and spatial scale, gear selectivities, sampling intensity).
    b. Report metrics of precision for data inputs and use them to inform the model as appropriate.
    c. Describe and justify index standardization methods.
    d. Justify weighting or elimination of available data sources.
2. Evaluate models used to estimate population parameters (e.g., F, biomass, abundance) and biological reference points.
    a. Did the model have difficulty finding a stable solution?
    b. Were sensitivity analyses for starting parameter values, priors, etc. and other model diagnostics performed?
    c. Have the model strengths and limitations been clearly and thoroughly explained?
    d. Have the models been used in other peer reviewed assessments? If not, has new model code been verified with simulated data?
    e. Compare and discuss differences among alternative models.
3. State and evaluate assumptions made for all models and explain the likely effects of assumption violations on model outputs, including:
    a. Calculation of M.
    b. Choice of selectivity patterns.
    c. Constant or variable ecosystem (e.g., abiotic) conditions.
    d. Choice of stock-recruitment function.
    e. Choice of reference points (e.g. equilibrium assumptions).
4. Evaluate uncertainty of model estimates and biological or empirical reference points.
    a. Choice of weighting likelihood components.
5. Perform retrospective analyses, assess magnitude and direction of retrospective patterns detected, and discuss implications of any observed retrospective pattern for uncertainty in population parameters (e.g., F, SSB), reference points, and/or management measures.
6. Recommend stock status as related to reference points.
7. Develop detailed short and long-term prioritized lists of recommendations for future research, data collection, and assessment methodology. Highlight improvements to be made by next benchmark review.

Gulf States Marine Fisheries Commission

Blue Crab Review Workshop (GDAR01)

GDAR01-RW Terms of Reference

1. Evaluate the data used in the assessment, addressing the following:
    a. Are data decisions made by the DW and AW sound and robust?
    b. Are data uncertainties acknowledged, reported, and within normal or expected levels?
    c. Are data applied properly within the assessment model?
    d. Are input data series reliable and sufficient to support the assessment approach and findings?
2. Evaluate the methods used to assess the stock, taking into account the available data.
    a. Are methods scientifically sound and robust?
    b. Are assessment models configured properly and used consistent with standard practices?
    c. Are the methods appropriate for the available data?
3. Evaluate the assessment findings with respect to the following:
    a. Are abundance, exploitation, and biomass estimates reliable, consistent with input data and population biological characteristics, and useful to support status inferences?
    b. Is the stock overfished? What information helps you reach this conclusion?
    c. Is the stock undergoing overfishing? What information helps you reach this conclusion?
    d. Is there an informative stock recruitment relationship? Is the stock recruitment curve reliable and useful for evaluation of productivity and future stock conditions?
    e. Are the quantitative estimates of the status determination criteria for this stock reliable? If not, are there other indicators that may be used to inform managers about stock trends and conditions?
4. Consider how uncertainties in the assessment, and their potential consequences, are addressed.
    - Comment on the degree to which methods used to evaluate uncertainty reflect and capture the significant sources of uncertainty in the population, data sources, and assessment methods
    - Ensure that the implications of uncertainty in technical conclusions are clearly stated.
5. Consider the research recommendations provided by the Data and Assessment workshops and make any additional recommendations or prioritizations warranted.
    - Clearly denote research and monitoring that could improve the reliability of, and information provided by, future assessments.
    - Provide recommendations on possible ways to improve the GDAR process.

6. Provide guidance on key improvements in data or modeling approaches which should be considered when scheduling the next assessment.
7. Prepare a Peer Review Summary summarizing the Panel's evaluation of the stock assessment and addressing each Term of Reference. Develop a list of tasks to be completed following the workshop. Complete and submit the Peer Review Summary Report in accordance with the project guidelines.

Preface

This regional assessment was completed through the Gulf States Marine Fisheries Commission's (GSMFC) Gulf Data, Assessment, and Review (GDAR) Program as GDAR01. It is the culmination of a year-long effort to gather and analyze the available data from the commercial fishery, the recreational fishery, and the individual state agencies' independent sampling programs for blue crabs. Each of the five state marine resource agencies provided blue crab experts and analysts to develop indices of abundance for use in stage-based and surplus production models. Much of this work was influenced by assessments already completed in Louisiana, Florida, Texas, and the Chesapeake Bay.

The GDAR01 draft report was generated and provided to three reviewers from the Atlantic region with expertise in both blue crabs and stock assessment. A Review Workshop was held in June 2013 for the reviewers to address any concerns they had and ask the analysts and agency representatives any additional questions that arose during their reviews. Finally, a report was generated with the reviewers' comments and overall opinion of the data sources, models, and results. Following the receipt of the Reviewers Report (Appendix C), the Assessment Team became concerned with potential misunderstanding of the sensitivity runs in the two models which were only used to explore the uncertainty in the data indices.

Therefore, this GDAR01 Final Report includes some highlighted language which the assessment team thought could be misinterpreted and footnotes were added after completion of the Review Report to explain these sensitivity runs specifically. The footnotes do not change any of the interpretation of the final results; they are intended to prevent a reader from taking that language out of context.

The Assessment Team wishes to thank the reviewers for their expertise and time that supported the completion of the first regional stock assessment for blue crabs in the Gulf of Mexico.

Executive Summary

The blue crab, *Callinectes sapidus*, has the broadest latitudinal distribution of all the *Callinectes* species, ranging from Nova Scotia and Maine to northern Argentina and is found throughout the US Gulf of Mexico (GOM). Based on tagging and genetic investigations, two potential management populations may exist in the Gulf of Mexico: a Florida or "Eastern GOM stock" occurring along the Florida coast to Apalachee (centered in Tampa Bay), and a "Western GOM stock" occurring from central Texas to Apalachicola Bay and centered in Louisiana. Using this population structure, we provide quantitative analyses on the status of the Western and Eastern stocks through 2011.

Total reported commercial blue crab landings in the Gulf have increased from less than one million pounds in the late 1800s when landing statistics were first collected, to approximately 18 million lbs prior to World War II. Landings increased markedly in the late 1950s with introduction of the wire trap that replaced traditional trotlines by the mid-1960s. The increased availability of raw product associated with adoption of the wire trap stimulated processing capacity and market development, and landings continued to rise through the 1980s. Record landings of 78 and 79 million pounds occurred in 1987 and 1988, respectively. Although landings continue to fluctuate, a general downward trend in Gulf-wide landings began in 2000 and has continued through 2010. Natural and anthropogenic events as well as changes in management measures may have directly influenced landings. These include a number of catastrophic hurricanes and the sinking of BP's Deepwater Horizon oil platform off Louisiana in 2010 that closed most of the north-central GOM to harvest during the most productive portion of the fishing season.

Fishery-independent estimates of abundance for both juvenile and adult stocks have shown either decreasing or steady trends throughout the last two decades while commercial landings have declined. The Western stock has undergone a strong decline in juvenile abundances since the mid-1980s, and a decline in adult abundances from the mid-1980s until the mid-1990s, after which it has remained relatively stable. Eastern stock adult abundances have shown a similar trend (declining through the mid-1990s and stable since), while the juvenile abundance has been relatively stable since the late 1980s. In both stocks, the abundances have experienced substantial variability from year-to-year, and in the case of the Eastern stock, these abundances typically peak in years following high rainfall.

In this assessment, we employed two separate modeling approaches to address the GOM stocks. The primary model was a modified catch-survey analysis similar in structure to those used in previous blue crab stock assessments (Chesapeake, Louisiana, Florida, Delaware), while the supporting model was a surplus production model. The estimated MSY from the base model configuration was 164 million individuals for the Western GOM stock and 23 million individuals for the Eastern GOM stock, where fisheries on both stocks have landed less than the MSY for the majority of the time series. The Western GOM stock experienced overfishing in 1999 and 2002, while the Eastern GOM stock experienced overfishing in 1996 and 1998. The base model found that both stocks are currently neither overfished nor undergoing overfishing, although the Western stock is in a depressed state and approaching an overfished limit.

1.0 Introduction

1.1 Definition of the Fishery

The fishery of concern for this stock assessment includes the harvest activities for hard and soft blue crabs, (*Callinectes sapidus* Rathbun, 1896) in the United States coastal waters along the Gulf of Mexico (GOM).

1.2 Brief Overview and History of US Coastal Gulf of Mexico Blue Crab Fishery

Hard Crabs

Commercial landing statistics were first collected in 1880. In the 1800s, crab fishermen waded in shallow water at night and used hand-held dip nets with lanterns or torches to harvest crabs. Dip nets were long-handled and fashioned with a metal ring to which shallow webbing was attached to facilitate removal of the crabs with a quick shake (Perry et al. 1984). Crabs were scooped up and dropped into towed skiffs, tubs, half-barrels, or burlap sacks. Crab fishermen also used drop nets consisting of a net-covered metal frame, with bait fastened in the middle, attached to a buoy line. The uniqueness and perishability of the product probably hampered early development of the fishery (Perry et al. 1984). Steele and Bert (1998) noted that during the 1890s in the Florida panhandle fishermen caught crabs with trotlines and bartered the product with local consumers. One of the first commercial crab fisheries in the Gulf developed near New Orleans to supply the French Market and local restaurants (Perry et al. 1984). The first processing plant for Louisiana crab meat was constructed in 1924 at Morgan City, and by 1931 there were seven additional plants in the Morgan City-Berwick area.

Total reported landings in the Gulf increased from less than one million lbs in the late 1800s to approximately 18 million lbs prior to World War II (Table 1.1). Landings increased markedly in the late 1950s with introduction of the wire trap (Table 1.2 and Figure 1.1). The increased availability of raw product associated with adoption of the wire trap stimulated processing capacity and market development, and landings continued to rise through the 1980s. Record landings of 78 and 79 million lbs occurred in 1987 and 1988, respectively. The dramatic increase in landings during the 1980s can be attributed to increased fishing effort and increased processing capacity in some states. Landings declined slightly after 1988 and ranged from approximately 50 to 70 million lbs and except for 1989, 1990, 1994, and 1995 remained above the 15-year (1983-1997) average of 60.7 million lbs.

Although landings continue to fluctuate, a general downward trend in Gulf-wide landings began in 2000 and has continued through 2010. Natural and anthropogenic events as well as changes in management measures may have directly influenced landings. The hurricanes of 2004-2005 displaced fishermen and gear and prevented harvest in the northern Gulf in 2005 and 2006. Two additional storms impacted Louisiana and Texas in 2008. The sinking of the British Petroleum's Deepwater Horizon oil rig in April 2010 led to the closure of most of the north-central Gulf during the most productive time of the fishing season. Effort reduction management in Texas (1997) and Florida (2007) may have reduced landings in those states (Table 1.3).

Soft Crabs

The first record of soft crab production in the Gulf dates back to 1887 when 133,000 lbs valued at $7,000 were harvested in Louisiana and 15,000 lbs worth $1,000 were recorded from Mississippi. Recorded production in Texas, Florida, and Alabama began much later with landings rarely exceeding 10,000 lbs (Table 1.4). Although landings have varied, Louisiana has historically been the major producer and supplier of soft crabs in the GOM (Perry et al. 1982).

Production by Region and State

During the 1950s and 1960s the fishery gradually evolved from a trotline to trotline drop net to a trap dominated fishery. The percentage of hard crab landings from the Gulf ranged from12.0% in 1952 to 36.7% in 1987 for the whole US. Throughout the 1960s, the Gulf States generally contributed less than 20% of US total landings but gradually increased 33% by 1977. Gulf hard crab landings fluctuated from around 25% to 35% throughout the 1980s to a peak of 36.8% by 1987. Gulf production averaged 26.8% of the total US hard crab landings during the 1990s but since 2000, has averaged around 34%, despite the reduction in effort for several of those years. In 2006, immediately after hurricanes Katrina, Rita, and Wilma of 2005, the Gulf's contribution reached an all time high of 41.3% of the total US hard crab landings.

Florida's contribution to total Gulf landings decreased from 35.0% in 1981 to 13.3% in 1987. The percent contribution of Texas to Gulf landings increased through the early 1980s, dropped to 12.9% from 21.9% in 1984, and then rose again to 17.9% in 1986. On a percentage basis, Alabama landings have remained fairly consistent over time, usually ranging from 3% to 8%. Mississippi landings averaged 12.2% of the total during the 1950s but then gradually declined; by the 1990s Mississippi landings decreased to 0.6% of the total. The average percent contribution by state during the 1980s and 1990s were: Louisiana, 60.9%; Florida, 17.7%; Texas, 14.3%; Alabama, 4.9%; and, Mississippi, 1.9%. In the last decade, Louisiana has continued to dominate the blue crab landings for hard and soft crabs in the Gulf, increasing from 75.5% of the total Gulf landings in 2000 to 86.6% by 2009. Landings in Florida averaged around 10%, Alabama 4%, Mississippi 1%, and Texas 7% of the Gulf region total harvest over the same period (NOAA unpublished data).

1.3 Geographic Distribution and Management Unit

Geographic Distribution: Callinectes sapidus (Rathbun) is distributed throughout the GOM. The type locality is the eastern coast of the United States. Williams (1974) defined the range as: occasionally Nova Scotia, Maine, and northern Massachusetts to northern Argentina, including Bermuda and the Antilles; Oresund, Denmark; the Netherlands and adjacent North Sea; northwest and southwest France; Golfo di Genova; northern Adriatic; Aegean, western Black and eastern Mediterranean seas; and Lake Hamana-ko, central Japan. Williams (2007) noted that the species has been introduced to California (Cohen and Carlton 1995) and Hawaii (Carlton and Eldredge 2009).

Management Unit: The blue crab *C. sapidus* comprises 100% of the hard crab landings. In southwest Texas, *C. rathbunae* may occasionally enter the catch.

Two potential management populations may exist in the GOM; a Florida or “Eastern Gulf” population occurring along the Florida coast to Apalachee (centered in Tampa Bay), and a “Western Gulf” population occurring from central Texas to Apalachicola Bay and centered in Louisiana (Figure 1.2). This separation is based on a study by Darden (2004) who examined molecular variance and phylogenetic analyses in multiple locations around the GOM (see Section 3.1 for genetics details). Darden found that gene flow was restricted among western Gulf locations, particularly among Louisiana and Texas bays (sample locations), while the Florida “populations” from Goodland to Apalachicola showed no significant population structuring. Seasonal current circulation patterns, larval mixing and larval migration behaviors (Johnson and Perry 1999, Perry et al. 2003, Johnson et al. 2009) and migration patterns of adult females (Steele 1987 and 1991) along the West coast of the Florida Peninsula further support separation into eastern and western populations in the GOM. This population separation was also suggested for red snapper by Johnson et al. (2009 and 2013) who found that red snapper larval transport across the northern GOM from west to east was complicated by topographic impediments to the along-shelf flow that included the Apalachicola Peninsula. They noted that there “seems to be a natural population break near Florida’s Apalachee Bay”, just east of Apalachicola Bay in the panhandle region.

Other species exhibit faunal discontinuities in the GOM. Portnoy and Gold (2012) noted that at least 15 pairs of fishes and invertebrates described as sister species (species, subspecies, or genetically distinct populations) can be found in a marine suture zone whose eastern boundary is located in the Apalachee Bay area of Florida. Within the zone, multiple vicariance events have occurred over geological time scales that may have contributed to observed patterns of divergence for these species.

Bycatch considerations and the management unit: Blue crabs are captured in large numbers in gear used in the shrimp fishery. Bycatch of blue crabs in the Texas inshore shrimp fishery averaged 82 million blue crabs annually from 1990 to1994 (Hammerschmidt et al. 1998). Based upon an estimated 1989 bycatch of 227.8 million lbs in the Louisiana shrimp fishery and the percentage by weight (9%) of blue crab (Adkins 1993), the annual Louisiana blue crab bycatch would have been approximately 20.5 million lbs; considering that much smaller individuals are captured in trawls, skimmer nets, and wingnets than in crab traps, the number of blue crabs captured in the shrimp fishery exceeds that number harvested by commercial crab fishermen. Since the early 1990s, regulations imposed by the states related to bycatch in the shrimp trawl fishery have reduced the number of crabs retained by commercial shrimpers in the Gulf region. Since 1994, landings of blue crabs from the commercial trawl fishery have been less than 1% of the total hard crab landings in the region (NOAA unpublished data).

Research has indicated that capture in shrimp gear and subsequent culling may have significant effects on blue crab survival (Murphy and Kruse 1995). The average mortality rate of blue crabs captured in trawls was 36% overall; 6% during the winter months and 80% during the summer (McKenna and Camp 1992). Delayed mortalities of trawl bycatch may vary because of differences in temperature, exposure time, amount and level of physical injury, and total catch biomass (Smith and Howell 1987, Wassenberg and Hill 1989). The use of salt boxes to separate bycatch from the shrimp may also contribute to juvenile crab mortality. Although survival of crabs subjected to salt box separation is more affected by tow and culling time than by immersion in the brine solution (TPWD and ADCNR unpublished data), increases in delayed mortality may result from prolonged exposure and repeated dippings. Mortality of blue crabs also occurs in lost or abandoned traps that continue to fish ("ghost traps").

Animals become entrapped and perish, thus effectively re-baiting or auto-baiting the trap to continue attracting additional animals. Arcement and Guillory (1993) found that mortality of blue crabs was significantly less in traps with escape rings (5.3/trap) than in unvented (17.3/trap) traps because lower numbers of sublegal blue crabs were captured. Derelict trap programs in the Gulf continue to remove lost and abandoned traps from coastal waters, reducing this source of mortality.

1.4 Regulatory History

> "Management of the fishery in the GOM can be characterized as preventive (Jamieson 1986), with protection of spawning stock and nursery grounds, areal closures, and gear restrictions implemented with anticipation of obtaining optimum resource utilization over the long term. Adoption of these conservative management measures has not resulted in increased stock abundance or brought stability to the fishery as measured by traditional means."
>
> Guillory et al. 1998

The GOM blue crab fishery and its industry is governed by the five individual Gulf States.

Size Limits

Retention of sublegal (<127 mm CW) blue crabs in commercial traps has been recognized since the introduction of the gear in the Chesapeake in the 1930s and the Gulf in the 1950s (Davis 1942, Green 1952). As the traditional trap evolved, the design included 1.5" vinyl-coated hexagonal mesh. A more recent innovation includes 1.5" square mesh wire which, while lighter in weight, has increased the retention of undersize crabs (Guillory 1996, Guillory 1998a, Guillory and Prejean 1997, Guillory and Hein 1998).

The states realized early that an increased harvest and sale of sublegal crabs may reduce catches of larger, more-desirable crabs, and because smaller crabs are less likely to be processed, this portion of the resource is wasted at the processing level. Therefore, all five Gulf States have a minimum size of five (5) inches carapace width (CW), measured from tip of one lateral spine to tip of the opposite lateral spine. However, for most, the minimum size limit does not apply to the harvest of peeler crabs or crabs to be used as live bait.

In addition, escape rings in crab traps are currently required in Florida, Louisiana, and Texas in an effort to reduce the catch of undersized crabs, especially in areas with high densities of sublegals. However, Louisiana regulations allow rings to be blocked during Apr-Jun and Sep-Oct for peeler crab harvests.

Bag/Possession Limits

Commercial: In the commercial crab trap fisheries across the Gulf, there are no bag or possession limits. There is a 200lb/trip limit on blue crabs captured in Florida shrimp trawls as bycatch.

Recreational: There are possession limits for the recreational fisheries in Florida, Alabama, and Louisiana. In Florida waters, no person shall harvest in any one day or possess while in or on state waters more than ten gallons of whole blue crabs. In Alabama, licensed recreational shrimp boats taking crabs in open water are limited to no more than one five-gallon container of legal size crabs per boat. If crabs are taken by recreational shrimp boats for bait, they are restricted to the number of crabs held by a one-gallon container per boat per day but are exempt from the minimum size limit. Licensed Alabama commercial shrimpers are limited to one five-gallon container of legal size crab per boat. In Louisiana, except for certain refuges or wildlife management areas, a recreational limit is twelve dozen daily and in possession.

Protection of Female Crabs

Blue crab management in the GOM has been directed toward protection of egg-bearing females. This strategy assumes a density-dependent relationship between spawning stock and recruitment levels that would be expected to produce a more stable population. However, despite it being illegal to catch or retain any female sponge crab or any female crab bearing visible eggs at any time within the marine waters of Florida, Mississippi, Louisiana, and Texas, the fishery continues to exhibit wide annual fluctuations in harvest.

Fishing Area Closures

While each of the five Gulf States have individual areas in which commercial fishing activity is not allowed (National Seashores, Estuarine Reserves, etc.), Alabama and Mississippi have the most clearly defined lines of demarcation for restriction of commercial fishing. In Alabama, it is illegal to attempt to take or harvest crabs by the use of crab traps north of a line described as Interstate Highway 10 eastbound lane (except that portion of Interstate Highway 10 which lies north of State Highway 90 Battleship Parkway, in which case the line follows the Battleship Parkway). It is illegal to take crabs for commercial purpose in named rivers, creeks, bayous, or other named water bodies.

In Mississippi, it is illegal to commercially take crabs from the marine waters north of the CSX railroad bridge in the three coastal counties (Jackson, Harrison, and Hancock). This closure prevents commercial gear from being set in the upper Pascagoula, Biloxi, and St. Louis bays.

In each of the five Gulf States there are regulations in place that allow the respective marine agencies to schedule a temporary seasonal or areal closure for the purposes of removing lost or abandoned derelict crab traps from public waters. Each state has the ability to open and close as needed depending on complaints from the public or suggestions from agency staff identifying problem areas.

Retention of Blue Crabs as Bycatch

Bycatch of blue crabs in other commercial fisheries is generally allowed with very specific provisions. Blue crabs in Florida may be retained as incidental bycatch of shrimp trawls during lawful shrimp harvesting. However, there is a maximum of 200 lbs of blue crabs allowed per vessel per trip. Undersized blue crabs (< five inches CW) intentionally harvested with a dip or landing net or incidentally as bycatch by live bait shrimp trawls, may not exceed ten gallons per person or per vessel per day, whichever is less.

Commercial and recreational shrimpers in Alabama waters are limited to one five-gallon container of legal size crab per boat. There is zero retention of blue crabs harvested as bycatch in shrimp trawls or other gear in Mississippi waters unless the boat operating the gear has a valid commercial crab license.

Louisiana commercial shrimpers may retain any blue crabs caught incidentally during routine fishing but they must be of legal size. Texas shrimpers who possess a Commercial Shrimp Boat Captain's License, may retain any combination of aquatic products including blue crabs provided it doesn't exceed 50% of the total shrimp landings (by weight). The minimum five inch carapace width still applies however.

1.5 Assessment History

1.5.1 GOM Assessments

Blue crab stock assessments in the GOM have been hampered by the lack of fishery dependent catch-per-unit-effort (CPUE) data, and a poor understanding of blue crab population age structure. Steele and Perry (1990) noted that the lack of adequate CPUE data hampered derivation of maximum sustainable yield (MSY). Lack of these same data were described as major shortcomings in the assessment attempt of the 2001 Blue Crab Management Plan (Guillory et al. 2001) with the result that no quantitative management reference points were provided. In spite of these shortcomings, some of the Gulf States were able to independently publish quantitative stock assessments capable of providing biological reference points. Florida, Texas and Louisiana produced quantitative stock assessments using various statistical techniques to handle the uncertainty inherent to fishery dependent data. Without an adequate understanding of population age, later assessments have all been restricted to length-based or dynamic biomass structured models.

Florida

The first quantitative blue crab stock assessment in the GOM was performed by Murphy et al. of the Florida Fish and Wildlife Conservation Commission's Florida Marine Research Institute in 2001. A catch survey analysis (Collie and Sissenwine 1983) was employed to estimate abundance and fishing mortality. The optimal fishing mortality $F_{0.1}$ criterion was used as a benchmark of overfishing. This benchmark was derived using the M/k ratio relationship (Deriso 1987), where $F_{0.1}$ is approximately equal to natural mortality (M) over the range $1 < M/k < 4$. This assessment found that fishing mortality had increased rapidly during the early 1990s on

Florida's Gulf coast; however, the assessment of stock condition depended heavily on the chosen value of natural mortality. In choosing a natural mortality coefficient value of $1.0\ \mathrm{yr}^{-1}$, it was deduced that the fishery was not overfished.

A second more detailed stock assessment was performed by Murphy et al. (2007). Three models were used in this assessment, a catch survey analysis (Collie and Sissenwine 1983), a non-equilibrium biomass dynamic model using ASPIC (Prager 1994), and a stochastic stock reduction analysis (Walters et al. 2006). Using newly derived instantaneous natural mortalities for exploited blue crabs of $(0.77 - 1.34\ \mathrm{yr}^{-1})$ from a Tampa Bay Ecopath with Ecosim (EwE) model, the $F_{0.1}$ benchmark was revised to be in range of $(0.77 - 1.61\ \mathrm{yr}^{-1})$. Comparing the average 2003-2005 F's to this benchmark, the status of blue crabs on Florida's Gulf coast was considered to have not undergone overfishing (average F's from each model were 0.36 CSA, 0.65 ASPIC, 0.56 SRA).

Louisiana

A catch survey analysis (Collie and Sissenwine 1983) was used to assess blue crabs in Louisiana (West et al. 2011). The model used survey data to account for declines in abundance from one stage to the next (i.e. recruits to harvest size) using a constant natural mortality estimate of M = 1.0 and scaling the balance to commercial catch numbers. Model requirements include: 1) annual abundance indices for the recruit and fully-recruited life stages, 2) annual harvest estimates as individuals, 3) an estimate of instantaneous natural mortality, and 4) the relative selectivity of the recruit and fully-recruited life stages to the survey gear.

The Gompertz model (Winsor 1932) was used to describe blue crab growth because it provided better fits to reported blue crab CW-at-age data than what could be derived using a von Bertalanffy growth function. It was used to split monthly survey length frequency data into the constituent recruit and fully-recruited life stage indices needed for input into the analysis.

Although no decline in recruitment was observed over a broad range of fully recruited biomass indices, the view taken was that the implication of overfishing results in an unacceptable risk of reduced recruitment and therefore, an overfishing limit should be defined. Here a precautionary limit was suggested requiring that biomass not fall below the average biomass of the three lowest years. Fishing mortality rate limit (F_{Limit}) and spawning stock biomass limit (SSB_{Limit}) were estimated at $1.02\ \mathrm{yr}^{-1}$ and 15.53 million lbs, respectively. According to these limits, the Louisiana blue crab stock was considered overfished during 1995-1996 and experienced overfishing in 2002.

Texas

A Texas blue crab stock assessment was completed in 2007 (Sutton and Wagner 2007). Stocks were assessed by fitting a non-equilibrium logistic surplus production model (Schaefer 1954) to a time series of catch-per-crab fisherman data between 1967 and 2005. Model parameters, adjusted for the best model fit using the least sum of squares method, were: q = 0.0017569, r = 0.653, K = 21,699,014 (kg), B_{1967} = 10,564,277 (kg). The maximum sustainable yield (MSY) and maximum sustainable effort (E_{MSY}) were estimated at MSY = 3,541,549 (kg) and E_{MSY}= 186 crab fishermen respectively.

Bootstrapping techniques (Efron 1979) were used to ameliorate problems in using fishermen as the standard unit of effort (i.e. inherent variability in the amount of effort exerted by one fisherman). Here randomly selected residuals between observed and predicted catch-per-crab fisherman were used to establish 95% confidence intervals around best fit parameters (Table 1.5). Results suggested an additional 15% reduction in fishing effort would be needed to achieve maximum sustainable yield.

1.5.2 Other Blue Crab Stock Assessments

Several blue crab fisheries stock assessments exist for states or regions on the Atlantic seaboard. Chesapeake Bay has led the development of catch survey models, but equally applicable versions have been emulated in Delaware (Helser and Khan 2001) and North Carolina (Eggleston et al. 2004). Two stock assessment models from this region have been included in this report. They are 1) the most recent Chesapeake Bay assessment (Miller et al. 2011) because it covers some new ground in applying catch survey models and 2) the traffic light method (Caddy 1999 and 2002) introduced by North Carolina as an alternative to their catch survey analysis. The North Carolina assessment does not provide quantitative management reference points, but rather a precautionary approach based on historic trends.

Chesapeake Bay

The most recent blue crab stock assessment for Chesapeake Bay applied a sex specific catch multiple survey model to establish management reference points and stock status (Miller et al. 2011). The main difference between this and prior catch survey analyses done was the inclusion of sex specific stages and a built in Ricker type renewal function to model production. Production outputs were dependent on the number of age 1+ females. Four stages were used: (age 0 males, age 0 females, age 1+ males, and age 1+ females) each with stage-specific selectivity. Natural mortality (M) was assumed to be stage and sex-independent and constant, $0.6 < M < 1.1$. Population density was relative to the abundance of (age 1+ males and females). A sex ratio of 52% females was assumed based on empirical data. In the modeling process, indices series were fit to time series of total and sex-specific catches using a penalized log likelihood scheme. The model used the abundance of age1+ crabs in the winter dredge survey as estimate of absolute abundance—abundances of all other stages and surveys were considered as relative abundance. The following management reference points were recommended:

1. The overfishing limit should be defined as the exploitation rate of age-0+ crabs that coincides with maximum sustainable yield. Best estimate of U_{MSY} for age-0+ female crabs was equal to 0.34.
2. A target exploitation be established equivalent to 0.75* U_{MSY}. Best estimate for age-0+female crabs was equal to 0.255.
3. An overfished abundance threshold be established based on the estimate of 0.5* N_{MSY} (0.5 x numbers at MSY). Their best estimate for an overfished definition was 70 million age-1+female crabs.

4. A target abundance reference point should be established equivalent to the equilibrium abundance expected if the target exploitation rate is achieved.

North Carolina

The Traffic Light method (Caddy 1999 and 2002) was adopted by North Carolina after it was decided that previously applied catch survey and surplus production models were unreliable given some of the data constraints and limitations. The traffic light method, as used here, provides a precautionary approach to fisheries management. It is able to process large amounts of data from different sources and presents them in an easy to understand and visual manner. Limits can be set using any criteria including lower and upper percentile boundaries from historic data sets. The method attributes a set of red, yellow and green lights to the criteria used to define management reference points. Management action can then be set accordingly and can take on any agreed upon version of what constitutes an undesirable condition. While the assessment is quantitative in the sense it can calculate indicator percentiles, it is more of a qualitative assessment in nature. It does not provide quantitative reference points such as exploitation rate threshold or an estimate of MSY. North Carolina defined the overfished condition for blue crabs such, that when the proportion of red for the production Traffic Light is greater than the third quartile (>=0.75) for three consecutive years, the stock is considered overfished.

Table 1.1 Historical GOM hard crab landings (X1000 lbs) by state, 1980-1950 (-- indicates data not available). Partial surveys were done prior to 1912 and in 1934, 1936 through 1940, 1945, 1948 and 1949 (NOAA unpublished data).

Year	FWC	AL	MS	LA	TX	Total
1880				288	36	324
1887	--	--	38	837	111	
1888	3	96	16	851	115	1,081
1889			48	842	189	1,079
1890			33	851	191	1,075
1891						
1892						
1895						
1897	6	24	132	1,459	138	1,759
1898						
1899						
1901						
1902	1	75	235	312	43	666
1904						
1905						
1908	2	246	380	244	199	1,071
1915						
1918		96	216	282	193	787
1919						
1920						
1921						
1922						
1923		84	435	312	109	940
1924						
1925						
1926						
1927	12	32	2,426	1,091	121	3,682
1928	7	102	1,518	2,320	300	4,247
1929	2	103	1,247	2,675	163	4,190
1930	4	80	673	4,186	29	4,972
1931	4	78	454	4,985	49	5,570
1932	4	70	320	5,878	45	6,317
1933						
1934	49	257	603	11,676	258	12,843
1935						
1936	821	997	2,011	12,576	320	16,725
1937	775	756	1,435	14,717	922	18,605
1938	1,104	511	1,016	10,533	971	14,135
1939	722	558	1,469	11,228	406	14,383
1940	1,170	1,381	1,488	14,062	252	18,353
1941						
1942						
1943						
1944						
1945	1,092	2,207	5,639	31,280	339	40,557

1946						
1947						
1948	--	2,373	5,503	21,110	526	
1949	2,056	2,128	4,163	17,874	374	26,595
1950	684	599	4,040	13,106	387	18,816

Table 1.2 Hard crab landings (X1000 lbs) by state, 1951-2011 (NOAA unpublished data).

Year	FWC	AL	MS	LA	TX	Total
1951	2,076	1,109	1,623	8,710	280	13,798
1952	1,984	655	1,726	7,334	338	12,037
1953	3,153	1,087	1,412	8,131	432	14,215
1954	2,903	972	1,256	7,085	379	12,595
1955	4,954	1,613	1,763	10,811	356	19,497
1956	3,728	725	1,979	9,402	195	16,029
1957	5,302	1,462	2,400	8,559	201	17,924
1958	8,693	1,182	2,124	9,336	570	21,905
1959	13,895	1,093	3,003	9,570	1,192	28,753
1960	18,648	499	2,812	10,050	2,867	34,876
1961	17,130	838	2,505	11,910	2,875	35,258
1962	10,356	634	907	9,523	4,473	25,893
1963	13,148	1,297	1,112	7,982	2,980	26,519
1964	14,068	1,762	1,286	5,692	2,484	25,292
1965	20,598	1,812	1,692	9,284	3,622	37,008
1966	16,547	2,183	1,457	7,986	2,778	30,951
1967	13,976	2,353	1,015	7,559	2,625	27,528
1968	9,008	1,980	1,136	9,551	4,084	25,759
1969	11,584	1,920	1,740	11,602	6,343	33,189
1970	14,786	1,407	2,027	10,254	5,525	33,999
1971	12,279	1,997	1,259	12,186	5,810	33,531
1972	10,673	1,612	1,362	15,083	6,464	35,194
1973	9,599	2,098	1,814	23,080	6,881	43,472
1974	10,134	1,826	1,167	20,639	6,088	39,854
1975	12,807	1,639	1,137	17,144	5,992	38,719
1976	12,049	1,299	1,334	15,211	6,668	36,561
1977	15,832	2,174	1,919	16,154	8,249	44,328
1978	11,679	2,009	1,940	15,074	7,470	38,172
1979	11,198	1,341	1,313	21,334	8,312	43,498
1980	11,276	1,557	2,760	18,183	8,953	42,729
1981	14,788	2,462	1,867	16,237	6,952	42,306
1982	8,871	1,266	1,297	17,284	8,010	36,728
1983	9,337	1,412	1,140	19,616	8,829	40,334
1984	12,912	4,216	2,250	29,617	7,229	56,224
1985	12,273	2,261	1,649	29,848	9,722	55,753
1986	7,644	2,886	1,303	31,611	9,482	52,926
1987	10,425	2,507	1,374	52,345	11,688	78,339
1988	10,403	3,869	863	53,554	10,428	79,117
1989	8,197	4,090	651	33,390	9,066	55,394
1990	6,915	3,302	390	39,135	8,599	58,341
1991	5,235	2,731	454	51,987	6,137	66,538
1992	7,654	3,550	443	51,744	6,135	69,578
1993	8,459	2,554	230	45,847	8,288	65,378
1994	8,458	2,744	171	36,664	5,154	53,891
1995	8,725	2,520	321	36,914	5,787	53,925
1996	11,140	3,219	407	39,902	6,310	62,250
1997	9,246	3,476	683	43,440	5,739	62,584
1998	12,771	3,478	592	43,480	6,989	67,309
1999	11,047	3,768	920	46,328	6,472	68,534

2000	6,413	4,780	839	51,446	4,653	68,131
2001	4,548	2,457	432	41,398	5,163	53,998
2002	5,489	2,575	716	49,751	7,037	65,568
2003	7,141	2,957	875	47,705	4,811	63,489
2004	8,008	3,329	811	44,069	3,961	60,177
2005	7,312	1,024	429	37,880	3,119	49,763
2006	8,565	2,384	1,127	53,252	1,966	67,294
2007	6,074	2,554	737	44,902	3,454	57,722
2008	2,627	1,799	450	41,617	2,635	49,128
2009	3,313	1,458	545	52,848	2,844	61,010
2010	5,709	927	366	30,599	3,436	41,037
2011	1,616	1,616	370	43,698	2,893	50,192

Table 1.3 Number of resident crab fishermen commercial trap fishery, GOM based on license sales, 1994-2011 based on state license sales (FWC, ADCNR, MDMR, LDWF, TPWD).

Year	FL	AL	MS	LA	TX	Gulf
1994	822	115	148	2498	345	3,928
1995	732	150	148	3423	327	4,780
1996	822	220	143	2904	335	4,424
1997	824	177	194	2529	345	4,069
1998	741	176	230	2331	318	3,796
1999	698	169	213	3468	287	4,835
2000	596	176	208	3561	265	4,806
2001	560	174	217	3228	244	4,423
2002	490	169	253	3342	231	4,485
2003	478	158	262	3386	234	4,518
2004	474	170	189	3421	229	4,483
2005	427	157	122	2996	224	3,926
2006	393	120	110	3230	222	4,075
2007	366	148	138	3125	221	3,998
2008	307	188	155	3006	216	3,872
2009	325	183	138	3107	211	3,964
2010	391	327	291	3523	206	4,738
2011	374	338	223	3631	195	4,761

Table 1.4 Soft crab landings (X1000 lbs) by state, 1950-2011 [Landings not recorded or 0 indicated by "--"; (1) = less than 1000 lbs]. Texas landings are not identified as soft or hard so totals are not given here (NOAA unpublished data).

Year	FL	AL	MS	LA	TX	Total
1950	(1)	(1)	--	364	--	364
1951	4	(1)	6	350	--	360
1952	15	--	15	448	--	478
1953	3	--	(1)	488	--	491
1954	(1)	--	--	455	--	455
1955	1	--	7	581	--	589
1956	1	--	6	600	--	607
1957	10	--	17	551	--	578
1958	1	--	20	577	--	598
1959	3	--	11	605	--	619
1960	4	--	5	514	2	525
1961	5	--	7	620	2	634
1962	(1)	--	2	344	6	352
1963	4	--	3	329	2	338
1964	13	--	2	200	(1)	215
1965	12	--	1	204	--	217
1966	1	--	1	128	--	130
1967	7	--	1	146	--	154
1968	--	--	1	284	--	285
1969	(1)	--	(1)	197	--	197
1970	(1)	--	--	90	--	90
1971	--	--	--	127	--	127
1972	(1)	--	--	102	--	102
1973	--	--	--	119	--	119
1974	(1)	--	--	96	--	96
1975	2	--	--	111	--	113
1976	--	--	(1)	88	--	88
1977	--	--	--	225	--	225
1978	22	--	2	133	--	157
1979	9	--	--	147	--	156
1980	17	--	--	118	--	135
1981	23	--	--	100	--	123
1982	53	(1)	--	164	--	217
1983	36	(1)	--	101	--	137
1984	28	(1)	(1)	75	--	103
1985	17	3	--	82	--	102
1986	9	(1)	--	79	--	88
1987	12	--	--	139	--	151
1988	17	--	--	162	--	180
1989	39	--	19	172	13	230
1990	37	--	4	249	--	290
1991	22	--	2	200	(1)	224
1992	35	1	2	240	--	277
1993	21	--	(1)	99	--	121
1994	52	--	1	100	--	159
1995	52	--	2	52	--	111

1996	61	0	1	99	--	161
1997	66	10	2	86	--	164
1998	92	1	1	177	--	271
1999	123	--	2	336	--	461
2000	160	3	1	602	--	766
2001	99	--	1	402	--	502
2002	78	--	1	372	--	451
2003	85	1	1	384	--	471
2004	75	--	--	328	--	404
2005	58	--	--	220	--	278
2006	45	--	--	142	--	188
2007	35	3	--	205	--	243
2008	36	--	--	96	--	132
2009	50	--	--	212	--	262
2010	49	--	--	131	--	180
2011	37	--	--	187	--	224

Table 1.5 Bootstrap estimates of with 95% confidence intervals.

Parameter	Bootstrap Estimates		
	lower	mean	upper
q	0.0009729	0.0016427	0.0022947
r	0.325	0.609	0.901
K	16,962,974	26,156,070	44,709,618
B1967	7,089,573	13,025,780	27,724,484
MSY	3,163,356	3,481,401	3,718,528
E_{msy}	159	183	206

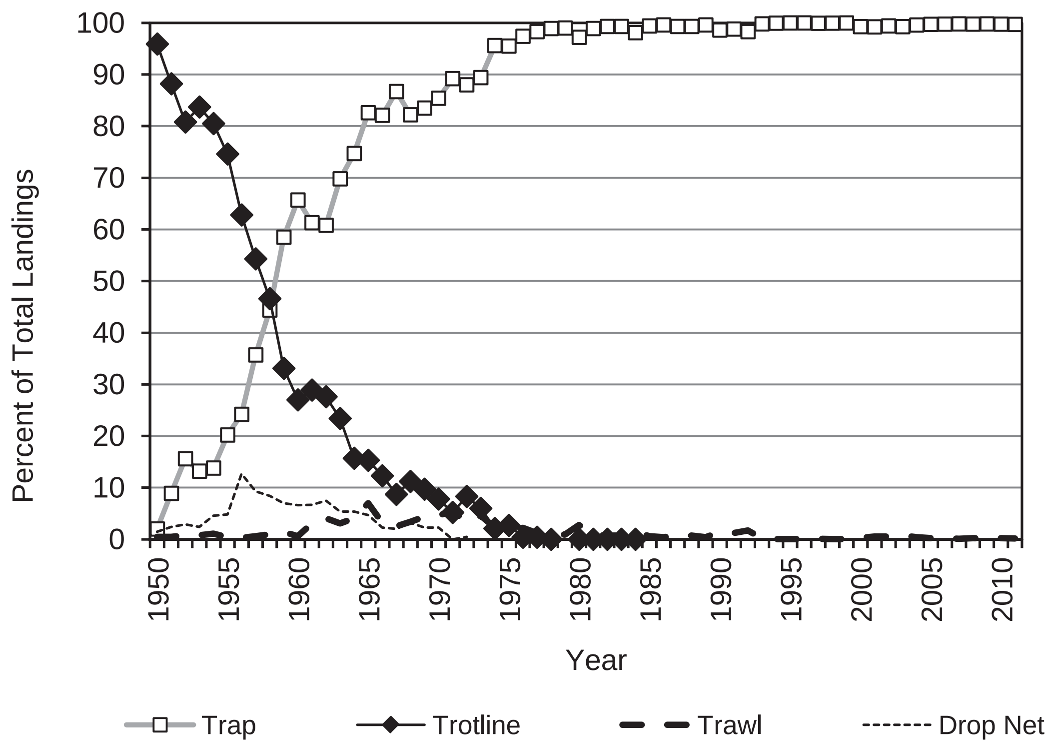

Figure 1.1 Total GOM crab landings by major gear from 1950-2011 (NOAA unpublished data).

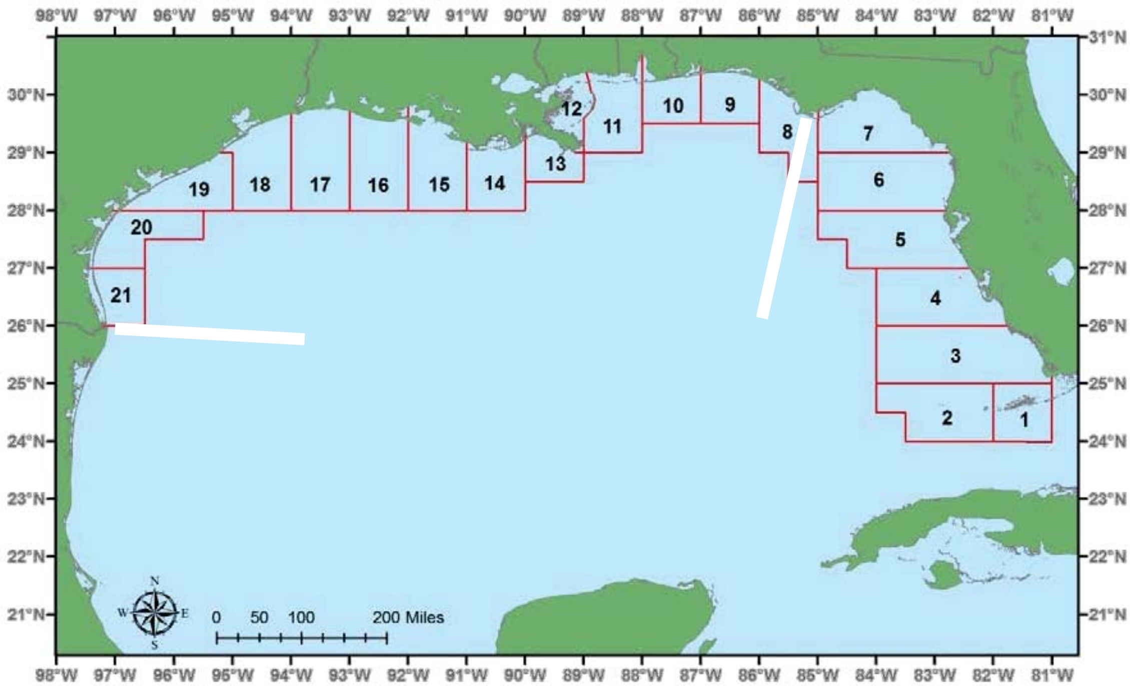

Figure 1.2 Proposed stock division of GOM blue crabs based on genetics and tagging studies in the northern Gulf. White line in NMFS statistical zone 8 (Apalachicola, Florida) defines the break between eastern (Zones 1-7) and western Gulf blue crab stocks (Zones 8-21).

2.0 Habitat Description

2.1 General Conditions

The life history of the estuarine-dependent blue crab involves a complex cycle of planktonic, nektonic, and benthic stages which occur throughout the estuarine-nearshore marine environment. A variety of habitats within the estuarine environment are occupied depending upon the particular physiological requirements of each life history stage (Perry et al. 1984). These habitats can be divided into offshore and estuarine phases. Female blue crabs are catadromous; they migrate from hyposaline waters to higher salinity water to spawn and hatch their eggs. The high salinity, oceanic water not only serves as habitat for the spawning female but ensures larval development, increases dispersal capabilities, decreases osmoregulatory stress, and reduces predation. Fertile eggs hatch into free swimming larvae (zoeae) which pass through a series of molts.

Newly-hatched blue crab larvae normally develop through seven zoeal stages before transforming into a megalopal stage. Megalopae return to the estuary where they metamorphose into the first crab stage. The estuarine phase is perhaps the most critical because all postsettlement growth and the major components of the reproductive cycle occur there. Male blue crabs usually remain within the estuary during their entire postsettlement life. Juvenile and adult blue crabs exhibit wide seasonal and areal distribution within estuaries.

2.2 Physical Habitat

The partitioning of estuarine habitat among size classes of blue crabs is thought to be related to predator avoidance (including cannibalism), food availability and nutritional requirements, reproductive success, and growth (Millikin and Williams 1984, Perry et al. 1984, Hines et al. 1987, Thomas et al. 1990).

Eggs and Larvae - Female *C. sapidus* spawn near the offshore barrier islands in the northern GOM (Perry 1975, Adkins 1972) or in high-salinity waters near bay mouths. Vertical and areal patterns of zoeal distribution are similar for the Atlantic and Gulf coasts. After hatching, first stage zoeae move into surface waters where they remain for the duration of larval development and are exported from estuaries on an ebbing tides. Subsequent zoeal development and metamorphosis to the megalopal stage takes place on the adjacent continental shelf.

Megalopae - Stuck and Perry (1981) reported that peak numbers of blue crab megalopae in plankton samples occurred during late spring/early summer and late summer/early fall in barrier island passes along the Mississippi Coast with peak settlement occurring from July through September. Morgan et al. (1996) found that settlement of megalopae in Mobile Bay, Alabama occurred from June through November with a peak during July to mid-October. Chemical cues from the estuary have been shown to speed metamorphosis of megalopae to the first juvenile stage (Wolcott and DeVries 1994, Forward et al. 1994, Brumbaugh and McConaugha 1995, Forward et al. 1996 and 1997). If a preferred habitat is not present when molting to the first crab stage becomes obligatory, settlement and metamorphosis can occur anywhere (Orth and van

Montfrans 1990). In the northcentral GOM, megalopae settle in shoreline habitats (Guillory et al. 2001) and prefer vegetated habitats to unvegetated habitats (Morgan et al. 1996).

Juveniles - Juvenile blue crabs show wide areal distribution in GOM estuaries and numerous studies have shown the vegetated habitats (seagrass and salt marsh) are important nursery areas for estuarine dependent species such as the blue crab. Orth and van Montfrans (1990) noted that vegetated habitats were characterized by higher overall abundances of blue crabs and lower predation rates than were non-vegetated habitats. The quantity of marsh and seagrass habitats may contribute to stock size by providing food and refuge which increases survival of early juvenile stages. Studies in Texas estuaries demonstrated that juvenile blue crabs were significantly more abundant in flooded salt marshes than in subtidal areas without vegetation (Zimmerman and Minello 1984, Thomas et al. 1990). Unvegetated substrates with drift algae or attached macroalgae also provide important habitat in some areas. Stunz et al. (2010) and Shervette et al. (2011) both showed that blue crab densities were similar in marsh edge and oyster habitats and that both were significantly higher when compared to unvegetated substrates. An association of juvenile blue crabs with soft mud sediments has been noted in several GOM studies suggesting that unvegetated soft-sediment habitats also provide protection from predation. Although juvenile blue crabs occur over a broad range of salinities, they are most abundant in low to intermediate salinities characteristic of middle and upper estuarine waters which may explain the wide range of habitat usage.

Adults - Throughout the GOM, adult blue crabs are widely distributed and occur on a variety of bottom types in fresh, estuarine, and shallow oceanic waters. Adult blue crabs use submerged vegetation (including macroalgae), unvegetated sediments, and Spartina marsh for refuge and foraging (Heck and Thoman 1984, Wilson et al. 1990). Although adult blue crabs are ubiquitous throughout an estuarine system, they are distributed seasonally with respect to salinity and sex (Steele and Bert 1994). Three subhabitats (spawning, wintering, and maturation) were recognized in the Barataria, Louisiana, estuary by Jaworski (1972). The spawning habitat for females included tidal passes and nearshore GOM waters, while the lower bays where juvenile and male crabs concentrated after water temperatures fell below 15ºC comprised the wintering habitat. The maturation habitat included the shallow, brackish marshes of the upper estuaries.

2.3 Temperature and Salinity

Daud (1979) concluded that shallow, brackish to saline waters are the major habitat for the early crab stages (5-10 mm). As they grow to a larger size, these blue crabs move into fresher waters. Swingle (1971), Perret et al. (1971), and Perry and Stuck (1982) determined the distribution of juvenile blue crabs by temperature and salinity using temperature salinity matrices. Rounsefell (1964) and Daud (1979) observed a movement of crabs into low salinity Louisiana marshes with growth. Juvenile crabs in Christmas Bay, Texas, were larger in salt marshes than in seagrass or on sand and mud bottoms (Thomas et al. 1990); possible reasons for the observed habitat-related size patterns included differential predation, differential recruitment of megalopae, inability of small crabs to effectively move with tides in and out of salt marshes, and active selection.

Both Perret et al. (1971) and Swingle (1971) found maximum abundance for larger juveniles in salinities <5.0 ppt. In contrast, Perry and Stuck (1982) found highest average catches of juvenile blue crabs were associated with salinities >14.9 ppt. Hammerschmidt (1982) found no direct relationship between catches of juvenile blue crabs and salinity in Texas. Steele and Bert (1994) found maximum abundance for subadult males and adult females in salinities >20.0 ppt in Tampa Bay, Florida. High salinity waters (>30.0 ppt) are occupied almost exclusively by mature crabs, particularly females.

3.0 Life History

3.1 Stock Definition and Genetics

Appropriate management of a species must consider the potential for multiple stocks or genetic populations. In addition to influencing jurisdictional and logistical aspects of management, the implications of stock assessments are more accurately interpreted within the context of a well-defined genetic background. Although genetic characterization of population structure is recognized as an important component of fisheries resource management, relatively few studies have been conducted on blue crabs. The studies that do exist on the genetic structure of GOM blue crab populations are useful only when used in concert with larval dispersal, behavioral and migration studies.

In Texas, Kordos and Burton (1993) examined allele frequencies in blue crab megalopae and adults and found significant spatial and temporal heterogeneity in Texas that was attributed to seasonal variation in larval source populations, low gene flow, and genetic drift. Berthelemy-Okazaki and Okazaki (1997) assayed 28 enzymes and proteins from adult crabs from four northern Gulf estuaries (Aransas Bay, Texas; Barataria Bay, Louisiana; Lake Pontchartrain, Louisiana; Mobile Bay, Alabama). They found a low level of genetic variation between the populations and noted that genetic exchange was not impeded by physical or physiological barriers in the western region of the GOM (Texas through Alabama).

Studies of the genetic structure of blue crab populations from Mexico to New York were performed by McMillen-Jackson et al. (1994) and McMillen-Jackson and Bert (2004). These studies examined the genetic structure of blue crab populations over a broad geographic range using electrophoretic allozyme analysis (1994) and mitochondrial DNA (2004). They found genetic homogeneity throughout the range with greater latitudinal clines in the Atlantic than in the GOM. The 2004 study, using mtDNA, suggested regional gene flow occurs over short ecological time periods while long distance gene flow may be low and occur over longer evolutionary time periods. The range-wide genetic patchiness and a clinal variation within and between populations was of similar magnitude, and these authors attributed the genetic patchiness to pre-settlement processes associated with larval pulses, dispersal and settlement, and post-settlement ontogenetic changes brought about by localized selection. Comparing their results with those of Kordos and Burton (1993), they suggested post-settlement processes modify allele frequencies in pre-settlement assemblages that are already genetically heterogeneous.

Concurrent genetic analyses of blue crabs in the GOM by Darden (2004) supports the patchy but broad-scale structure suggested by McMillen-Jackson et al. (1994) and McMillen-Jackson and Bert (2004) for the entire Gulf and the local structuring seen in western locations (Kordos and Burton 1993). Darden concluded that dispersal is accomplished primarily by a stepping stone effect rather than consistently long distance dispersal, resulting in isolation by distance between the east and west GOM as well as among several western GOM locations. Gene flow among locations in the western GOM was determined to be restricted while eastern GOM locations showed no significant population structure (Darden 2004). McMillen-Jackson and Bert (2004) concurrently made similar conclusions over a larger geographic range in the GOM (Mexico to the Florida Keys). They found low haplotype diversity in Mexico and the Florida Keys due to these locations being furthest from the regional center of blue crab abundance in the northern GOM and suggested that they could represent the periphery of the populations in the GOM.

The genetic ‘dividing line’ for GOM blue crab populations is not clear; however, the influences of seasonal current circulation patterns, larval mixing, and larval migration behaviors (Johnson and Perry 1999, Perry et al. 2003 and Johnson et al. 2009), as well as long-distance migration of adults (Evink 1976, Oesterling 1976, Oesterling and Evink 1977, Oesterling and Adams 1982, Steele 1987 and 1991) may combine to separate “east from west” blue crab populations in the GOM (Figure 1.2). Studies by Darden 2004 revealed detectibly significant population structure suggesting a distinct “western” Gulf population that may have resulted from less influential seasonal wind-driven currents than those observed in the northern and eastern GOM. When combined with larval transport and tagging/migration studies, Darden’s work suggests population structuring between eastern and western regions and thus has important management implications for blue crabs in the GOM.

A similar population separation was reported for red snapper (*Lutjanus campechanus*) by Johnson et al. (2009 and 2013) who found that red snapper larval transport across the northern GOM from west to east was complicated by topographic impediments to the along-shelf flow that included the Apalachicola Peninsula. They noted that there “seems to be a natural population break near Florida’s Apalachee Bay”, just east of Apalachicola Bay in the panhandle region.

Other species exhibit faunal discontinuities in the GOM. Portnoy and Gold (2012) noted that at least 15 pairs of fishes and invertebrates described as sister species (species, subspecies, or genetically distinct populations) can be found in a marine suture zone whose eastern boundary is located in the Apalachee Bay area of Florida. Within the zone, multiple vicariance events have occurred over geological time scales that may have contributed to observed patterns of divergence for these species.

3.2 Ageing

Although no quantitative procedure exists for determining size at age for blue crabs, the need to derive parameters for stock assessment models has necessitated estimation of size at age for the determination of growth rates used in estimating total mortality. Climatologically different study sites and the winter hibernation of blue crabs in northern estuaries preclude application of northern studies to GOM blue crab populations. Winter temperatures in the Chesapeake Bay region significantly affect the molting/growth and the subsequent timing of recruitment to the fishery (Smith 1997, Brylawski and Miller 2006). During winter, blue crabs experience several months of inactivity in the Chesapeake Bay estuary. In that region, blue crabs spawned in late summer recruit to the fishery and females reach maturity by the late summer or early fall of the following year (Miller et al. 2011). Blue crabs in the GOM have not been documented to hibernate during cold months, however Steele and Bert (1994), suggested the potential for semi hibernation needs further study. In many Gulf States, blue crabs are found to grow throughout the winter.

Tagatz (1968a) determined molt increment and growth per molt for crabs maintained in floats at two areas in the St. Johns River, Florida. Using mean percentage growth per molt and mean molt interval, he estimated size at age one of 142 mm. Perry (unpublished data) found mean pre and post-molt carapace widths of 119 and 163 mm, respectively, for pubertal molt females (n=159) taken in traps in Mississippi. Pre and post-molt carapace widths for male crabs (n=49) approaching one year of age were 120 and 151 mm, respectively, a size more closely approximating the estimate of Tagatz (1968a). Assuming that crabs in the northern Gulf reach maturity within a year (Perry 1975, Tatum 1980), these crabs provide an estimate of size at age one. The average size of mature female crabs in Perry's study was comparable to data from other areas: average size of mature females in Delaware Bay was 160 mm CW, and in Chesapeake Bay mature females were 165 mm CW. Larger size at age one (163 mm CW) for mature females when compared to the estimated size of 142 mm CW proposed by Tagatz (1968a) may be attributed to sex-related morphological changes associated with lateral spine length in pubertal molt females (Gray and Newcombe 1938, Olmi and Bishop 1983, Guillory and Hein 1997) and/or greater incremental growth in female crabs (sub-adult) than in similar-sized male crabs (Tagatz 1968a).

Size at age data for pond reared crabs in Florida indicates that crabs spawned during the summer are able to mature and recruit to the fishery at 127 mm CW by the end of that winter or early spring of the following year, at an age of ~6 to7 months (Crowley 2012). This rapid growth is supported by blue crab aquaculture studies in Mississippi where similar trends were reported (H. Perry and D. Graham pers. comm).

3.2.1 Ageing Techniques

Accurate age estimates are essential to fisheries management and stock assessments (Beamish and McFarlane 1983). Aging of crustaceans is hindered by their complicated life cycles, inconsistent growth patterns and lack of retention of mineralized structures. Biological interactions, discrete and determinate growth patterns and the effects of environmental parameters (salinity and temperature) on molting have significant effects on blue crab growth (Steele and Bert 1994, Hartnoll 2001) thus precise age determinations using length-frequency measurements (commonly used in vertebrates) are precluded. When size-distribution and modal analysis has been applied to crustacean fisheries it has usually proved unsuccessful in accurate age estimation (Puckett et al. 2008) due to its vulnerability to interpretation (Hartnoll 2001).

Researchers in Florida attempted to apply the extraction techniques developed by Ju et al. (1999 and 2001) and Puckett et al. (2008) to aging blue crabs in the Florida fishery (Crowley 2012). Crowley (2012) investigated the robustness of the extraction technique for lipofuscin age determination in Florida blue crabs using two known age cohorts. Cohorts were from different sources, one wild (n=570) and one from the Blue Crab Aquaculture program at the University of Southern Mississippi's Gulf Coast Research Laboratory (n= 188). Each cohort was cultured under different conditions to develop a known age curve and subsequently determine the reliability of the extraction technique for ageing blue crabs before its application in the Florida blue crab fishery. Results of the Florida study did not support the conclusions of Ju et al. (1999 and 2001) and Puckett et al. (2008) that linked accumulation of extractable lipofuscin with chronological age in blue crab (Crowley 2012). In contrast to those authors, the Florida study found negative correlations with age in the pond (y= - 0.05x + 0.43, $p<0.001$, $R2 = 0.13$) and tanks (y= - 0.012x + -0.919, $p<0.07$, $R2 = 0.002$). The lipofuscin indices generated by the extraction method were not correlated with age and precluded the development of a calibration curve and age determination of blue crabs in the Florida fishery. Use of lipofuscin methodology has been found to be unsuccessful in other studies on different species (Manibabu and Patnaik 1997, Majhi and Patnaik 2000) and Sheehy (2008) noted that the accuracy of the extraction methodology may not be sufficiently vetted for use in ageing.

3.3 Maturation

The length of time required for crabs to reach maturity varies regionally. Up to 18 months is necessary for maturation in Chesapeake Bay (Van Engel 1958), while blue crabs in the GOM may reach maturity within a year (Perry 1975, Tatum 1980). Florida pond studies of Crowley (2012) found the first mature female raised from a wild cohort in a ¼ acre pond at 7.7 months of age and the last immature female was captured in the pond at 10.3 months of age.

One of the more controversial issues concerning growth and maturation involves the concept of permanent anecdysis in female crabs. Havens and McConaugha (1990) and Steele and Bert (1994) found seasonal size differences in mature females and proposed that females may not enter a permanent anecdysis. Mature females with limb buds (11.2% of sampled population), molting by females with ablated eyestalks, and seasonal size differences in mature females prompted Havens and McConaugha (1990) to suggest that females can molt following the pubertal ecdysis. Although mature females in the process of molting (Abbe 1974) or in proecdysis (Olmi 1984, Millikin and Williams 1984) have been observed in other studies, they have been few in number suggesting that this rarely occurs. Smith and Chang (2007) noted that both sexes have the physiological ability to molt following attainment of the terminal instar, but do not. There is little evidence for molting of mature females in the northern Gulf.

Size at maturity is highly variable, and a number of factors appear to influence maturation size. Temperature exerts control on maximum size by affecting incremental growth and molt interval. Tagatz (1968a) suggested that differences in growth per molt and molt interval within juvenile size groups may account for observed variation in size at recruitment to adult populations. Morphological changes associated with maturation also contribute to variability in size. Newcombe et al. (1949a), Olmi and Bishop (1983), and Guillory and Hein (1997) found maturity associated differences in width-weight relationships between male and female crabs. They attributed these differences to changes in carapace form (pubertal molt transformation in females to the long-spined form) and heavier individual body components in male crabs. Perry (unpublished data) examined growth per molt between males and pubertal molt females of similar size. There was no significant difference in pre-molt size between males and females in her study; however, post-molt females were significantly larger in size. Percent gain in carapace width was 28% for males and 40% for females (Figure 3.1).

3.4 Longevity, Maximum Size, and Growth

Estimation of growth parameters in blue crab populations is problematic due to their discontinuous or stepwise pattern of incremental growth. Somatic growth takes place during ecdysis or molting, while small increases in weight occur during intermolt as a result of changes in tissue content (Millikin and Williams 1984). The rate of growth is determined by the increase in size at each molt (molt increment) and the interval between successive molts (molt interval); thus, growth per molt and molt frequency are used as determinants of growth. Early crab stages have short molt intervals with molting occurring every few days. As crabs increase in size the molt frequency decreases. Blue crab growth is determinate (Hartnoll 1985) in both females and males (Smith and Chang 2007). Both sexes have the physiological capability of molting after the terminal instar, but do not (Smith and Chang 2007). Females reach the terminal instar at their nuptial molt with males passing through additional adult molts to reach a terminal instar. Newcombe et al. (1949b) estimated the postlarval instars for male and female blue crabs to be 20 and 18, respectively. Maximum size attained thus reflects incremental growth per molt rather than the number of molts (Leffler 1972).

Growth data exist for GOM blue crabs from length-frequency distributions and more recently from aquaculture studies conducted in Florida and Mississippi. Perry (1975) estimated seasonal (July through January) growth by tracing modal progressions in monthly width-frequency distributions for crabs in Mississippi Sound. The estimated growth rate of 24-25 mm/month is somewhat higher than rates found for other Gulf estuaries. Adkins (1972) found growth in Louisiana waters to be about 14 mm/month for young crabs with slightly higher rates (15-20 mm/month) as crabs exceeded 85 mm in carapace width. Darnell's (1959) growth estimate of 16.7 mm/month for crabs in Lake Pontchartrain falls within the average reported by Adkins. More (1969) noted a growth rate of 15.3-18.5 mm/month in Texas. Plotting the progression of modal groups from February through August, Hammerschmidt (1982) reported higher growth rates for crabs in Texas (21.4 and 25.2 mm/month for seine and trawl samples, respectively) and attributed these rates to the use of seasonal rather than yearly data. Tatum (1980) also found seasonal changes in the rate of growth of young blue crabs in Mobile Bay, Alabama. He observed monthly rates of 19, 10, and 5 mm for crabs recruited in April, August, and December, respectively. Pond studies in Florida (Crowley 2012) found growth rates of males and females from 15 mm to a legal size of 127 mm to be 12.4 and 12.7 mm/month, respectively. Mississippi aquaculture research has estimated crab growth from studies in tanks and ponds (Perry unpublished data). During the early grow-out period (megalopae to beginning crab stages) in recirculating tanks, crabs had a growth rate of 16.5 mm/month. In pond studies (early juvenile crabs to adults), crab growth was 20.2 mm/month.

Blue crab growth rates in the GOM can be modeled using the von Bertalanffy growth equation,

$$CW_t = CW_\infty \, (1\text{-}e^{-K(t-t_0)}) \quad [1]$$

where CW_t is the carapace width at time t; CW_∞ is the mean carapace width of very old blue crabs occurring in the GOM; K is the von Bertalanffy growth coefficient; and t_0 is the time at which carapace width is theoretically zero. This continuous growth function does not literally describe the incremental growth of blue crabs, but since model fitting is essentially a data smoothing technique and since members of a cohort molt at different times, the average growth of a cohort becomes a smooth curve (Sparre et al. 1989). Smith (1997) and Rothschild and Ault (1992) modified the von Bertalanffy model to consider incremental growth but this assessment agreed with Rugolo et al. (1997) who concluded that the von Bertalanffy model adequately described blue crab widths at ages. Required inputs for the model included estimates of CW_∞, widths at ages, and maximum age.

In addition to the von Bertalanffy growth model, a temperature-dependent individual-based molt-process model was adapted from Bunnell and Miller (2005) and fit to the aquaculture studies from both Florida and Mississippi (W. Cooper pers. comm.). The model was structurally similar to Bunnell and Miller (2005), but instead of basing the growth parameters on Tagatz (1968a), the growth parameters (growth per molt, GPM; intermolt period, IP) were fit to the aquaculture size-at-age data using metaheuristic maximum likelihood approach. To provide more flexibility in GPM as a function of size, GPM was modeled using a polynomial spline, while the IP parameters were modeled as in Bunnell and Miller (2005). Growth and temperature data were available for one aquaculture study in Florida, and seven aquaculture studies in Mississippi (Figure 3.2). The molt-process model was fit to the combined studies from Florida and Mississippi, providing a single set of parameter estimates for GPM as a function of size and IP a function of size and temperature. The fit of the model to the observed growth data from the eight aquaculture studies are shown in Figure 3.3.

Due to the strong temperature dependence on growth in blue crabs, von Bertalanffy growth parameter estimates from individual studies would only be appropriate for individuals spawned during similar months, since those spawning in spring could have markedly different growth parameter estimates than those spawned in the fall. To distill a single set of growth parameter estimates for the western and eastern stock in the GOM, the climatological average of temperatures for the two regions were calculated from the fisheries independent monitoring data, and these temperature time series were input into the molt-process model to simulate size-at-age data for individuals spawning throughout the entire spawning season. The spawning season was based on the proportion of ovigerous females sampled in various studies, and these proportion data were used to assign the spawning date using an empirical distribution. A von Bertalanfy model was then fit to these simulated size-at-age data for the east and western stocks to obtain a single estimate for both stocks (Figure 3.4):

$$CW_t \text{ (western stock)} = 165.95\ (1\text{-}e^{-1.9325(t\text{-}0.1668)}) \quad [2]$$

$$CW_t \text{ (eastern stock)} = 166.05\ (1\text{-}e^{-2.1582(t\text{-}01740)}) \quad [3]$$

Maximum age of GOM blue crabs was assumed to be six years. Fischler (1965) found crabs attaining an age of at least five years in a tagging study conducted in North Carolina. Smith (1997) inferred a maximum age of 5.5 years based on a molt-process model and Churchill (1919) presumed 6 years from anecdotal evidence. Rothschild and Ault (1992) also assumed a maximum age of six years in their assessment of Chesapeake Bay blue crabs.

Studies examining the influence of environmental parameters on molt frequency and incremental growth are conflicting. Newcombe (1945), Porter (1955), Cargo (1958), and Van Engel (1958) associated increasing size with decreasing salinity and suggested a possible correlation of size with the salinity of the water in which growth occurred. Van Engel (1958) believed that an osmoregulatory mechanism was involved; differences in the levels of salt concentration between the crabs and their environment affected the uptake of water resulting in increased growth per molt. Millikin and Williams (1984), however, reported that salinity values ranging from 6.0‰ to 30.0‰ did not differentially affect growth of juvenile and adult blue crabs. In studies of growth increments occurring during the terminal molt of female blue crabs under different salinity regimes, Haefner (1964) found that growth was not affected by salinities of 9.0‰, 16.0‰, or 27.0‰. Haefner and Shuster (1964) concluded that "within the parameters of the experiment, the salinity variation of the environment was not related to percentage increase in length at the terminal molt." Tagatz (1968a) found that a decrease in salinity did not produce an increase in size and suggested that some factor other than salinity appeared to account for larger crabs in certain waters. Perry examined size increases in pubertal molt females in salinities of 5.0‰, 12.0‰, and 25.0‰ for crabs in Mississippi and also found that percent increases in carapace width were not significantly different among the test groups (Guillory et al. 2001). Average increases were 38.5%, 40.4%, and 40.5% at salinities of 5.0‰, 12.0‰, and 25.0‰, respectively. Tagatz (1968a) reported incremental growth increases in pubertal molt females of 34.4% and 30.2% in salt (>5‰) and fresh (<1‰) waters, respectively. Smith and Chang (2007) noted that the influence of salinity on molting was subtle and was more easily observed at salinity extremes. At very low or very high salinities, the general response was a decrease in molt increment or an increase in the intermolt period, or both (Hartnoll 1982).

Growth of blue crabs appears to be more strongly affected by temperature. In laboratory studies, Leffler (1972) demonstrated that the molting rate (molts per unit of time) increased rapidly with increasing temperature from 13.0°C to 27.0°C but continued at a slower rate between 27.0°C and 34.0°C. Growth per molt was significantly reduced above 20.0°C, and at temperatures below 13.0°C, growth virtually ceased. Cadman and Weinstein (1988) and Holland et al. (1971) observed accelerated growth with increasing temperature until a threshold was reached, after which growth per molt decreased and Winget et al. (1976) found growth per molt higher at 20°C. Thus, while the molting rate increases with temperature, the number of molts necessary to attain a certain size also increases. Leffler (1972) reported that the number of molts required for a 22 mm CW crab to attain 60.0 mm CW increased from five at 15°C to seven at 34°C. Leffler (1972) noted that because the number of molts is fixed, maximum size attained reflected growth per molt modified by ambient thermal surroundings; thus, environmental temperatures may contribute to observed variation in size at maturity. In contrast, Tagatz (1968a) found that growth per molt was similar in summer and winter regardless of temperature; however, intermolt intervals increased in colder months. Winter temperatures in his study averaged about 14°C with an average summer temperature of approximately 26°C. Tagatz's crabs were held in outdoor floats as opposed to controlled laboratory temperatures, and fluctuating temperatures associated with the natural environment may not have affected growth per molt as profoundly as constant exposure to low temperature.

Tagatz (1968a) observed that growth per molt and molt interval were highly variable within juvenile size groups and noted that this variability may cause irregularity in recruitment. He found growth per molt ranged from 7.8% to 50.0% with a mean of 25.3%. Millikin and Williams (1984) noted that growth rate of juvenile crabs did not vary between males and females. A summary of blue crab growth studies from the GOM can be found in Table 3.1.

Carapace-width-to-weight relationships have been estimated for blue crabs sampled from estuaries the GOM. Guillory and Hein (1997) developed a relationship for blue crabs from the

Terrebonne Basin, Louisiana. Blue crab weight (grams) at CW for both sexes combined was determined as:

$$Weight = 8.26x10^{-4}CW^{2.446} \quad [4]$$

Relationships from Mississippi fishery-independent monitoring are presented in Figures 3.5 and fishery-dependent are presented in Figures 3.6. The composite weight-length relationship (both sexes, fisheries independent, FID, and dependent data, FDD) and category-specific relationships were estimated as follows:

$$Weight\ (Composite) = 8.88x10^{-4}CW^{2.429} \quad [5]$$

$$Weight\ (FDD, Males) = 1.41x10^{-3}CW^{2.373} \quad [6]$$

$$Weight\ (FDD, Females) = 2.64x10^{-3}CW^{2.199} \quad [7]$$

$$Weight\ (FID, Males) = 1.85x10^{-4}CW^{2.751} \quad [8]$$

$$Weight\ (FID, Females) = 3.37x10^{-4}CW^{2.613} \quad [9]$$

In Florida, multiple data sources were used from commercial biostatistical sampling, disease sampling contracted through commercial crabbers, and fishery-independent monitoring (n=11,727 crabs) to produce the following relationships for the composite fit to all data, and separated out by category (Figures 3.7, 3.8):

$$Weight\ (Composite) = 8.42x10^{-3}CW^{1.998} \quad [10]$$

$$Weight\ (FDD, Males) = 2.27x10^{-3}CW^{2.278} \quad [11]$$

$$Weight\ (FDD, Females) = 8.43x10^{-3}CW^{1.967} \quad [12]$$

$$Weight\ (FID, Males) = 4.63x10^{-4}CW^{2.583} \quad [13]$$

$$Weight\ (FID, Females) = 2.13x10^{-3}CW^{2.228} \quad [14]$$

3.5 Reproduction

3.5.1 Mating

For most estuarine animals mating and spawning are synonymous; however, in the case of the blue crab the two events occur at different times. Prior to her pubertal molt, the female travels to brackish waters of the upper estuary to mate. Teytaud (1971) observed that unimpregnated pubertal molt female crabs retained sexual receptivity for over two weeks and were able to mate even though the exoskeleton had hardened. Field studies have indicated that approximately 12% of females mate twice (Jivoff 1997).

Harvest of large male crabs has increased concern over the incidence of insemination in female blue crabs. However, Wenner (1989) surveyed the commercial catch in South Carolina and found that 97% of the females were inseminated, despite heavy fishing pressure on males. Similarly, Hines et al. (2003) found that >98% of females were mated at sites in Maryland, Virginia, and Florida. While blue crabs have very high mating success, there is evidence that females become sperm limited at the end of their lifetime. Females producing their final broods can have infertile eggs (Hines et al. 2003, Dickinson et al. 2006, Darnell et al. 2009).

3.5.2 Spawning

Spawning of blue crabs in northern Gulf waters is protracted with egg-bearing females occurring in coastal Gulf and estuarine waters in the spring, summer, and fall (Gunter 1950, Daugherty 1952, More 1969, Adkins 1972, Perry 1975). Additionally, Adkins (1972) found evidence of winter spawning in offshore Louisiana waters based on commercial catches of "berried" females in December, January, and February. Daugherty (1952) noted that crabs in southern Texas may spawn year-round in mild winters. Spawning usually occurs within two months of mating in the spring and summer. Females that mate in the fall usually delay spawning until the following spring.

Sperm transferred to the female are used for repeated spawnings. Females have been found to produce a first brood 23 days after mating (Darnell et al. 2009). Most females spawn more than once and have the potential to spawn up to 18 times over their lifetime (Hines et al. 2003). Dickinson et al. (2006) found that females that began spawning in June had as many as seven broods by October of the same year. In North Carolina, larger crabs had a longer clutch production interval than smaller crabs (Dickinson et al. 2006, Darnell et al. 2009). There is some evidence of sperm limitation in blue crabs that influences lifetime reproductive potential (Kendall and Wolcott 1999, Kendall et al. 2001, Hines et al. 2003, Dickinson et al. 2006). Females generally return to inland waters to develop their second sponge (Tagatz 1968b, Adkins 1972). After spawning for the second time, females generally do not re-enter estuaries (Tagatz and Frymire 1963, More 1969). Crabs that have been offshore are usually encrusted with the acorn barnacle, *Chelonibia patula*, and are a dull grey/green in color (Tagatz 1968b). Perry (1975) reported that large numbers of spent females occasionally litter barrier island beaches in the northern Gulf during the late summer, and these females are fouled with *C. patula* and heavily infested with the parasites *Carcinonemertes carcinophila* and *Octolasmis lowei*. Perry (1975) used the ovarian stages described by Hard (1942) to define the reproductive potential of the population in Mississippi. Recently mated females (Stage I) and crabs with developing ovaries (Stage II) were found in the spring, summer, and fall. Females with mature ovaries (Stage III) occurred throughout the year. Stage IV (berried) females appeared in March and April suggesting that overwintering Stage III females spawned when the water temperatures rose in the spring. Stage IV females were also abundant during the middle and late summer corresponding with the influx of "Gulf" crabs from offshore waters.

3.5.3 Spawner/Recruit Relationship

Stearns (1976) suggested that for populations in fluctuating environments, age and size at first reproduction should be respectively lower and smaller, reproductive effort higher, size of young smaller, and number of young per brood higher. This combination of life history traits (labeled r-selection) is associated with organisms that mature early, produce a large number of young, practice semelparity, have a large reproductive effort, and exercise no parental care. With the exception of semelparity, blue crabs exhibit those life history strategies associated with r-selection. Based on these traits, Van Engel (1987) summarized blue crab life history characteristics relevant to management of the fishery as follows:

> "The blue crab is characterized by the annual production of a large number of young, inter-annual fluctuations in production, rapid growth, early attainment of maturity, high mortality, and a short life span. These are the characteristics of a density-independent species, exposed to a variable environment in which the population's resources are spent mostly on reproductive (r) functions. In short, the blue crab appears to be an r-selected strategist. Because of these characteristics, the blue crab can be fished at high levels of fishing effort, and, because of the short life span and rapid succession of year classes, would have a quick recovery if overfishing occurred."

Several authors have attempted to quantify the spawner-recruit relationship for blue crabs in the Chesapeake Bay region. Rugolo et al. (1997) fitted forty-two pairwise stock-recruitment model combinations and found weak to no relationships between adult stock and subsequent recruitment. Lipcius and Van Engel (1990) fit a Ricker-type model to Virginia commercial landings data and trawl data from two stations in the York River, Virginia. They found a significant correlation between recruits as measured by trawl survey abundance and spawning stock (catch in the winter dredge fishery). No stock recruitment relationship has been quantified for the GOM blue crab stocks (see GDAR01-AW02).

3.5.4 Fecundity

Estimates of fecundity are based on the number of eggs spawned per batch and on the number of batches produced per season. Early studies estimated the number of eggs per brood to be between 1.75×10^6 and 2.00×10^6 (Churchill 1919, Van Engel 1958). The more recent estimates are higher: 2.75×10^6 (Hines 1982), 3.2×10^6 (Prager et al. 1990), $2.1\text{-}3.2 \times 10^6$ (Hsueh et al. 1993), 3.5×10^6 (Ealy 2001), and 2.8×10^6 (Graham et al. 2012). Hines (1982) noted that of the factors that may place allometric constraints on the mass or volume of reproductive output, physical or mechanical constraints (not energetics) were limiting in many species of Brachyura, including *C. sapidus*. Volume of the body cavity limits brood size: rigidity of the exoskeleton in brachyurans precludes distensibility of the body during yolk accumulation and thus places an anatomical constraint on brood size. Brood weight was generally constrained to approximately 10% of body weight. Fecundity in brachyuran crabs is variable and highly dependent upon the size of the female. Similar to the positive correlation between female body weight and fecundity found by Hines (1982), a positive relationship between carapace width and fecundity (Prager et al. 1990, Darsono 1992, Ealy 2001, Pereira et al. 2009, Graham et al. 2012) and carapace width and clutch volume (Darnell et al. 2009 and 2010) have been well documented.

Early studies suggested that blue crabs only produced one to six broods (Churchill 1919, Truitt 1939, Van Engel 1958, Tagatz 1968b). New studies suggest that females may produce up to eight broods in a spawning season, with potential for 18 broods during their lifespan (Hines et al. 2003, Dickinson et al. 2006). Ealy (2001) suggested primiparous (first brood) females were less fecund than multiparous (second and successive broods) crabs; however, Graham et al. (2012) did not find a statistical difference between fecundity for primiparous and multiparous crabs. Research on clutch volume, an alternative measure of fecundity, has been found to decrease with successive egg masses (Dickinson et al. 2006, Darnell et al. 2009 and 2010). In these studies, females producing three or more broods showed a consistent decrease in clutch volume.

Prager et al. (1990) found that fecundity varied within and between years, but did not vary significantly over the course of embryonic development for *C. sapidus* in the Chesapeake Bay region. Ovigerous blue crabs have been found to commit egg mass mutilation when captured in crab traps (Dickinson et al. 2006, Darnell et al. 2010). Graham et al. (2012) found 30% brood loss in primiparous females, compared to 3% loss of eggs with multiparous crabs.

Hines (1982) noted that *Callinectes sapidus* had extremely small eggs (251 μm mean ovum diameter), large numbers of eggs per brood, and a high adjusted yearly fecundity. Egg size increases throughout embryonic development for the blue crab (Davis 1965, Amsler and George 1984, Jacobs et al. 2003). Seasonal differences in egg size in *C. sapidus* were noted by Jacobs et al. (2003); spring eggs were 6% larger than summer eggs. Graham et al. (2012) found similar results, with spring eggs 9.9% larger than summer/fall eggs. This study also found an egg diameter positive relationship between egg diameter and maternal size and an inverse relationship between fecundity and egg diameter. Other studies found that egg diameter was not correlated to carapace width or clutch number for *C. sapidus* (Darnell et al. 2009 and 2010).

3.6 Migration and Transport

3.6.1 Migration Studies

Blue crabs are migrants that occupy various estuarine and nearshore habitats, according to the physiological requirements of each life cycle stage. After a period of larval development in high salinity offshore waters, the megalopae recruit to estuarine waters. Molt to the first crab stage takes place in the estuary with early crab stages (5-10 mm CW) found in shallow areas of low to intermediate salinity. Juvenile crabs remain in the upper and middle estuary where growth, maturation, and mating take place. Following mating, female crabs move to more saline waters to spawn while males tend to remain in brackish waters. Jaworski (1972), through observations of commercial fishing activity, identified five migration patterns in the Barataria estuary that are probably applicable to other Louisiana estuaries: 1) spring up-estuary migration of large juveniles and adult males; 2) recruitment of small juveniles to the upper estuary; 3) return of spawned females from offshore to the lower estuary in the summer; 4) upper-to-lower estuary and offshore migration of gravid females in autumn (the fall run of females); and 5) down-estuary migration of large juveniles and adult males from the upper estuary in November and December. Similar migration patterns in which movements appear to be related to phases of the life cycle have been reported by Cronin (1954), Van Engel (1958), Darnell (1959), Tagatz (1968b), More (1969), Judy and Dudley (1970), Perry (1975), and Eldridge and Waltz (1977).

Tagging studies in the Gulf include those of More (1969), Perry (1975), Oesterling and Evink (1977), and Steele (1987). Migrational patterns observed by More (1969) and Perry (1975) were typical of the onshore/offshore movements as characterized in previous studies (Fiedler 1930, Van Engel 1958, Fischler and Walburg 1962, Tagatz 1968b, Judy and Dudley 1970, Benefield and Linton 1990).

Perry (1975) tagged and released 1,023 adult blue crabs (155 males, 868 females) in the fall in Lake Borgne, Louisiana, and Mississippi Sound. Total recoveries numbered 304 (29.7% return), of which 69 were males and 235 were females. Ninety-two percent of females and 81% of males were recovered in Mississippi Sound northeast of release sites. Recovered crabs traveled from two to 38 mi, with recapture times ranging from four to 261 days. Results confirmed Darnell's (1959) theory that female crabs leave the low salinity waters of lakes Pontchartrain and Borgne in Louisiana to overwinter in high salinity waters of Mississippi Sound as water temperatures decrease. During the spring and summer, Perry (1975) tagged and released adult crabs in the estuaries adjoining Mississippi Sound: Biloxi Bay, Bay St. Louis, and Pascagoula River. Recoveries were generally made within 40 days of release. Movements appeared to be random with little movement between adjacent estuaries.

More (1969) studied adult crab movement in Galveston Bay, Texas. About 85% of male and 45% of female crabs were recovered within 3.5 km (2.2 mi) of the release site. Females demonstrated a southward movement to areas of higher salinity, whereas male crabs remained in the brackish areas of the bay. In Trinity Bay, Texas, Benefield and Linton (1990) tagged and released 300 adult blue crabs (249 males, 51 females) during December. Fifty-four crabs (48 males, six females) were recaptured (18% recovery). Crab movement was generally southward. Average distance traveled was 7.9 km (4.9 mi) for males and 19.1 km (11.9 mi) for females. Time to recapture averaged 112 days and ranged from 76 to 144 days.

Blue crab migratory patterns along the west coast of Florida differ from patterns observed in the northern Gulf. Oesterling (1976), Evink (1976), Oesterling and Evink (1977), Oesterling and Adams (1982), and Steele (1987 and 1991) provided evidence of an alongshore movement of females in Florida coastal waters. In their studies, females moved to sites north of their mating estuary. Oesterling (1976) tagged and released 6,287 blue crabs (51.4% males, 48.6% females) from September through March. The overall return rate was 10.7%, of which 51% were females and 48% were males. Females traveled the greatest distance. While 95% of recaptured males were found within 17.7 km (10.6 mi) of the release site, approximately 25% of recaptured females moved >48.3 km (30.2 mi), 43% moved >16.1 km (10.1 mi), 4% traveled >322 km (201 mi), and three individuals traveled 494.1 km (306.9 mi) from release sites. All non-local movement of females was in a northerly direction along the west coast of peninsular Florida and westerly along the panhandle, with the majority of returns near Apalachicola Bay. Based on the return data, Oesterling and Evink (1977) characterized the Apalachicola Bay region as a primary spawning area and Oesterling and Adams (1982) suggested that surface circulation patterns associated with the Loop Current and the Apalachicola River may be responsible for transport of blue crab larvae to southwestern Florida, thus providing for blue crab recruitment along the entire Gulf coast of peninsula Florida.

Steele (1991) tagged 13,366 blue crabs in Tampa Bay, Florida, during 1982-1983. As in previous studies, an alongshore, single sex migration of female blue crabs in a northward direction was indicated. The overall return rate was 24.9%. Several crabs traveled >800 km (500 mi) in approximately 100 days. Twenty-nine of the tag returns were recovered >765 km (478 mi) from Tampa Bay. Steele (1991) also conducted a two part tagging program during 1984-1985. In the first segment, crabs (n = 2,767) were tagged in Apalachee Bay; 43% crabs were returned. Only 5% of the crabs were recaptured west of the tagging area suggesting that the low salinity barrier created by the Apalachicola River impedes further westward migration. In the second part of the study, crabs were tagged along the southwest coast of Florida from Key Largo to Sarasota Bay to determine the contribution of various populations to westward migration. Some of these tagged crabs moved northward along the west coast of Florida as far as Apalachee Bay. Crabs tagged at the Key Largo site moved northward along both coasts. Those crabs migrating along the east coast moved as far as Biscayne Bay.

3.6.2 Larval Transport Mechanisms

In GOM estuaries, eggs of the blue crab hatch near offshore barrier islands and are immediately transported to open ocean environments in seaward flowing waters (Perry and Stuck 1982, McClintock et al. 1993). Subsequent development in offshore surface waters as buoyant free-drifting plankton includes seven or, occasionally, eight zoeal stages with an at-sea duration of approximately 30 to 50 days (Costlow and Bookhout 1959, Costlow 1967, Bookhout and Costlow 1975, Sulkin 1978). Toward the end of this planktotrophic phase, metamorphosis to the megalopal stage occurs. Blue crabs recruit to GOM estuaries as megalopae and settle in nearshore habitats (Stuck and Perry 1981, Perry and Stuck 1982, Perry et al. 1995, Morgan et al. 1996).

Johnson and Perry (1999) traced the at-sea stage of hypothetical larvae spawned in the Mississippi Bight with a climatologically driven numerical model. They noted that seasonality of spawning coincided with climatological inner shelf circulation patterns that transport zoeae offshore initially but then act to retain the larvae within the Mississippi Bight and to bring them back to shore at the appropriate stage. Circulation in the Mississippi Bight follows seasonal wind patterns. There is a general surface drift toward the west within the Bight for most of the year, countered by light eastward winds during summer, but reversing to westward in early fall. Optimal retention of planktotrophic larvae within the Bight would occur during spring and summer, a time period coincident with spawning peaks of *C. sapidus* in the northern GOM (Perry et al. 1995, Rabalais et al. 1995, Morgan et al. 1996). Model results clearly demonstrated that a window of opportunity occurred between April and October for a successful planktonic stage. Since the principal spawning and recruitment activities fall within this window, they hypothesized that wind driven advection was a principal contributor to larval success or failure.

Perry et al. (2003) tested this hypothesis using megalopal settlement data for Mississippi. The authors found that “eastward wind stress during July and August, and westward wind stress during September and October produced the highest correlation with settlement, thus supporting the concept of retention in the Mississippi Bight against the ambient westward flow around Apalachicola during mid-summer spawning and a return to the estuaries during late summer."

Data on larval transport of red snapper (*Lutjanus campechanus*) also found limited eastward movement of larvae around the Cape San Blas/Apalachicola peninsula. Johnson et al. (2009) examined transport of red snapper larvae in the northern GOM using advective current fields developed from drifter and moored currents (22 year database) augmented by an operational nowcast/forecast model of the GOM (Choi and Kantha 1997). They examined transport pathways across topographic impediments (Mississippi River delta, DeSoto Canyon, and Cape San Blas/Apalachicola peninsula) and found that the largest impediment to eastward flux of larvae from the central and western GOM was the Cape San Blas/Apalachicola peninsula. While eastward transport of larvae during summer months occurred, it was limited and diverted southward into deep water on the outer continental shelf. They noted "efforts to find a pathway from west to east indicated that the majority of eastward flow was directed outward along the West Florida outer continental shelf rather than around the Apalachicola peninsula into the Big Bend area." The authors observed that the potential for limited transport of larvae across these impediments suggests separate management of eastern and western populations may be warranted.

3.7 Mortality

3.7.1 Biotic Factors

3.7.1.1 Predation

Blue crab populations in the GOM are regulated by post-settlement biotic processes that affect juvenile survival. Predation-induced juvenile mortality in the GOM is extremely high and a primary determinant of population size (Heck and Coen 1995). Heck and Coen (1995) observed predation rates of 80% per day on early crab stages in Alabama estuaries and noted that although megalopal numbers in the Gulf greatly exceeded numbers in Atlantic Coast estuaries, higher predation rates in the Gulf resulted in similar juvenile abundances. They attributed the predation rate to a large and diverse suite of predators, fewer predation-free refuges, and year round predation activity (i.e., a lack of seasonality in predation). Intraspecific predation also contributes to mortality. Blue crabs are highly cannibalistic, and in some size classes, blue crabs make up as much as 13% of larger crabs diets (Darnell 1958, Tagatz 1968b, Laughlin 1979). Peery (1989) suggested that the potential of larger crabs to cannibalize juveniles is great enough to produce strong density-dependent regulation of juveniles. Predation on blue crab zoeae and megalopae is largely unknown because remains of early stage brachyurans in fish stomachs are seldom identified other than as "crab zoea," "brachyuran zoea," or "megalopae" (Van Engel 1987). Larval blue crabs are fed upon by other plankters, fish, jellyfish, and comb jellies (Van Engel 1958).

3.7.1.2 Parasites/Disease

Heavy parasite loads and disease have the potential to reduce the survival of blue crabs at all life stages and can significantly impact their population dynamics. Although mass mortalities have been associated with disease and may contribute to periodic fluctuations in population levels, most outbreaks are seasonal, localized and relatively short-lived (Couch and Martin 1982, Bonami and Zhang 2011, Shields and Overstreet 2007, Newman and Ward 1973).

There are a significant number of viruses found in blue crabs, some of which have been associated with mortality. A reo-like virus (RLV), also known as CsRV (Tang and Lightner 2011), was associated with significant mortality in soft shell crab culture systems on the Atlantic coast and at least one soft shell system in the GOM (Bowers et al. 2010).

The barnacle, *Loxothylacus texanus*, is a true parasite of blue crabs in the GOM. The influence of this barnacle on blue crab stocks is of particular concern due to the stunting effect it has on its host. Rhizocephalan parasites interfer with molting resulting in reduced growth or cessation of growth in the infected crab (Overstreet 1978, Overstreet et al. 1983, Høeg, 1995). Shields (2012) reported infection rates of 30-70% in blue crabs from estuaries in the GOM.

The highly pathogenic amoeba, *Paramoeba perniciosa*, is responsible for outbreaks of gray crab disease with mass mortalities of blue crabs occurring in South Carolina, North Carolina, and Georgia in June 1966 and in South Carolina and Georgia in June 1967. While the pathogenic amoeba (*P. perniciosa*) was alluded to as a possible cause of the mortalities, there was some implication that pesticides may have been involved. According to Newman and Ward (1973), blue crab mortalities of greater and lesser magnitude have occurred during May and June along the Atlantic Coast with *Paramoeba* involved in the majority of the kills that were investigated. *Paramoeba perniciosa* has not been detected in samples of blue crabs from the GOM (Messick 2002).

Hematodinium sp., a dinoflagellate found predominantly in the hemolymph, has been identified from *C. sapidus* from the GOM (Couch and Martin 1982, Messick and Shields 2000). The disease exhibits no external signs although infected crabs are weak and lethargic. A study by Messick and Shields (2000) found a moderate to high prevalence of the disease along the Atlantic and GOM coasts. In Georgia, a local collapse of the blue crab fishery was associated with *Hematodinium* in 1999/2000 (Frischer et al. 2006).

Heavy infestations of ectocommensal ciliate protozoans have been implicated in mortalities of blue crabs held in confinement. Couch (1966) identified peritrichous ciliates of the genera *Lagenophrys* and *Epistylis* from gill lamellae of blue crabs from Chincoteague and Chesapeake bays. He suggested that severe infestations of these epibionts may interfere with respiration and contribute to mortality of crabs in holding or shedding tanks. Couch and Martin (1982) reported that the prevalence and intensity of infestation of *Lagenophrys callinectes* in natural populations of *C. sapidus* in Chincoteague Bay increased through the spring and summer peaked in August. They noted that this ciliate may seasonally affect the survival of blue crabs, particularly at times when oxygen tension in the water is low. The parasitic scuticociliate, *Mesanophrys chesapeakensis*, has been associated with mortalities in the Chesapeake Bay (Messick and Small 1996). A more lethal parasitic scuticociliate, *Orchitophyra stellarum*, was recently discovered in blue crabs being held in outdoor enclosures in Virginia (Small et al. 2011). Ciliate protozoan infestations appear to be more prevalent along the Atlantic Coast.

Several species of *Vibrio* have been identified from blue crabs. Davis and Sizemore (1982) isolated bacteria taxonomically identical to *V. cholerae*, *V. vulnificus,* and *V. parahaemolyticus* from blue crabs collected in Galveston Bay, Texas. Species of *Vibrio* were the predominant bacterial types in the hemolymph occurring in 50% of the crabs sampled in the summer. *Vibrio cholerae* and *V. vulnificus* were isolated from 3.5% and 9.0% of the crabs, respectively, with *V. parahaemolyticus* occurring in 30% of the study organisms. *Vibrio parahaemolyticus* has caused mortalities in blue crabs and food poisoning symptoms in humans eating contaminated crabs (Overstreet 1978).

Synopses of the parasites and pathogens of blue crabs have been provided by several authors over the past three decades: Couch and Martin (1982); Couch (1983); Johnson (1983); Overstreet (1983); Brock and Lightner (1990); Meyers (1990); Messick and Sinderman (1992); Bradbury (1994); Messick (1998); Noga et al. (2000); Shields and Overstreet (2007); Wang (2011); Bonami and Zhang (2011).

3.7.2 Abiotic Factors

A wide variety of abiotic variables affect blue crab populations. The diversity of these parameters and their possible synergistic effects make precise identification of the influence of specific variables difficult. Additionally, the effect of variables such as salinity may be intrinsic (physiological) and/or extrinsic (affecting the composition of the biotic environment). Mortalities associated with chemical and biological pollutants, sediment, temperature, salinity, and dissolved oxygen were discussed by Van Engel (1982). Millikin and Williams (1984) provided a review of chemical toxicity of organic compounds and inorganic contaminants on life history stages of the blue crab.

3.7.2.1 Temperature/Salinity

Costlow (1967) emphasized that survival and rate of megalopal development were highly variable under different conditions of temperature and salinity. Megalopal development was most rapid (5-11 days) at 30°C in salinities from 10-40‰. Duration of the megalopal stage was prolonged from 30-67 days at salinities ≥20‰ at a temperature of 15°C. Costlow (1967) concluded that survival and duration of the megalopal stage were directly associated with: 1) the time of hatching, 2) the time at which the megalopal stage is reached in relation to seasonal changes in water temperature, and 3) the salinity of the water when the final zoeal molt occurs.

Temperature/salinity tolerance limits of blue crabs have been reported by Tagatz (1969), Mahood et al. (1970), and Holland et al. (1971). Both Tagatz (1969) and Holland et al. (1971) found that blue crabs were less tolerant to temperature extremes at lower salinities. A temperature-salinity tolerance zone was constructed by Mahood et al. (1970) for adult blue crabs using 96-hour total lethal mortality (TL_m) values. Crabs were acclimated to 20°C. At 0°C, there was no survival at any salinity. At 8.6‰ the tolerance zone extended from 3.2°-22°C, and at 36‰, it extended from 18.5°-35.2°C. The greatest tolerance zone extended over 27°C at a salinity of 24.2‰. Tagatz (1969) evaluated maximum and minimum median thermal tolerance limits of juvenile and adult blue crabs acclimated at 7‰ or 35‰ in temperatures of 6°, 14°, 22°, or 30°C. At both low and high salinities, the upper and lower thermal tolerance limits increased as acclimation temperature increased. Tolerance limits for adults and juveniles were similar. Blue crab mortalities in nature have been related to extreme cold or to sudden drops in temperature (Gunter and Hildebrand 1951, Van Engel 1982, Couch and Martin 1982).

3.7.2.2 Pollutants

The dissolved phases of cadmium and mercury, methoxychlor, malathion, Mirex, Kepone, juvenile hormone mimic (MONO-585), and insect growth regulator (Dimilin) have been found to be toxic to blue crab larvae and a review of these contaminants can be found in Millikin and Williams (1984). One of the most serious instances of chemical pollution affecting the blue crab fishery occurred in Virginia and was associated with the release of the chlorinated hydrocarbon Kepone into the James River from the 1950s to late 1975. The annual mortality of young and adult blue crabs due to exposure to Kepone remains unknown; however, both commercial landings and juvenile crab abundance have been lower in the James River than in the York or Rappahannock rivers for the past 15 years (Van Engel 1982). Lowe et al. (1971) reported Mirex, a compound closely related to Kepone, to be toxic to blue crabs either as a contact or stomach poison. Mirex accumulation in blue crabs and their sensitivity to this compound have been documented (Williams and Duke 1979). In a cooperative study among the states of North Carolina, South Carolina, Georgia, and Florida, Mahood et al. (1970) found 35% of the crabs collected contained detectable levels of Mirex. McHugh (1966) speculated that the ban on DDT and other chlorinated hydrocarbons resulted in the recovery of the blue crab resource in New York in the late 1970s. High mortality rates of blue crabs near Alligator Harbor, Florida, in November and December of 1973 were attributed to reduced temperatures (<18°C) and high body burdens of DDT (Koenig et al. 1976).

Oil pollution of oceanic and nearshore waters occurs naturally with one-third to one-half of the oil coming from seeps (Farrington and McDowell 2013). Long-term effects of oil exposure can alter the physiology and ecology of populations; however, there have been few studies on the cumulative effect of chronic inputs of oil into the marine ecosystem (Farrington and McDowell 2013). Catastrophic spills can devastate the environment with the impact dependent upon the type and toxicity of the oil involved, duration of the spill, species and life history stage present, and environmental conditions at the time of the spill (Cooper and Cristini 1994). Acute effects occur quickly and are usually associated with intake of elevated levels of water-soluble components and physical clogging and morphological damage to gills or lungs. The largest release of crude oil in history occurred in the north-central GOM between 20 April and 15 July, 2010. The Deepwater Horizon (DWH) disaster was unprecedented due to the amount of oil released and depth of occurrence.

Anderson (2010) reviewed routes of exposure. Blue crabs can be exposed directly to the oil or they can ingest it from contaminated plant and animal material they consume. Mortality and toxicity effects are not always immediate. Long-term chronic effects are often decreased survival and can include lowered reproductive success. Oil contaminants that do not result in immediate death may be passed along to offspring resulting in defects in future generations or increased juvenile mortality. Karinen and Rice (1974) found that Tanner crabs, *Chionoecetes bairdi*, exposed to oil suffered reduced molting success and limb autotomy and noted that oil pollution may cause significant biological damage other than immediate death of the affected organisms.

The DWH disaster coincided with the spawning of blue crabs in the northern GOM. During the spring developmental period, ~40% of the blue crab larval grounds were covered with surface oil and dispersant, exposing both zoeae and megalopae to oil and oil-related contaminants. As a result of the spill, megalopal settlement rates in 2010 were investigated through an NSF-funded Rapid Response Grant (Fulford et al. 2013). Total settlement intensity in 2010 was lower than in years preceding 1995 but similar to more recent years for which there are data (Perry et al. 2003). Mean daily settlement appeared to be related to differences in climatic conditions before (wet conditions) and after 1995 (drought conditions) with higher numbers associated with wet years. Patterns of settlement observed in 2010 were more consistent with an impact on the source of larvae rather than on larval mortality alone. A shorter settlement pulse (1-2 days) and a longer inter-settlement period (15-17 days) were noted in 2010 compared to previous years (3-5 days; 7-8 days) and this pattern change suggests an association with the DWH disaster. The data suggest a causal relationship between the oil spill and the settlement pulse/inter-settlement period with settlement patterns in 2010 affected at larval source. This relationship would have impacted periodicity of settlement without necessarily altering pulse intensity. Similar indirect effects were noted as a part of analysis of the collapse of the Pacific herring fishery following the Exxon Valdez Spill in Alaska, USA (Hose et al. 1996, Carls et al. 2002). In that case, direct adult mortality was present but low and it was reduced egg and larval viability that may have interacted with other factors to generate a population level effect. Their findings indicated the possibility for indirect effects on reproductive potential and support further examination of egg viability effects, possibly through impacts on ovigerous females in nearshore waters.

3.7.2.3 Dissolved Oxygen

Anoxic bottom conditions have not been reported for most of the eastern Gulf with the exceptions of local hypoxic events in several bay systems in Florida (Tampa, Sarasota, and Florida bays). Extensive areas (1,650,000 ha) of low bottom oxygen levels (<2 ppm) occur in the Gulf off of Louisiana and Texas during summer (Rabalais et al. 1995, Rabalais et al. 1997). Increased levels of nutrient influx from freshwater sources coupled with high summer water temperatures, strong salinity-based stratification, and periods of reduced mixing appear to contribute to what is now referred to in the popular press as the dead zone, an area approximately 18,200 km^2 located south of Louisiana on the continental shelf (Justic et al. 1993). Blue crabs appear to be moderately susceptible to the low oxygen levels and generally move out of the area when dissolved oxygen levels get too low resulting in displacement rather than mortality.

Trap death due to anoxia is a serious problem in many areas. Tatum (1982) reported that oxygen deficient bottom waters covered as much as 44% of Mobile Bay, Alabama, in the summer of 1971, and blue crab mortalities were commonly associated with this event. Jubilees are natural phenomena that occur annually along the shores of Mobile Bay, Alabama. During a jubilee, massive numbers of crabs, shrimp and demersal fishes push ashore trying to escape low-oxygenated waters. During the summer, large areas of bottom water in Mobile Bay experience oxygen depletion in summer due to salinity stratification and decomposition of accumulated organic material on the bay floor (Loesch 1960). When these low-oxygen water masses are forced against the beach by winds and tides, demersal fishes and crustaceans migrate shoreward. May (1973) reported that 81,000 kg of blue crabs died during an anoxic event along Great Point Clear, Alabama. Smaller jubilees have been reported in Mississippi Sound and are associated with localized blooms of phytoplankton (Gunter and Lyles 1979).

3.7.2.4 Freshwater Inflow

Oceanic atmospheric modes of variability from the Atlantic and Pacific Oceans influence the strength and position of the mid-latitude and subtropical jet streams and Bermuda High and thus determine climatic conditions along the US GOM. The jet streams and Bermuda High are associated with the interaction of dry cold air from the polar region and moist warm air from the Pacific and Atlantic oceans and GOM. The confluence of these distinct air masses generates storm fronts across the continental US affecting the series of watersheds that drain into the northern GOM. The size and location of those watersheds determine the climatic influence that decadal and annual climate factors have on hydrology. The vast basin of the Mississippi River and its distributary, the Atchafalaya River, respond to decadal meteorological and hydrological regimes imposed by the Atlantic and Pacific oscillations. Rivers with basins located entirely within the coastal region respond strongly to inter-annual meteorological and hydrological conditions driven by the equatorial Pacific oscillation (ENSO, El Niño/La Niña events). Climatically, the GOM region is divided into three distinct sub-regions: western, eastern, and central. The western sub-region covers Texas; the central sub-region includes Louisiana, Mississippi and Alabama; and the eastern sub-region includes all of Florida (Twilley et al. 2001). Four major rivers (Mississippi, Atchafalaya, Pearl and Pascagoula Rivers) in Louisiana and Mississippi (central region) discharge more than 90% of fresh water into the GOM (Perret et al. 1971, Eleuterius 1978) and this area is highly influenced by decadal climate regimes. In smaller coastal rivers in the central region, inter-annual ENSO events can be detected and can also be important in determining hydrological response. Coastal river discharge in Texas (western region) is primarily associated with minor influxes of fresh water into coastal areas and inter-annual ENSO events are influential. Coastal river discharge in Florida (eastern region) is also associated with smaller influxes of fresh water into coastal areas making inter-annual ENSO important. Because of the proximity of Florida to the Atlantic Ocean, hydrology also responds to the Atlantic multi-decadal and North Atlantic oscillations.

Current research in the GOM has related juvenile blue crab abundances to the influence of global climate factors on regional hydrology and how it structures habitat (Sanchez-Rubio et al. 2011). Even though physiography, geology, climatology, watershed characteristics, water quality, and population demographics differ among the subregions, the critical driver of blue crab population dynamics in all areas appears to be freshwater inflow.

In the northcentral GOM, climate and hydrology operate to structure available habitat in ways that influence survival of juvenile blue crabs. Sanchez-Rubio et al. (2011) examined decadal (Atlantic Multidecadal Oscillation, Pacific Decadal Oscillation, North Atlantic Oscillation) and annual (ENSO) climate regimes affecting hydrology in the northern GOM and related juvenile blue crab abundances in Louisiana and Mississippi to global climate factors and their effect on regional hydrology. They identified two dominant climate-related hydrological regimes; a wet regime from 1973 -1994 (AMO cold, NOA positive) and a dry regime from 1997 – present (AMO warm, NAO negative). Years of high juvenile abundance occurred during the wet years with years of decreasing abundance occurring during the dry period: declines in numbers in the dry period were significant in both States. Riedel et al. (2010) noted that significant downward trends in the abundance of juvenile blue crabs and other estuarine-dependent species taken in trawls in Alabama and Mississippi have occurred over a period characterized by drought and unprecedented changes in habitat associated with catastrophic storms and the cumulative consequences of man-made alterations to coastal wetlands. For many species (including blue crabs), they noted that recruitment has been adequate and numbers of postlarvae and early juveniles did not exhibit the significant declines evident in the trawl data.

High river flows in northern GOM estuaries have been linked to increased commercial landings of blue crabs in Texas (More 1969) and Florida (Wilber 1992 and 1994). Wilbur (1992 and 1994) correlated 38 years of commercial landings to flows from northwestern Florida rivers (Apalachicola, Suwannee, Econfina, St. Marks and Ochlokonee) and concluded that significant long term spatial and temporal relationships existed between flows and crab productivity in the region. Both commercial landings and abundance of juvenile crabs (<40 mm carapace width [CW]) were related to high river flow in Louisiana (Guillory 2000). Gandy et al. (2010) reviewed the relationships between freshwater inflow and blue crab abundance from Texas to Georgia in a report to the Southwest Florida Water Management District and found statistically positive, negative and mixed correlations between freshwater inflow and blue crab abundance. In general, studies showing positive associations used long term, life history based, lagged inflow regressions applied over large regional data sets to identify significant associations. Negative associations were commonly generated from short term, life history based, lagged inflow regressions applied to data collected within an individual river. Using fishery-independent data from long-term monitoring programs, Sanchez-Rubio et al. (2011) linked abundance of juvenile blue crabs in Louisiana and Mississippi estuaries to hydrological conditions with highest crab densities associated with increased river flow.

Demands on freshwater resources by cities, farms, and industries is expected to continue to increase leaving the Gulf Coast vulnerable to even slight changes in the seasonal or geographic distribution of fresh water (Twilley et al. 2001). Increases in water withdrawals for public use and agriculture have already resulted in declines in groundwater levels in Florida aquifers and groundwater rationing is already being implemented periodically during dry conditions in urban regions of Texas, Alabama, and Florida. Twilley et al. (2001) noted that the increasing drawdown of surface and underground water reservoirs could combine with sea-level rise to increase saltwater contamination of aquifers near the coast and in most of South Florida. They reported that large groundwater withdrawals in the coastal zones of Baldwin and Mobile counties in Alabama, which include the Mobile Bay and Gulf Shores regions, have increased salinity in wells and drinking water supplies taken from the Mississippi River for coastal communities such as New Orleans are frequently threatened by saltwater intrusion caused by a combination of sea-level rise, land subsidence, and periodic low river flows. Changes in the supply and distribution of rainfall could have significant impacts on estuarine productivity and threaten blue crab fishery sustainability.

Table 3.1 Summary of growth studies for blue crabs in the GOM.

	Molt Interval (Days)	Molt Increment	Growth Rate	Data Source	Reference
Field Studies					
MS					
Width-frequency distribution			24-25 mm/mo.	seine & trawl data (July - Jan)	Perry 1975
pubertal molt females		38.5-40.5% increase			Perry, unpublished data
LA					
young crabs			14 mm/mo.		Adkins 1972
crabs >85 mm			15-20 mm/mo.		Adkins 1972
young crabs			16.7 mm/mo.	seine data (June - Sept)	Darnell 1959
TX					
Width-frequency distributions			15.3-18.5 mm/mo.	seine & trawl data	More 1969
Seine data			21.4 mm/mo.	seine data (Feb - Aug)	Hammerschmidt 1982
Trawl data			25.2 mm/mo.	trawl data (Feb - Aug)	Hammerschmidt 1982
AL					
April recruits			19 mm/mo.		Tatum 1980
August recruits			10 mm/mo.		Tatum 1980
December recruits			5 mm/mo.		Tatum 1980
FL					
pubertal molt females		30.2-34.4% increase			Tagatz 1968b
Aquaculture					
MS					
Grow-out (early juvenile)			16.5 mm/mo.	Tanks	GCRL unpublished data
Grow-out (late juvenile – adult)			20.2 mm/mo.	Ponds	GCRL unpublished data
FL					
Pond					
Male growth rate from 15 mm to 127mm (legal size)			12.4 mm/mo.	Ponds with wild cohort	Crowley (2012.)
Female growth rate from 15 mm to 127mm (legal size)			12.7 mm/mo.	Ponds wild cohort	Crowley (2012.)
Laboratory Studies					
Temperature					
15℃	25.5-61.0	15.95-21.55%	7.0 mm/mo.	Controlled experiment	Leffler 1972
20℃	17.3-40.7	19.66-39.54%	7.82 mm/mo.	Controlled experiment	Leffler 1972
27℃	11.7-29.5	13.49-27.08%	11.3 mm/mo.	Controlled experiment	Leffler 1972

34℃	7.4-18.6	13.31-23.35%	14.8 mm/mo.	Controlled experiment	Leffler 1972
16℃		GPM*, 118.1%		Controlled experiment	Brylawski and Miller 2006
20℃		GPM, 121.4%		Controlled experiment	Brylawski and Miller 2006
24℃		GPM, 116.1%		Controlled experiment	Brylawski and Miller 2006
28℃		GPM, 121.8%		Controlled experiment	Brylawski and Miller 2006
Salinity					
5 ppt			0.24 mm/day	Controlled experiment	Cházaro-Olvera and Peterson 2004
5 ppt Female			0.24 mm/day	Controlled experiment	Cházaro-Olvera and Peterson 2004
15 ppt Male			0.35 mm/day	Controlled experiment	Cházaro-Olvera and Peterson 2004
15 ppt Female			0.33 mm/day	Controlled experiment	Cházaro-Olvera and Peterson 2004
25 ppt Male			0.38 mm/day	Controlled experiment	Cházaro-Olvera and Peterson 2004
25 ppt Female			0.44 mm/day	Controlled experiment	Cházaro-Olvera and Peterson 2004

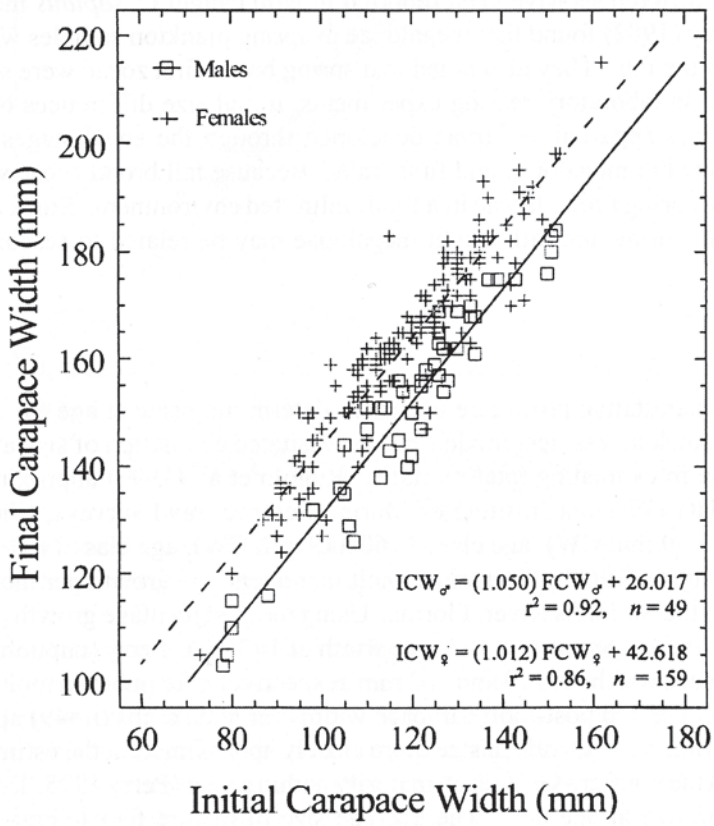

Figure 3.1 Post-molt gain in carapace width for similar-sized male and pubertal molt female blue crabs in Mississippi (Perry unpublished data).

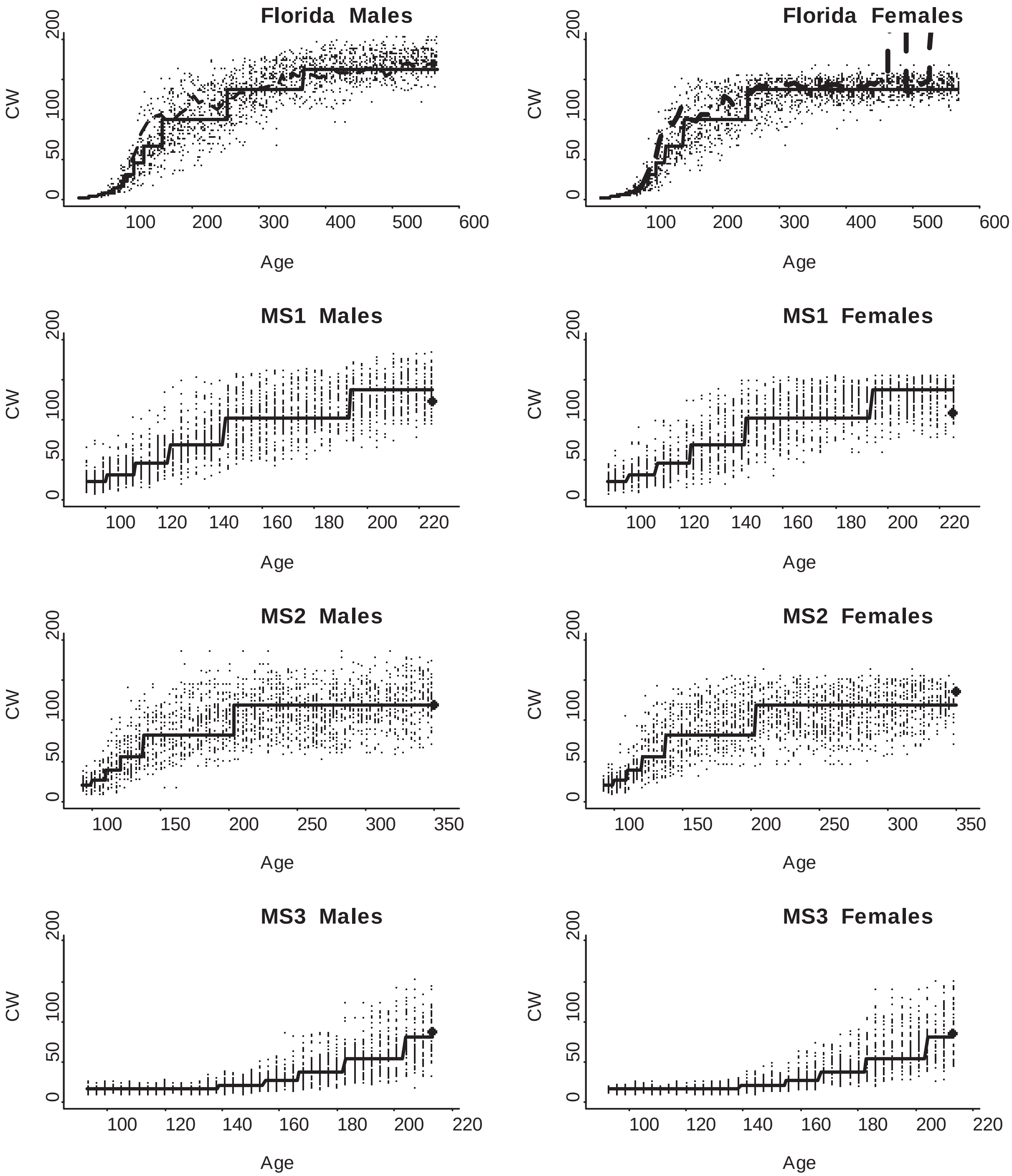

Figure 3.2 Estimated size-at-ages per sex for the temperature-dependent molt-process growth model, fit to aquaculture studies from Florida (one pond) and Mississippi (seven ponds, MS1-MS7). The solid line represents the expected size-at-age (i.e., no stochastic variability in growth parameters), while the dots represent the expected size-at-age for a sample of individuals with stochastic variability in their growth parameters. The dotted line for Florida is the observed mean size-at-age (weekly throughout time period), and the large points for Mississippi are the

observed mean size-at-age at the termination of each pond experiment.

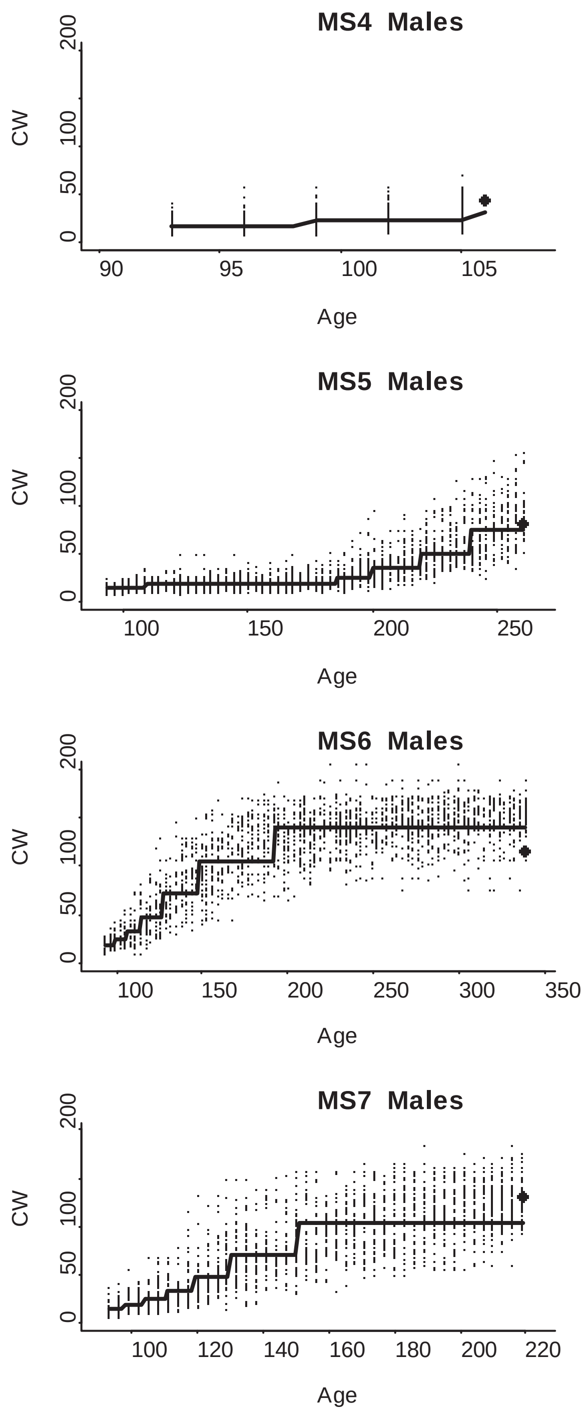

Figure 3.2 continued.

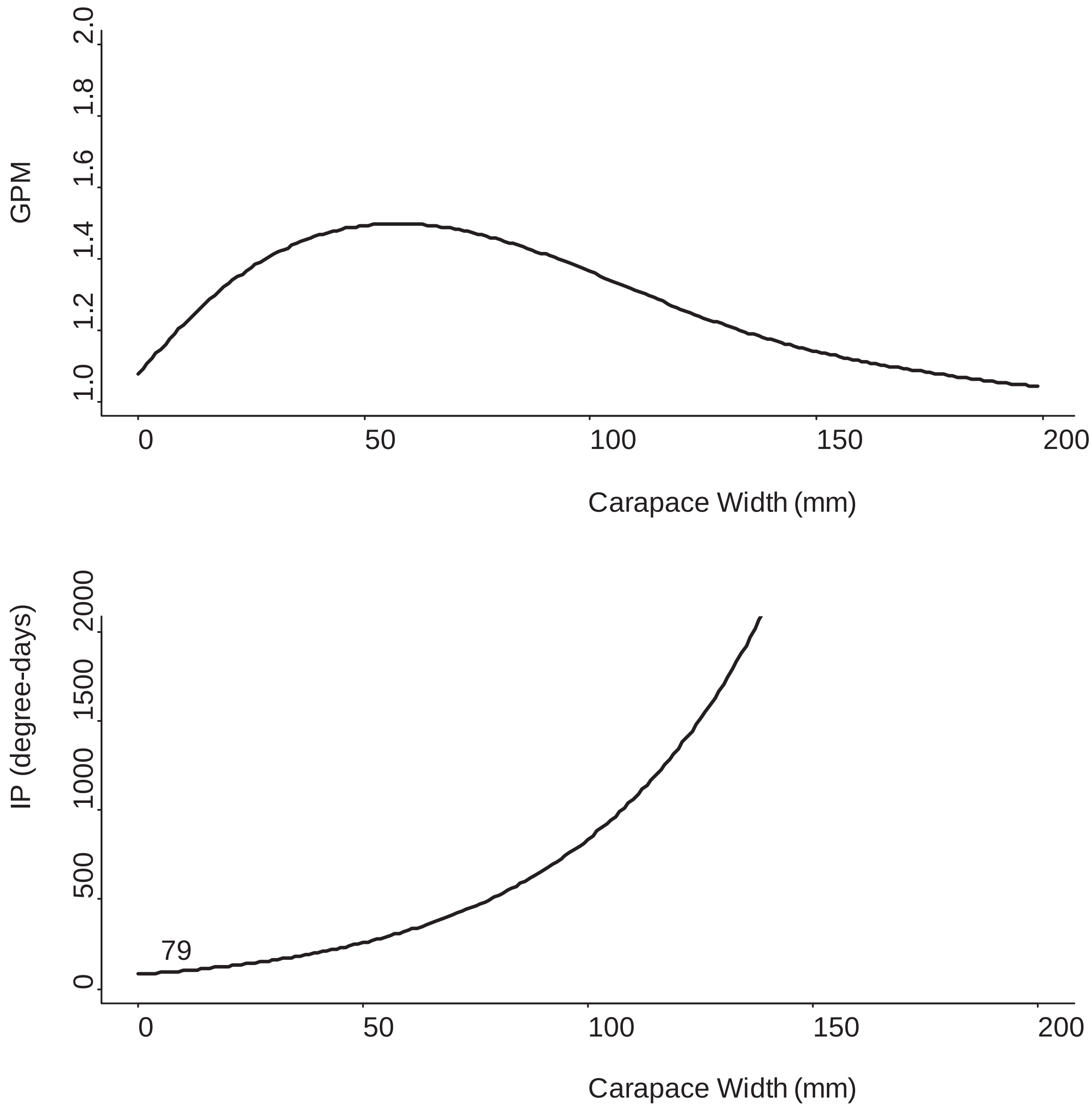

Figure 3.3 Estimated growth per molt (GPM) and intermolt period as a function of size from the temperature-dependent molt-process model.

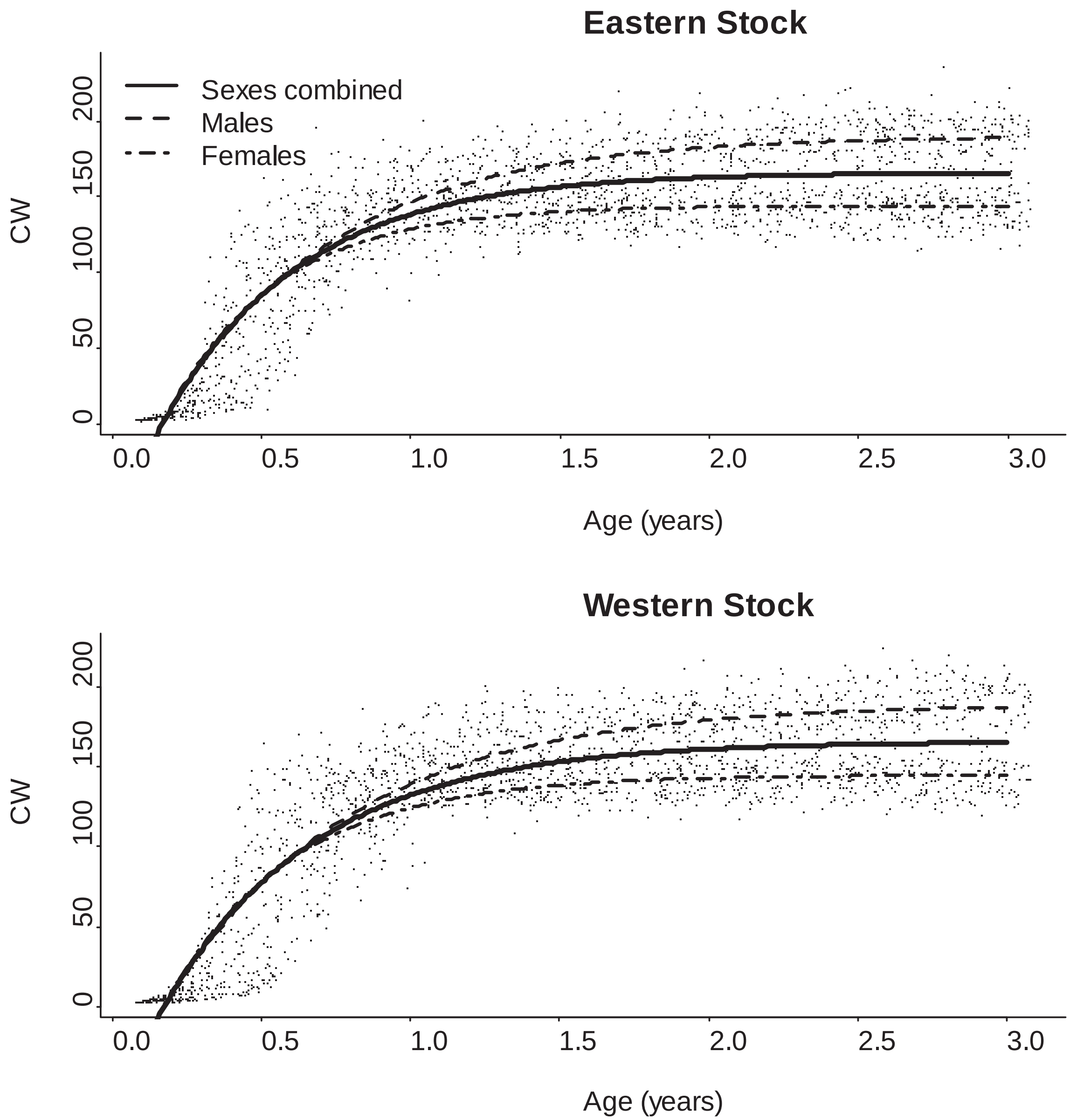

Figure 3.4 von Bertalanffy growth model fits to simulated size-at-age data from the individual-based molt-process growth model, using virtual individuals spawned throughout the entire spawning season (note: only a small sample of the virtual individuals used for the model fits are shown).

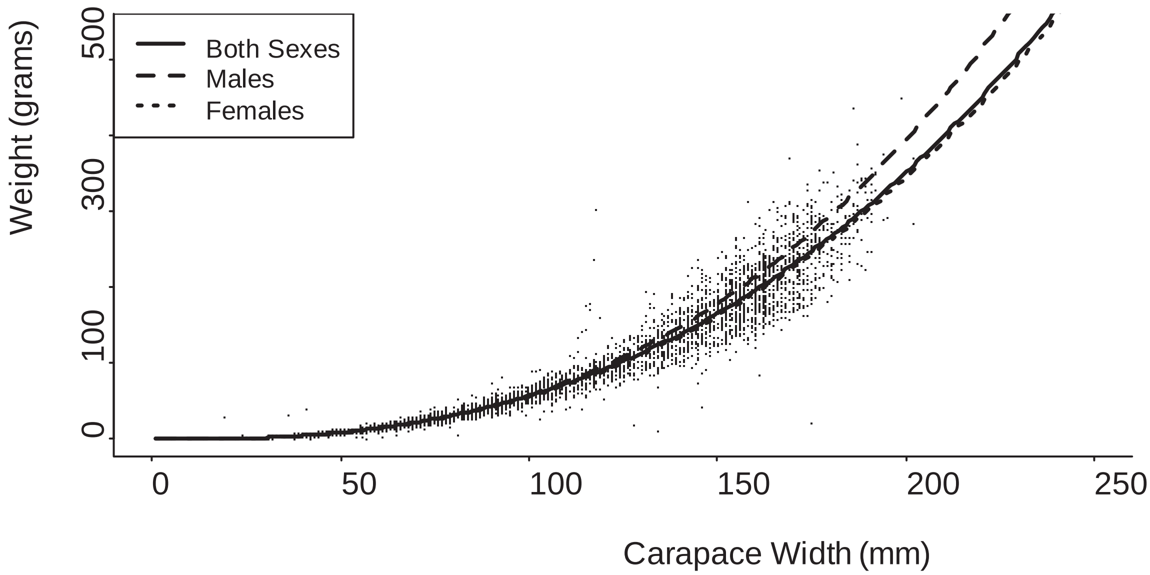

Figure 3.5 Carapace width-weight relationship for blue crabs from fishery-independent sampling in Mississippi (1973-2011).

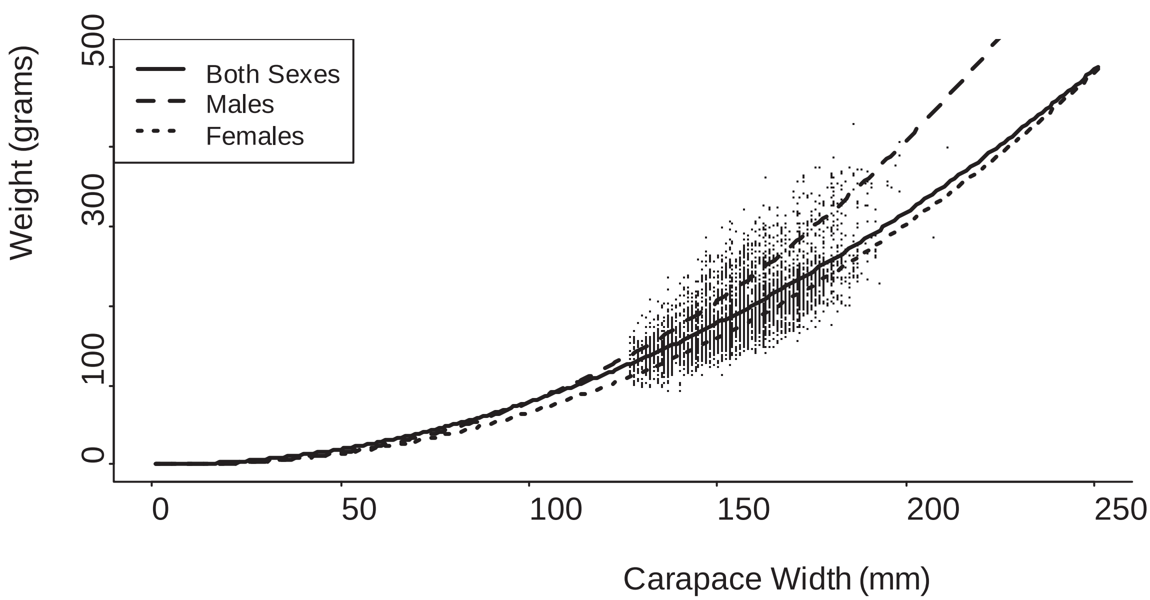

Figure 3.6. Carapace width-weight relationship for legal size (> 127 mm) blue crabs from fishery-dependent sampling in Mississippi (2007-2011).

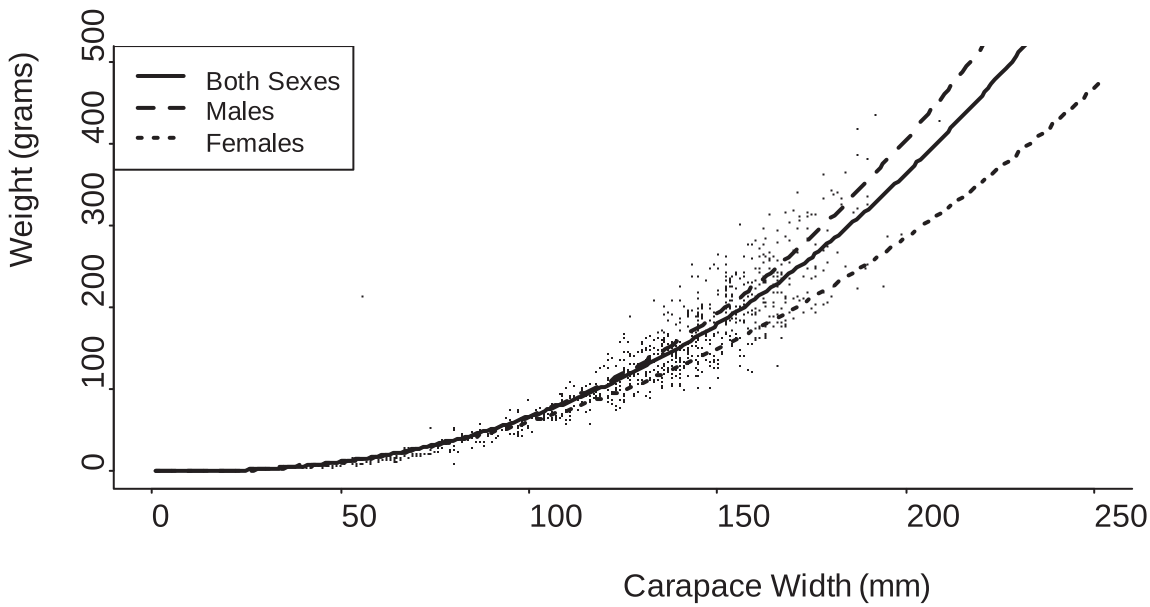

Figure 3.7. Carapace width-weight relationship for legal size (> 127 mm) blue crabs from fishery-independent sampling in Florida.

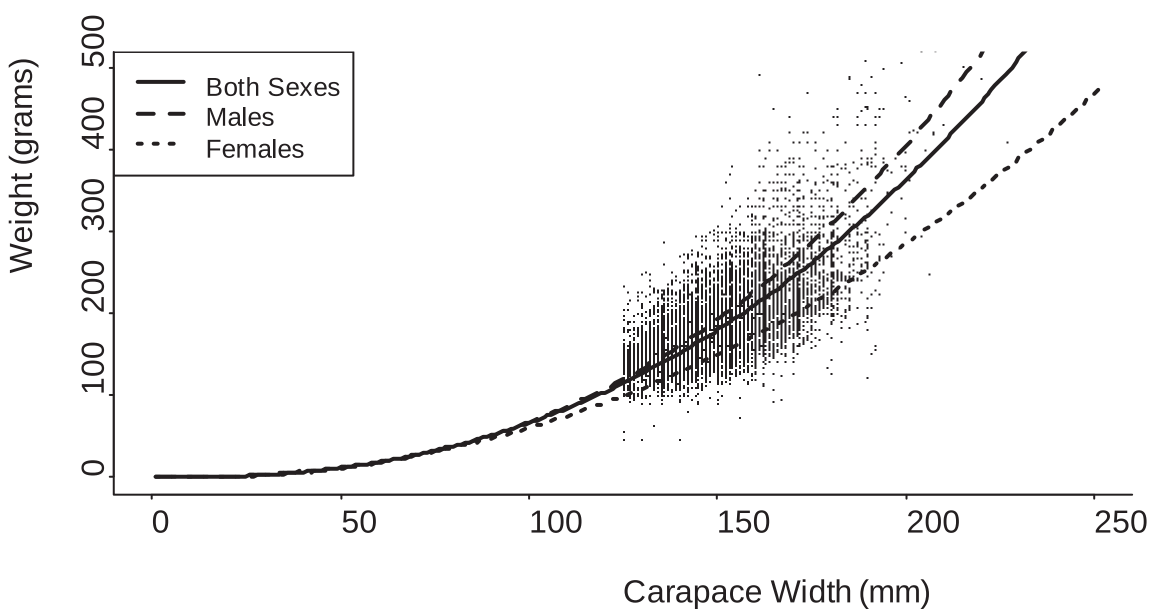

Figure 3.8. Carapace width-weight relationship for legal size (> 127 mm) blue crabs from fishery-dependent sampling in Florida.

4.0 Fishery Dependent Data Sources

4.1 Western GOM Stock

4.1.1 Commercial Blue Crab Fishery

The Western GOM commercial blue crab fishery, as defined in this assessment, is centered on the Mississippi Delta with the vast majority of landings coming from Louisiana (83% based on average landings from 1985 to 2011) and smaller contributions from Mississippi 1%, Texas 11%, and Alabama 5%.

4.1.1.1 Overview of the Fishery

During the 1950s and 1960s the Gulf-wide fishery gradually evolved from a trotline to trotline-drop net to a trap dominated fishery (Figure 1.1). Trotline landings comprised 95.9% of all landings in 1950 and at least 75% of the total through 1955 but then began a gradual decline until landings from this gear accounted for <0.1% during the early 1980s; trotline landings were not recorded after 1984. Although used only in Louisiana, drop nets averaged 6.9% of annual Gulf landings from 1954 to 1965 with a peak of 12.7% in 1956. Drop net landings gradually declined and were last recorded in 1972. The introduction and widespread adoption of the crab trap had a pronounced effect on the commercial fishery (Steele and Perry 1990). The NMFS statistics show that crab traps were used in Louisiana and Texas as early as 1948. From the late 1970s through the 1990s trap landings contributed 98%-99% of total landings. Reported landings of blue crabs taken in trawls have fluctuated widely. Although directed trawl fisheries exist, the fishing is seasonal and related to economic conditions in other fisheries. Trawl landings were highest in the 1960s and early 1970s, averaging 3.8% of the total; for the 1985-1994 period trawl landings comprised <1% of the total. Trawl landings declined steadily since the early 1990s as states imposed greater restrictions on bycatch in the shrimp fishery. Trap landings since 2000 have provided over 99% of the total Gulf landings for the states that identify contributions by gear.

4.1.1.2 Data Collection Methods

4.1.1.2.1 Development of Historical Commercial Landings (1880-1950)

Commercial landing statistics were first collected by the U.S. Fish Commission and Bureau of Commercial Fisheries in 1880, although prior to 1948 the data were not continuous (Table 1.1). The Bureau later became the National Marine Fisheries Service (NMFS). Additional commercial fisheries landings data were collected during surveys by a limited number of states and years between 1880 and 1951.

4.1.1.2.2 Commercial Catch Statistics from Historical Reports (1951-2011)

The NMFS has conducted comprehensive surveys of all coastal states commercial fisheries landings since 1951 (Table 4.1 and Figure 4.1). Data from various annual reports (Fishery

Industries of the United States 1920-1939, Fishery Statistics of the United States 1939-2010) are summarized for the entire historical fishery (1880-2011).

4.1.1.2.3 Commercial Trip Tickets (1984-2011)

Louisiana initiated its trip ticket program in 1999 for all commercial landings including freshwater species. Alabama started its program in 2001 and Mississippi began in 2003 for oysters only and has expanded to fin-fish and bait shrimp in 2005. Presently, they are working on implementation for all commercial species including blue crabs. Texas launched its program for all species in 2007.

In the last decade, NMFS receives monthly landings data directly from the states using the trip reported weights and values by vessel of landed product by fishermen and dealers (Figure 4.2). The trip ticket program requires seafood dealers and fishermen to report their landings by species as well as other data such as fishing effort (# trips) and area fished and has become the standard method throughout the nation for collecting marine commercial landings data.

4.1.1.3 Nominal Landings

4.1.1.3.1 Alabama

Hard crab landings remained below one million lbs until 1940. The early increases in production were probably associated with the development of improved transport systems. Landings ranged from 0.6 to 2.4 million lbs during the 1940s through the 1970s. Landings peaked in 1984 at 4.2 million lbs. The sharp increase in production during the 1980s was attributed to an increase in processing capacity due to an influx of Southeast Asians into south Alabama. During the 1990s average annual hard crab landings were around 3,129,000 lbs, which decreased to an average of around 2,322,000 per year since 2000 (Table 4.1).

The soft crab fishery is minimal and is based upon commercial hard crab fishermen shedding their own crabs. Annual soft crab production was less than 500 lbs prior to the 1990s. After 1990 soft crab production has been sporadic with less than 20,000 lbs total reported through 2011 and production occurring in only six years within the last two decades.

4.1.1.3.2 Louisiana

Landings of hard crabs increased gradually but erratically through the early 1980s from the late 1960s average of 11.6 million lbs. A sharp increase was documented in the mid 1980s when landings averaged 39.4 million lbs from 1984 through 1988 when several records were attained. Landings stabilized by 1988, and relatively low landings were documented in 1989, 1990, 1994 and 1995. Landings averaged 43.5 million lbs during the 1990s. Landings still averaged 45.3 million lbs from 2000-2010 although there were two years with poor landings (Table 4.1). Physical infrastructure and the commercial fleet were negatively impacted in 2005 by hurricanes Katrina and Rita and in 2008 by hurricanes Ike and Gustav; fishing effort and landings were subsequently suppressed. In 2010, the Deepwater Horizon oil spill occurred, and landings were well below average.

Soft crab production varied between 350,000 and 605,000 lbs during the 1950s, peaked at 620,000 lbs in 1961, and then declined to a low of 75,000 lbs in 1984. Production increased after 1984 with more than 200,000 lbs reported from 1990-1992. Annual production was 100,000 lbs or less from 1993 to 1997. Beginning in 1998, soft crab production doubled each year until the year 2000 when production increased to 601,515 lbs. The soft crab production from 1999 to 2005 equaled that during the late 1950s and early 1960s. Several estimates of the number of Louisiana soft crab shedders exist. Manthe (1985) estimated that there were 425 in 1985, and Caffey et al. (1993) estimated that there were from 228-300 in 1991. A total of 185 shedder's licenses were sold by the LDWF in 1996 but that number declined to 81 in 2006; a shedder’s license was replaced by a wholesale/retail seafood dealer license after 2006. High production in the 1950s and 1960s was due to better water quality in the upper estuaries as well as use of “bush lines” by peeler fishermen. A steady decline in soft crab production occurred until 1985 when better shedding systems were developed resulting in increased production. The increase in soft crab production after 1998 was likely due to the implementation and accuracy of the trip ticket system.

4.1.1.3.3 Mississippi

With the exception of the post World War II period when over 5 million lbs were landed, hard crab landings were stable and generally fluctuated between one to two million lbs until 1987. From 1970 to 1989 landings averaged 1,546,000 lbs. Reported landings declined in 1988 and continued to decrease; harvest during the 1990s averaged 397,400 lbs. Reduced landings were attributed to social, economic, and regulatory changes that have taken place in the fishery and not to major declines in stock abundance.

Blue crab commercial landings in Mississippi have fluctuated considerably from 2001 to 2011, ranging from 433,656 lbs in 2001 to 1,112,000 lbs in 2006 (Table 4.1). Events occurring during this period that have contributed to the variation include Hurricane Katrina in 2005, opening of the Bonne Carre Spillway in 2008 and 2011, and 2010 Deepwater Horizon oil spill and resulting precautionary fishery closures. Highest landings occur May through August, with the peak in July averaging 87,273 for the last ten years (excluding 2010 due to precautionary fishery closures). All other months for this period averaged 50,000 to 60,000 lbs, with the exception of March, which averaged only 34,270 lbs. A loss of seafood industry infrastructure is evident following Hurricane Katrina and it is estimated that a considerable portion of Mississippi blue crabs are sold to out-of-state dealers and processors.

The soft crab fishery is a small cottage-type industry and is based upon commercial hard crab fishermen shedding their own crabs. Annual soft crab production averaged less than 2,000 lbs prior to and during the 1990s. NOAA reported less than 5,000 soft crab lbs produced in Mississippi from 2000 through 2003, the last year soft crab numbers are documented for the state.

4.1.1.3.4 Texas

Total blue crab landings have roughly followed a parabolic shaped trend since the early 1950's, steadily increasing along with increased fishing effort before reaching a maximum of 11.7 million pounds in 1998. After this time landings began to decline, dropping to an all time low of 1.9 million pounds in 2006. After reaching this low point, landings begin to recover slightly pushing them back to the 2.5 to 3.5 million pound per annum range from 2007 through to 2011 (Table 4.1). Peak landings in 1987 correspond to the relatively high number of fishermen (317) operating in Texas that year. There are no data available on soft shell crab fishery landings in Texas.

4.1.1.4 Nominal Fishing Effort

4.1.1.4.1 Alabama

The number of trap fishermen according to NMFS data increased steadily from 1976 to a peak of 221 in 1989; thereafter, the number of fishermen declined to a low of 150 in 1995. The number of traps per fisherman averaged near 150 until the 1980s when the average peaked at approximately 350. The number of traps per fishermen decreased gradually to 250 in 1993. Catch per trap declined from 1980 to the early 1990s. In the last decade, the average number of resident commercial trap fishermen has been 196, with the low in 2006 of 120 and the high of 338 in 2011 (Table 4.2).

4.1.1.4.2 Louisiana

Since the 1960s, fishing effort has increased both in number of fishermen and units of gear. LDWF crab trap license sales increased from 751 in 1979 to 3,019 in 1989; decreased slightly and stabilized (2,503-2,807) from 1990-1994; increased sharply to 3,482 in 1995 and fell to 2,948 in 1996. In 1995, the increase was likely associated with speculative license purchases prior to a three-year trap license moratorium. The number of LDWF crab trap license sales rose to 3,533 in 1999 and has remained above 3,000 each year since. In 1999, LDWF began tracking commercial fishing landings and effort using a trip ticket system, which provided more accurate information. For instance, 3,533 commercial crab trap licenses were sold in 1999, but the actual number of commercial crab fishermen that sold crabs numbered 2,277. Based on the trip ticket data, there was a decline in the number of active commercial crabbers from 1999 to 2006 (2,156-1,317). There has been an increase in the number of active commercial crabbers from 2006 to 2011 (1,317-1,773) (Table 4.2).

The estimated number of traps per fisherman increased from 25 in 1957 to 228 in 1987 and then decreased to between 129 and 163 in the 1990s. The total number of traps used in Louisiana waters ranged from 75,760-139,044 from 1970 to 1983 but then increased dramatically during the mid and late 1980s to 441,710 in 1993. Based upon a 2006 LDWF Crab Fishing Effort Survey, the total number of traps per fishermen was 335, although fishermen actually only fished an average of 266 traps per trip. Using the number of active commercial crab trap fishermen and the average number of traps from the pilot study, the estimated number of traps in 2006 was 441,195.

4.1.1.4.3 Mississippi

According to NMFS estimates, the number of trap fishermen was very stable during the 1970s and 1980s; the average number was 61 and ranged from 43 to 73. During the 1990s, there was an average of 42 trap fishermen. In the last decade, resident commercial crab trap licenses averaged 188 annually, with the low of 110 in 2006 following Hurricane Katrina and the high of 291 in 2010 (Table 4.2). Based on voluntary trip ticket harvest data collected by the MDMR during the Hurricane Katrina Emergency Disaster Recovery Program from 2006 to 2008, the average number of fishermen actively participating in the fishery was 52. The average number of traps fished per fisherman was 107 with an average catch per trip of 126 lbs.

4.1.1.4.4 Texas

The number of crab fishermen operating in Texas has been established from several sources over time. They were first established via NMFS port agents from 1950 through to 1992, next using TPWD crab trap tag sales from 1992 to 1998 and finally TPWD commercial crab fisherman license sales from 1999 onwards. This number of crab fishermen peaked in 1994 at 345 fishermen and has since declined to 196 fishermen in 2011 (Table 4.2). TPWD's Crab License Management Program enacted by the legislature in 1997 has played a major role in facilitating this decline by adopting a limited entry and crab license buyback program.

Catch per fisherman (CPUE) indices followed a similar trend to landings, except that CPUE peaked earlier in 1979 at 85.6 thousand pounds per fisherman, and then dropped to 8.8 thousand pounds per fisherman in 2006. As in the landings data, these recovered slightly after 2006 with average values from 2007 until 2011 calculated as 14.4 thousand pounds per crab license sold. These are likely low estimates. Recent analysis of trip ticket data available after 2006 show that numerous license holders failed to report any annual landings and may be holding on to their licenses in speculation of appreciating monetary values after limited entry began. These data allow a distinction to be made between the number of licensed crab fishermen and the number of active crab fishermen, the latter being approximately double that calculated using licenses sold.

It should be noted that the number of traps being used by each fisherman, although initially reported by NMFS port agents through 1992, has not been monitored since this time and these data remain unavailable. The average number deployed by each fisherman has been estimated to be around 150 traps. A limit of 200 traps per crab fisherman license was set by TPWD in 1994.

4.1.1.5 CPUEs

Due to the unreliable nature of effort data, based mainly on the fact that the number of traps set by each fisherman is largely unknown, it was decided at the data workshop that these data would not be used to construct standardized CPUEs for use in the assessment.

4.1.1.6 Age and Size Composition

Limited size data are available for commercial crab landings in the Western Gulf states, but the average size caught is estimated to be approximately 146mm. This is based on the average size of crabs caught in FIM trawl survey data above the legal size limit (127mm for all Western Gulf states).

4.1.1.7 Potential Biases, Uncertainty, and Measures of Precision

The NMFS program to collect landings was seemingly most effective for fisheries where the majority of landings are made at the large-volume wholesale dealer outlets (fish houses). Blue crabs are most often landed in small amounts at both large and small fish houses so there is a potential negative bias in the early commercial landings.

Methods used to collect commercial fisheries landings data differs by state and therefore potential biases will differ accordingly. There are no state audits to make comparisons, but in general landings across the GOM are thought to be under reported. Adkins (1972), Moss (1982), Roberts and Thompson (1982), Keithly et al. (1988), Steele and Perry (1990) considered unreported landings in the GOM to be problematic. More recently, it is believed that trip ticket programs have improved compliance.

The actual magnitude of perceived underreporting if large enough might pose problems for stock assessment. However there is cause to believe these are not insurmountable. While small scale operators might go undetected if not reporting, most of the large processing plants and wholesale dealers do not and these make up the bulk of total blue crab landing at the state level. It was noted in Florida that the NMFS program to collect landings was seemingly most effective for fisheries where the majority of landings are made at the large-volume wholesale dealer outlets (fish houses).

Inconsistencies and potential biases over time are a separate issue, but it is possible to correlate commercial and FIM catch rates in some western stock data sets, which implies that reports are capable of capturing fluctuations in the fishery. Although there are acknowledged limitations associated with use of NMFS statistical data, long-term trends and cycles in landings can be identified.

4.1.2 Recreational Fishery

Quantitative data on Gulf-wide recreational blue crab catch and effort are lacking. The sport fishery is thought to contribute significantly to total fishing pressure, though estimates of the impact of recreational fishing on the resource vary widely. Louisiana and Florida recreational fishermen using traps are required to purchase a trap license, and a general sportfishing license is required in some states to crab recreationally. Recreational crabbing has probably increased Gulf-wide, as suggested by recreational crab trap gear licenses in Louisiana, which increased dramatically from 224 in the 1988-1989 license year to 3,328 in the 1995-1996 license year. Guillory (1998b) suggested increased recreational crabbing has probably resulted from a marked increase in coastal populations, mobility, leisure time, and discretionary income.

Several marine recreational surveys (Benefield 1968, Herring and Christmas 1974, Davidson and Chabreck 1983, Titre et al. 1988, Guillory 1998b) have provided important information on the Gulf recreational fishery; however, no long-term recreational surveys have been conducted which may be used to analyze historic changes in effort and harvest in the fishery. The annual recreational catch was estimated in pounds and expressed as a percentage of the commercial catch: 33,125 lbs (5.9%) in Galveston Bay, Texas (Benefield 1968); 50,000 lbs (less than 4%) in Mississippi (Herring and Christmas 1974); 20% of the commercial landings in Alabama (Tatum 1982); and 398,500 lbs (4.1%) in Terrebonne Parish, Louisiana (Guillory 1998b). Over 51,000 lbs were harvested from Rockefeller Refuge, Louisiana, in 1981 (Davidson and Chabreck 1983).

4.1.2.1 Data Collection Methods

None

4.1.2.2 Recreational Landings and Discards

None

4.1.2.3 Recreational Catch-at-Age

None

4.1.2.4 Potential Biases, Uncertainty, and Measures of Precision

None

4.2 Eastern GOM Stock

4.2.1 Development of Historical Commercial Landings (1873-1949)

Historic commercial landings data (sporadic during 1908-1949) were gathered from various reports of the U.S. Commissioner of Fisheries and subsequent agencies for the Gulf coast of Florida.

4.2.2 Commercial Crab Fishery (1950-2011)

The NMFS has conducted comprehensive surveys of all coastal states commercial fisheries landings since 1951 (Table 4.3). Data from various annual reports (Fishery Industries of the United States 1920-1939, Fishery Statistics of the United States 1939-2010) are summarized for the entire historical fishery (1880-2011).

4.2.2.1 Overview of the Fishery

The commercial fishery for blue crabs is conducted almost exclusively using traps. Information on the recreational fishery is lacking but various small traps, dip nets, and lines are used to catch blue crabs. Commercial landings peaked in the mid 1960's, and have shown a general decreasing trend since then. Superimposed on this pattern are large oscillations often related to extended years of drought when blue crab production is apparently low and wet years when blue crab production is apparently high. Hard shell crabs represent the major component of landings

(>99% average across years by weight; Table 4.3). Due to this, both hard and soft shell landings together were lumped together for the assessment model (Figure 4.3). In addition, all discussions below refer to the combined landings of both, except where noted.

The Florida blue crab fishery is highly mobile. Many fishermen with blue crab endorsements fish for blue crabs in both the GOM and Atlantic Ocean. The separation of the licenses based on the coast fished is not achievable using licenses. The licensing data presented here illustrate the overall changes within the Florida fishery. In 1995, there was a significant increase in the number of blue crab endorsements sold in Florida (Table 4.4). During this period a statewide ban on net fishing was implemented and many commercial finfish fishermen entered the blue crab fishery. The statewide number of endorsements increased from 4,933 in 1994 to 6,082 in 1995. After the increase in 1995 a steady decrease in endorsements has followed. In 2011, the total number of endorsements (VH, VS, VN, and VI) for blue crab fishing (950) were a fraction (15.6%) of the endorsements issued in 1995. The decrease in endorsements over the period was steady and was enhanced by the Blue Crab Effort Management Plan (BCEMP) in 2007. The BCEMP was enacted to address the problems of seasonal crowding of traps in confined waterways, lost traps, bycatch, overcapitalization, latent endorsements and conflicts between hard shell blue crab fishermen and soft shell blue crab fishermen.

On July 1, 2008 the BCEMP separated the blue crab endorsements by product type: hard shell (VH), soft shell (VS), non-transferable (VN) and incidental catch (VI) along with issuing tags for each trap fished based on where and how the blue crab trap was fished (inshore, offshore, soft shell and hard shell). The high number of traps for 2008 corresponds to a period when there was no charge for trap fees (year 1 of BCEMP) and the fishers ordered the maximum allowable number of their allotment of traps, the majority of which were not fished. Fees for trap tags were implemented in 2009 and the number more accurately reflects traps that are potentially used by the fishery. The BCEMP is structured so fishermen must annually re-qualify with documented landings in order to renew their endorsements. Non-renewals may appeal if there were extenuating circumstances that prevented them from renewing on time or attaining the minimum volume of landings for requalification. Otherwise, those non-renewal endorsements were lost, permanently decreasing the number of endorsements in the fishery.

4.2.2.2 Data Collection Methods

During the period 1950-1986, landings of both soft shell and hard shell blue crab were reported to the NMFS (and predecessor Federal agencies) through monthly dealer reports made by major fish wholesalers in Florida. Prior to this time (late 1800's through 1949), commercial landings were reported only occasionally by agents of the U.S. Commissioner of Fisheries. Since 1986, information on what is landed and by who in Florida's commercial fisheries comes from the FWC's Marine Resources Information System, commonly known as the trip-ticket program, which are then compiled through NMFS. Wholesale dealers are required to use trip tickets to report their purchase of saltwater products from commercial fishers. Conversely, commercial fishers must have Saltwater Products Licenses to sell saltwater products to licensed wholesale dealers. In addition, blue crab became a "restricted species" in 1995 so only fishers who have Restricted Species Endorsements on their Saltwater Products Licenses qualify to sell blue crab. Each trip ticket includes the Saltwater Products License number, wholesale dealer license number, date of the sale, fishing gear used, trip duration (time away from the dock), area fished, depth fished, number of traps or number of sets where applicable, species landed, quantity landed, and price paid per pound. Data prior to 1986 are only available on an annual basis through NMFS, while data since 1986 are available monthly.

Biostatistics sampling has come from a variety of sources along the Florida Gulf coast, providing data on 6,409 commercially-landed crabs since 2000. Samplers charged with monitoring Florida's commercial landings of marine resources (Trip Interview Program, TIP) have occasionally sampled blue crabs during 2000, 2001, 2002, 2006, 2007, 2009, and 2010 on the gulf coast. These samples are generally taken when animals are available and at the convenience of fish house operators. Sampling includes measurements of carapace width, weight, and sex. A special, FWC-FWRI Crustacean Fisheries biostatistics sampling effort for blue crabs landed in the commercial fishery was conducted during 2002-2004 at fish houses and on fishing boats in three regions on the Gulf coast (Panhandle, Big Bend, and Southwest), measuring CW, weight, and sex. In each region, a minimum of 100 crabs were weighed and measured each quarter, often from the same fish house. Finally, FWC-FWRI Crustacean Fisheries conducted a disease survey with commercial fisherman during the months of 2-4, 8, and 9 in 2011 at four regions on the Gulf Florida. Figure 4.4 shows the sampling intensity aggregated among all the various sampling programs, demonstrating the substantial lack of information for many month and year combinations.

4.2.2.3 Nominal Landings

Landings of crabs increased dramatically in the late 1950's to peak in 1965 at 21 million pounds, and have steadily declined since then to approximately 7 million pounds in 2011. Landings have been highly variable from year to year, presumably due to changes in fishing effort in response to natural fluctuations in the population (e.g., drought versus wet years).

4.2.2.4 Age and Size Composition

The average carapace width of crabs landed was 153.8mm, with an interquartile range of 142.0-165.0mm. The average weight is 185.6g, with an interquatile range of 150.0-214.0g. The smallest average size of crabs landed is during the late spring and early summer months, coinciding with maturation and recruitment of crabs to the fishery. This period also coincides with the peak monthly landings overall, suggesting a large portion of crabs landed may be newly recruited individuals (Figures 4.5, 4.6, and 4.7).

4.2.2.5 Nominal Fishing Effort

Following Murphy et al. (2007), nominal fishing effort was calculated as the number of traps pulled per year. This was estimated based on matching missing or inaccurate trip ticket records with complete and seemingly valid trip ticket records that shared some trait with the inaccurate records. The valid trip ticket records were those that contained saltwater products license numbers, measures of the time fished and the number of traps used and whose traps per time fished ranged from zero to 66 traps per hour, where 66 traps per hour is the 95% upper limit, used to exclude outlying numbers. This range more than encompassed the observed mean number of traps fished per hour by fishers interviewed in a fishery characterization study (McMillan-Jackson et al. 2003), where the average number of traps pulled per hour was approximately 25. The valid data were used to calculate the number of traps pulled per trip for the rest of the trip ticket data by matching them in a hierarchical pattern: (1) with mean monthly estimates of numbers of traps pulled per hour from those with matching SPL numbers, (2) with the average number of traps pulled per hour in that county, (3) with the average monthly number of traps used per hour in that fishing area, and finally (4) with the overall monthly average number of traps pulled per hour. The total number of traps used on each trip was calculated as the hours fished times the traps per hour.

Effort in the blue crab fishery increased from 1985 until it peaked in the mid 1990s, after which is had declined steadily, where the estimated effort in 2011 is below those levels in the mid 1980's (Figure 4.8). The increase in effort in the mid-1990s is generally attributable to the statewide ban on net fishing in Florida, when many finfish fishermen migrated to the blue crab fishery. Effort parallels the decrease in endorsements from the mid-1990s onward, and was likely enhanced by the BCEMP enacted in 2007 to address the problems of seasonal crowding of traps in confined waterways, lost traps, bycatch, overcapitalization, latent endorsements and conflicts between hard shell blue crab fishermen and soft shell blue crab fishermen. Although this effort data is readily available, it is generally considered unreliable. As such, a decision was made at the Data Workshop to not use these data for the base assessment model. These data were included however as a sensitivity run for the Eastern stock using the primary assessment model to assess whether the use of effort data had an effect on the model estimates.

4.2.2.6 CPUEs

Due to the unreliable nature of effort data, it was decided at the data workshop that these data would not be used to construct standardized CPUEs for use in the base assessment model. However, the standardized CPUE was developed as part of this exercise (Figure 4.8), and was included as a sensitivity run for the Eastern stock using the supporting assessment model. Landings per trip in pounds were standardized using a Generalized Linear Model (GENMOD procedure in SAS version 9.2) that assumed the pounds landed data represented a random, negative-binomial distributed variable that is a potential function of year, county, month, fishing location (bay or ocean), and $\log_e$ of the number of traps pulled. Final year-specific least-square means estimates and the standard errors of landings rate were used to generate distributions from a Monte Carlo simulation (5000 Student's *t* distributed realizations) that computed the median catch rates, quartiles and 95% confidence bounds. Diagnostics of the standardization included examination of the standardized deviance residuals for patterns and quantile-quantile plots of these residuals against a standard normal distribution (Figure 4.9).

4.2.2.7 Potential Biases, Uncertainty, and Measures of Precision

The NMFS program to collect landings was seemingly most effective for fisheries where the majority of landings are made at the large-volume wholesale dealer outlets (fish houses). Blue crabs are most often landed in small amounts at both large and small fish houses so there is a potential negative bias in the early commercial landings. However during 1985 and 1986, when two data collection systems operated concurrently, the NMFS-reported landings of blue crab were often considerably higher than those reported through the trip ticket program. This was generally considered a result of the reluctance of fishers to participate in the trip ticket program during the early years (Murphy et al. 2007) though some of the large-fish-house-sampling bias may still have been evident on the Atlantic coast in 1985. The General Canvass recorded 50% and 16% higher blue crab landings than did trip-tickets on the gulf coast during 1985 and 1986, respectively. On the Atlantic coast, the general-canvass reported blue crab landings were 14% lower than trip-ticket reported landings in 1985 and 44% higher in 1986. The General Canvass is generally considered the official commercial landings up through 1985 when it was displaced by the trip ticket system. It is assumed here that any mis-reporting by the official landings system is randomly distributed over the years. The mobility of the blue crab fleet may also introduce some bias into the reported landings, when blue crab caught on one coast are transported to the other coast and sold to a dealer without indicating the area fished on the trip ticket.

Biostatistics data collected under the TIPS program was generally collected from unsorted landings or the entire landings for a particular trip were sampled. The serendipitous encounter of blue crabs for sampling could have introduced unknown bias, particularly given the sporadic nature with entire years of sampling missing for both coasts. The biostatistics sampling that occurred statewide during 1997-2011 occasionally encountered landed blue crabs that some fishers or fish houses had sorted by sex, so the sex ratio of the crabs sampled may not be an accurate representation of the sex ratio of the catch. For the purpose of this assessment, the sex ratio data is considered unreliable, given the sporadic nature of sampling. Any additional biases in this sampling are unknown.

4.2.3 Recreational Fishery

There is very limited information on the recreational fishery for blue crabs in Florida. It is thought that landings may be significant. Steele and Bert (1998) found that 18% of all tag returns made during a 1983 to 1985 blue crab tagging study were from recreational crabbers. Female blue crabs are often caught using dip nets at passes when they begin migrating out of the bays to spawn. Recreational harvesters do not have to possess a saltwater products license unless they are fishing from a boat. Blue crabs are also caught for bait and for use as food by recreational fishers using up to five recreational blue crab traps per fisher, as allowed by FWC regulations.

4.2.3.1 Data Collection Methods

None

4.2.3.2 Recreational Landings and Discards

None

4.2.3.3 Recreational Catch-at-Age

None

4.2.3.4 Potential Biases, Uncertainty, and Measures of Precision

None

Table 4.1 Total blue landings (lbs x 1000) from NMFS for the Western GOM stock (hard and soft-shell combined) (NOAA Unpublished Data).

Year	AL	MS	LS	TX	Total
1950	599	4,040	13,106	387	18,132
1951	1,109	1,623	8,710	280	11,722
1952	655	1,726	7,334	338	10,053
1953	1,087	1,412	8,131	432	11,062
1954	972	1,256	7,085	379	9,692
1955	1,613	1,763	10,811	356	14,543
1956	725	1,979	9,402	195	12,301
1957	1,462	2,400	8,559	201	12,622
1958	1,182	2,124	9,336	570	13,212
1959	1,093	3,003	9,570	1,192	14,858
1960	499	2,812	10,050	2,867	16,228
1961	838	2,505	11,910	2,875	18,128
1962	634	907	9,523	4,473	15,537
1963	1,297	1,112	7,982	2,980	13,371
1964	1,762	1,286	5,692	2,484	11,224
1965	1,812	1,692	9,284	3,622	16,410
1966	2,183	1,457	7,986	2,778	14,404
1967	2,353	1,015	7,559	2,625	13,552
1968	1,980	1,136	9,551	4,084	16,751
1969	1,920	1,740	11,602	6,343	21,605
1970	1,407	2,027	10,254	5,525	19,213
1971	1,997	1,259	12,186	5,810	21,252
1972	1,612	1,362	15,083	6,464	24,521
1973	2,098	1,814	23,080	6,881	33,873
1974	1,826	1,167	20,639	6,088	29,720
1975	1,639	1,137	17,144	5,992	25,912
1976	1,299	1,334	15,211	6,668	24,512
1977	2,174	1,919	16,154	8,249	28,496
1978	2,009	1,940	15,074	7,470	26,493
1979	1,341	1,313	21,334	8,312	32,300
1980	1,557	2,760	18,183	8,953	31,453
1981	2,462	1,867	16,237	6,952	27,518
1982	1,266	1,297	17,284	8,010	27,857
1983	1,412	1,140	19,616	8,829	30,997
1984	4,216	2,250	29,617	7,229	43,312
1985	2,261	1,649	29,848	9,722	43,480
1986	2,886	1,303	31,611	9,482	45,282
1987	2,507	1,374	52,345	11,688	67,914
1988	3,869	863	53,554	10,428	68,714
1989	4,090	651	33,390	9,066	47,197
1990	3,302	390	39,135	8,599	51,426
1991	2,731	454	51,987	6,137	61,309
1992	3,550	443	51,744	6,135	61,872
1993	2,554	230	45,847	8,288	56,919
1994	2,744	171	36,664	5,154	44,733
1995	2,520	321	36,914	5,787	45,542
1996	3,219	407	39,902	6,310	49,838
1997	3,476	683	43,440	7,084	54,683
1998	3,478	592	43,480	6,989	54,538
1999	3,768	920	46,328	6,472	57,488
2000	4,780	839	51,446	4,653	61,719
2001	2,457	432	41,398	5,163	49,450

2002	2,575	716	49,751	7,037	60,079
2003	2,957	875	47,705	4,811	56,349
2004	3,329	811	44,069	3,961	52,169
2005	1,024	429	37,880	3,119	42,451
2006	2,384	1,127	53,252	1,966	58,729
2007	2,554	737	44,902	3,454	51,647
2008	1,799	450	41,617	2,635	46,501
2009	1,458	545	52,848	2,844	57,696
2010	927	366	30,599	3,436	35,328
2011	1,614	370	43,862	2,893	48,738

Table 4.2 Estimated number of commercial hard crab fishermen by state for the Western GOM stock, 1950-2011 (-- indicates not available) (NOAA Unpublished Data).

Year	AL		MS		LA		TX	
	No.	%	No.	%	No.	%	No.	%
1950	130	9.2	264	18.8	954	67.8	60	4.3
1951	123	9.3	250	18.9	902	68.3	46	3.5
1952	74	5.7	254	19.5	926	71.1	49	3.8
1953	94	7.5	96	7.6	1,007	79.9	64	5.1
1954	109	10.7	62	6.1	815	79.9	34	3.3
1955	127	13.3	66	6.9	737	77.2	25	2.6
1956	68	7.8	62	7.1	716	82.4	23	2.6
1957	58	6.8	64	7.5	704	82.3	29	3.4
1958	73	8.1	62	6.8	734	81.0	37	4.1
1959	81	8.7	79	8.4	744	79.6	31	3.3
1960	76	7.4	83	8.0	803	77.7	71	6.9
1961	78	6.8	74	6.4	923	80.2	76	6.6
1962	47	3.9	62	5.1	1,012	83.6	89	7.4
1963	68	5.4	33	2.6	1,086	85.6	82	6.5
1964	84	6.2	40	2.9	1,148	84.5	87	6.4
1965	74	5.2	49	3.5	1,225	86.4	70	4.9
1966	75	5.5	48	3.5	1,173	85.7	72	5.3
1967	85	6.1	49	3.5	1,195	85.7	66	4.7
1968	104	6.9	45	3.0	1,271	84.7	81	5.4
1969	85	5.5	75	4.8	1,298	83.6	95	6.1
1970	94	7.2	73	5.6	1,041	79.5	102	7.8
1971	88	6.6	65	4.9	1,087	81.7	90	6.8
1972	106	8.0	62	4.7	1,068	80.2	95	7.1
1973	95	7.6	68	5.5	958	76.8	126	10.1
1974	85	6.9	61	4.9	971	78.5	120	9.7
1975	75	5.7	63	4.8	1,031	78.0	152	11.5
1976	65	4.7	43	3.1	1,110	79.5	179	12.8
1977	76	5.7	66	4.9	1,026	76.9	167	12.5
1978	--	--	--	--	1,067	88.0	146	12.0
1979	98	7.3	65	4.83	1,085	80.7	97	7.2
1980	135	11.3	63	5.28	885	74.1	111	9.3
1981	127	10.7	61	5.12	891	74.8	112	9.4
1982	93	7.29	66	5.18	975	76.5	141	11.1
1983	111	9.88	55	4.9	826	73.6	131	11.7
1984	133	9.24	60	4.17	1,019	70.8	227	15.8
1985	113	8.06	64	4.56	1,030	73.5	195	13.9
1986	137	10.19	68	5.06	916	68.2	223	16.6
1987	157	8.87	66	3.73	1,231	69.5	317	17.9
1988	215	11.39	56	2.97	1,343	71.2	273	14.5
1989	221	8.98	44	1.79	1,892	76.8	305	12.4
1990	178	6.3	33	1.17	2,303	81.5	311	11.0
1991	193	5.57	34	0.98	3,020	87.2	215	6.2
1992	175	5.7	37	1.21	2,602	84.8	255	8.3
1993	188	5.82	65	2.01	2,711	83.9	269	8.3
1994	--	--	--	--	2,516	87.9	345	12.1
1995	--	--	--	--	3,488	91.4	327	8.6
1996	--	--	--	--	2,947	89.8	335	10.2
1997	--	--	--	--	2,554	88.1	345	11.9
1998	--	--	--	--	2,353	88.1	318	11.9

1999	--	--	--	--	3,533	92.5	287	7.5
2000	--	--	--	--	3,601	93.1	265	6.9
2001	--	--	--	--	3,286	93.1	244	6.9
2002	--	--	--	--	3,405	93.6	231	6.4
2003	--	--	--	--	3,437	93.6	234	6.4
2004	--	--	--	--	3,478	93.8	229	6.2
2005	--	--	--	--	3,028	93.1	224	6.9
2006	--	--	--	--	3,290	93.7	222	6.3
2007	--	--	--	--	3,177	93.5	221	6.5
2008	--	--	--	--	3,058	93.4	216	6.6
2009	--	--	--	--	3,158	93.7	211	6.3
2010	--	--	--	--	3,601	94.6	206	5.4
2011	--	--	--	--	3,716	95.0	195	5.0

Table 4.3 Total landings from NMFS per crab category (hard and soft-shell), and the corresponding landings, trips, and traps pulled from the Florida MRIS trip ticket dataset for the Eastern GOM stock (FWC unpublished data).

Year	Hard Lbs	Soft Lbs	Total Lbs	Total Lbs (FL)	Trips (FL)	Traps (FL)
1950	684,100	300	684,400			
1951	2,076,600	3,400	2,080,000			
1952	1,984,200	14,600	1,998,800			
1953	3,153,400	2,900	3,156,300			
1954	2,902,900	400	2,903,300			
1955	4,954,100	800	4,954,900			
1956	3,728,100	1,400	3,729,500			
1957	5,301,600	10,000	5,311,600			
1958	8,693,400	800	8,694,200			
1959	13,895,400	3,200	13,898,600			
1960	18,648,300	4,200	18,652,500			
1961	17,129,500	5,100	17,134,600			
1962	10,356,300	200	10,356,500			
1963	13,148,400	4,000	13,152,400			
1964	14,068,500	13,000	14,081,500			
1965	20,597,500	11,700	20,609,200			
1966	16,547,200	800	16,548,000			
1967	13,975,800	6,800	13,982,600			
1968	9,008,100	0	9,008,100			
1969	11,583,800	400	11,584,200			
1970	14,786,300	300	14,786,600			
1971	12,278,700	0	12,278,700			
1972	10,673,200	100	10,673,300			
1973	9,598,500	0	9,598,500			
1974	10,133,700	100	10,133,800			
1975	12,806,500	1,600	12,808,100			
1976	12,048,500	0	12,048,500			
1977	15,832,200	0	15,832,200			
1978	11,678,677	22,236	11,700,913			
1979	11,198,262	9,328	11,207,590			
1980	11,275,741	16,866	11,292,607			
1981	14,787,653	22,631	14,810,284			
1982	8,870,850	53,452	8,924,302			
1983	9,337,318	35,831	9,373,149			
1984	12,912,367	27,563	12,939,930			
1985	12,273,006	17,073	12,290,079			
1986	7,644,267	9,407	7,653,674	7,792,426	23,172	4,953,520
1987	10,412,930	11,718	10,424,648	10,498,404	27,654	5,236,177
1988	10,385,527	17,257	10,402,784	10,462,466	30,435	5,422,988
1989	8,158,507	38,876	8,197,383	8,438,583	30,365	5,018,056
1990	6,878,103	36,775	6,914,878	7,107,902	25,996	5,056,906
1991	5,212,938	22,029	5,234,967	5,456,284	23,922	3,854,758
1992	7,618,951	34,681	7,653,632	8,279,883	29,373	5,034,135
1993	8,501,970	21,412	8,523,382	8,638,649	33,619	5,716,788
1994	8,406,570	57,364	8,463,934	8,552,332	40,013	6,371,380
1995	8,724,825	56,008	8,780,833	8,849,470	37,873	6,188,208
1996	12,414,241	60,673	12,474,914	12,524,026	43,536	7,571,289
1997	9,254,589	66,587	9,321,176	9,330,034	40,262	6,931,567
1998	12,771,080	91,701	12,862,781	12,880,644	40,841	7,442,459
1999	11,046,665	122,802	11,169,467	11,187,745	40,786	6,824,154

2000	6,412,794	159,850	6,572,644	6,588,100	30,100	4,981,852
2001	4,547,898	98,762	4,646,660	4,654,594	24,070	4,401,740
2002	5,489,433	77,585	5,567,018	5,571,260	26,650	5,010,556
2003	7,140,725	84,648	7,225,373	7,218,472	27,958	5,516,763
2004	8,007,719	75,445	8,083,164	8,171,465	25,892	5,692,018
2005	7,312,485	57,518	7,370,003	7,401,564	23,798	5,206,611
2006	8,564,662	45,488	8,610,150	8,615,894	23,530	5,107,056
2007	6,074,386	35,439	6,109,825	6,115,092	20,593	4,333,320
2008	2,627,342	35,754	2,663,096	2,663,869	14,540	2,899,435
2009	3,313,987	50,227	3,364,214	3,365,110	16,062	3,051,610
2010	5,709,557	49,111	5,758,668	5,758,393	21,234	3,949,870
2011	6,795,718	37,488	6,833,206	6,856,585	21,605	3,924,216

Table 4.4 Licensing data for all of Florida. Due to the mobility of the blue crab fishery between both coasts, it is not possible to separate licensing data from the Gulf and Atlantic coasts (FWC unpublished data).

Year	Blue Crab Endorsements	Sub-divisions of Endorsements				Total Traps	Sub-divisions of Trap Tags			
		VH	VS	VN	VI		Inshore Trap Tags	Offshore Trap Tags	Soft Shell Trap Tags	Non-Transferable Trap Tags
1991	4,558									
1992	4,491									
1993	4,491									
1994	4,933									
1995[1]	6,082									
1996	5,519									
1997	5,737									
1998	5,920									
1999	5,297									
2000	4,784									
2001	4,376									
2002	3,435									
2003	3,222									
2004	2,931									
2005	2,798									
2006	2,579									
2007	2,283									
2008[2]	1,190	832	157	182	19	822,750	450,000	299,600	54,950	18,200
2009[3]	1,021	768	112	141		290,599	213,550	50,100	17,749	9,200
2010	1,035	727	95	103	110	257,050	192,850	38,550	17,700	7,950
2011	950	700	87	47	116	251,950	193,150	36,650	16,750	5,400

1 Start of the net ban
2 Effort Management Plan implemented
3 Implementation of the Trap Tag Fee

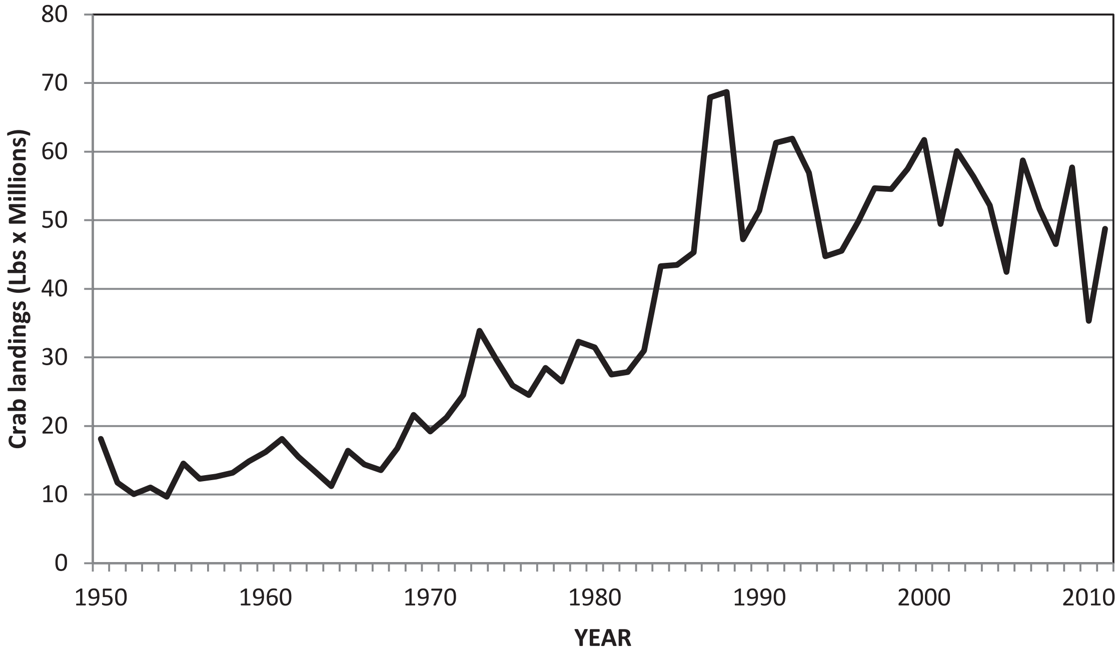

Figure 4.1 Total landings of crabs (hard and soft shell combined) for the Western GOM stock in millions of pounds (NOAA unpublished data).

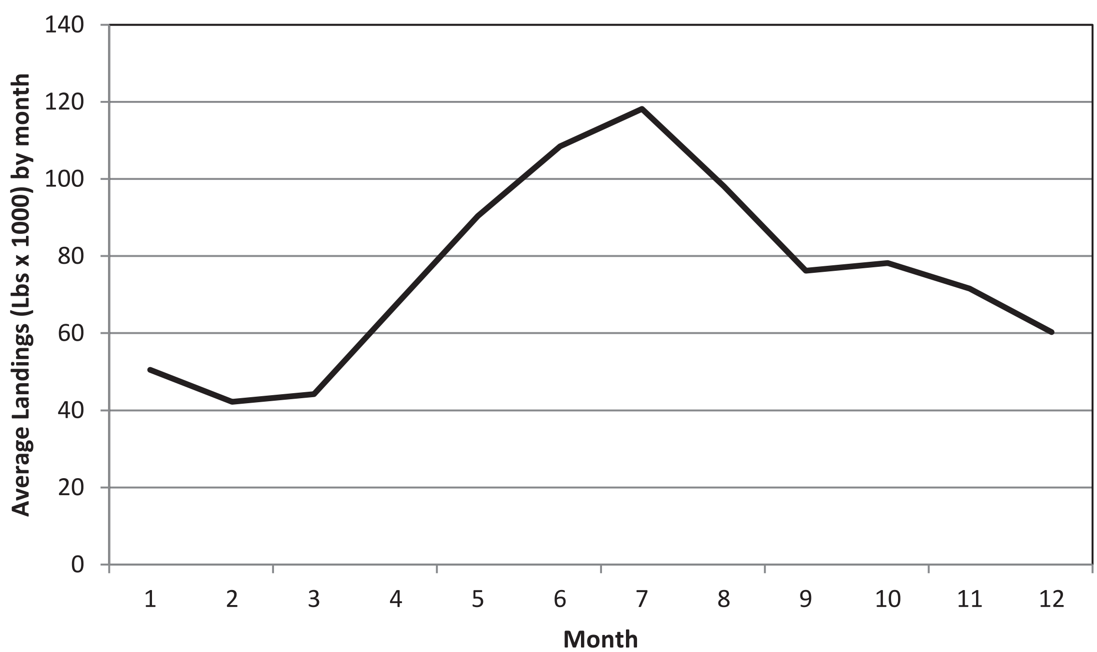

Figure 4.2 Mean monthly landings (poundsx1000) for the Western GOM crab stock from commercial trip tickets (1984-2011).

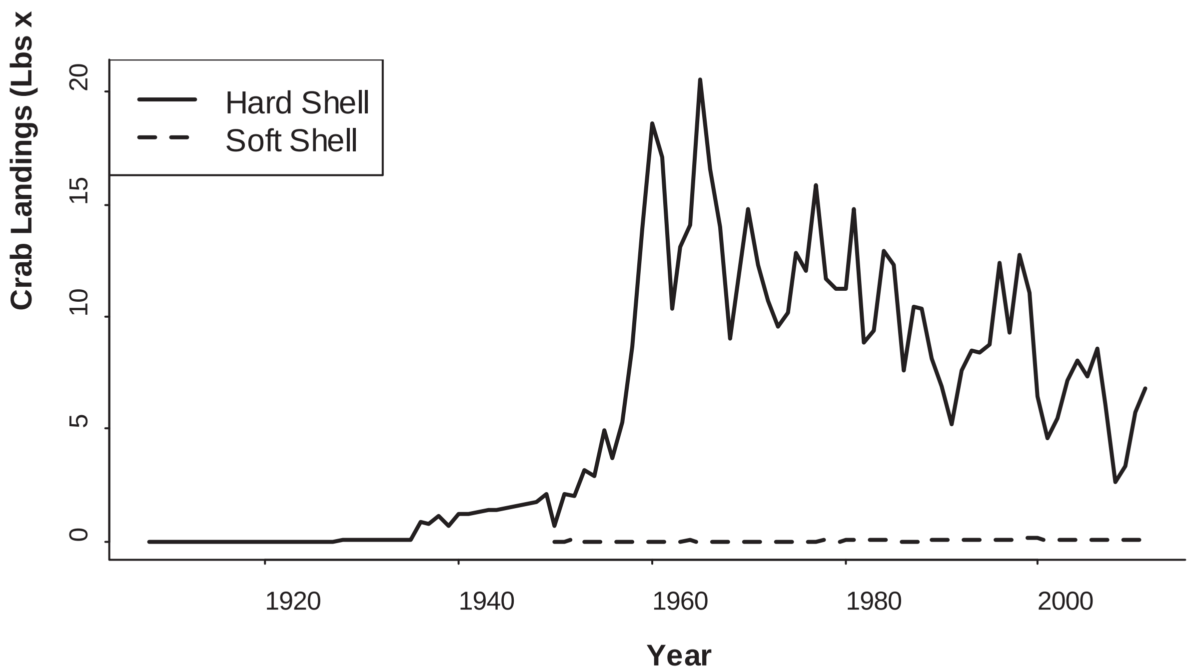

Figure 4.3 Total landings of Eastern GOM stock crabs along the Florida Gulf coast (FWC unpublished data).

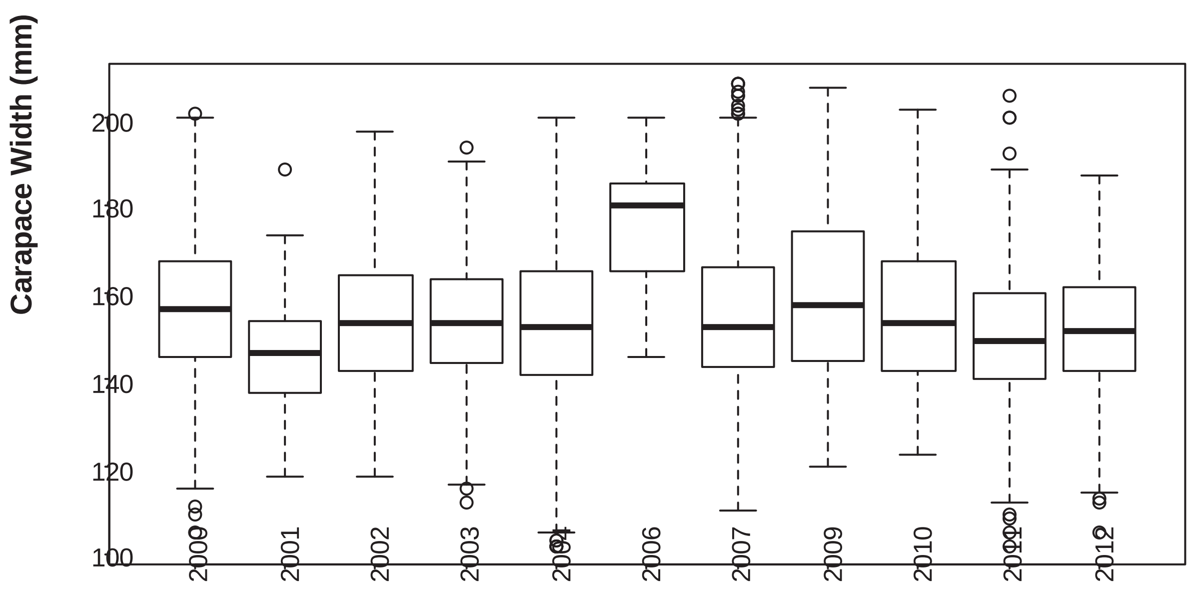

Figure 4.4 Size distribution of Eastern GOM stock crabs landed along the Florida Gulf coast per year from the combined biostatistical sampling programs.

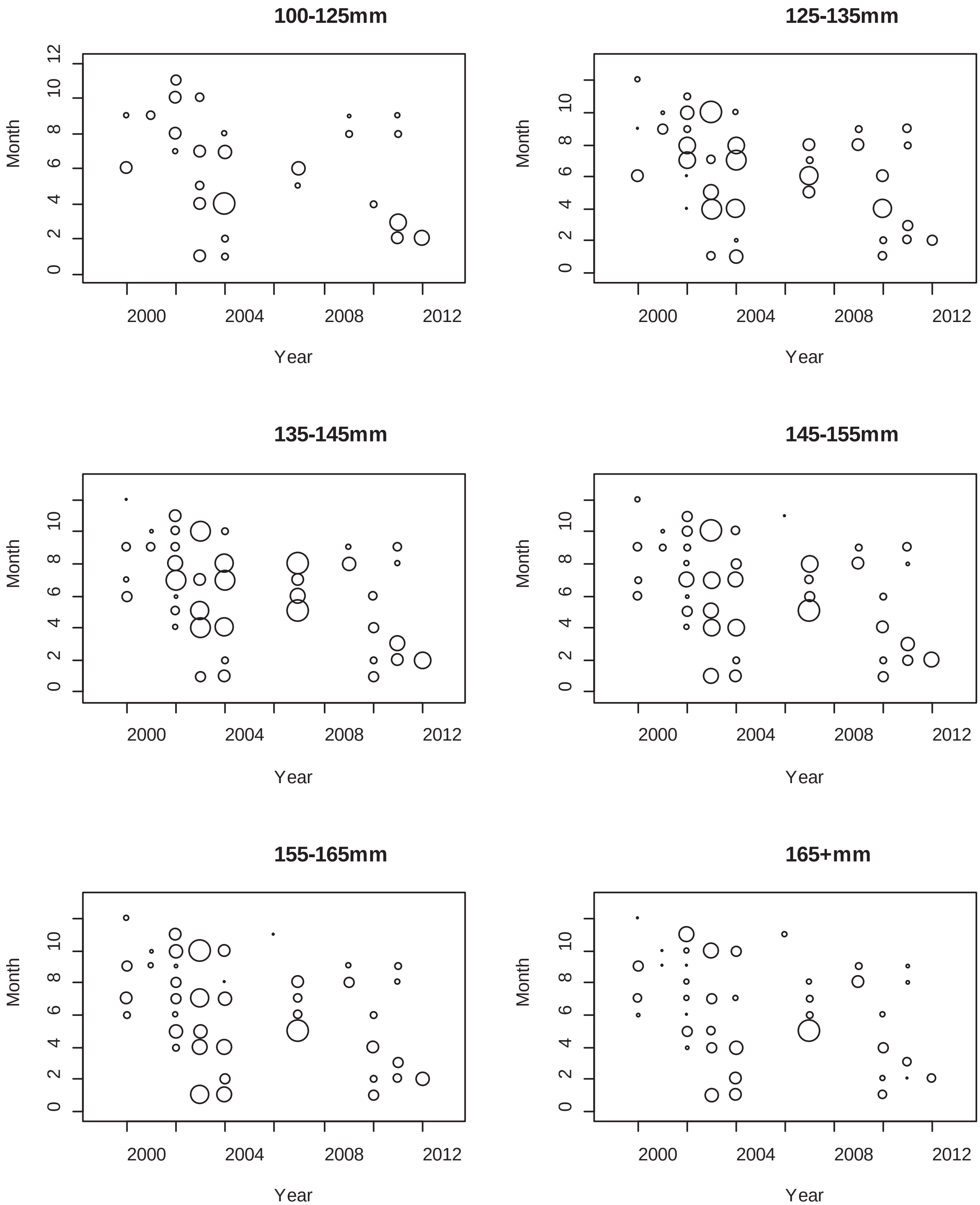

Figure 4.5 Number of Eastern GOM stock crabs sampled by size, month, and year for the combined biostatistical sampling along the Florida Gulf coast.

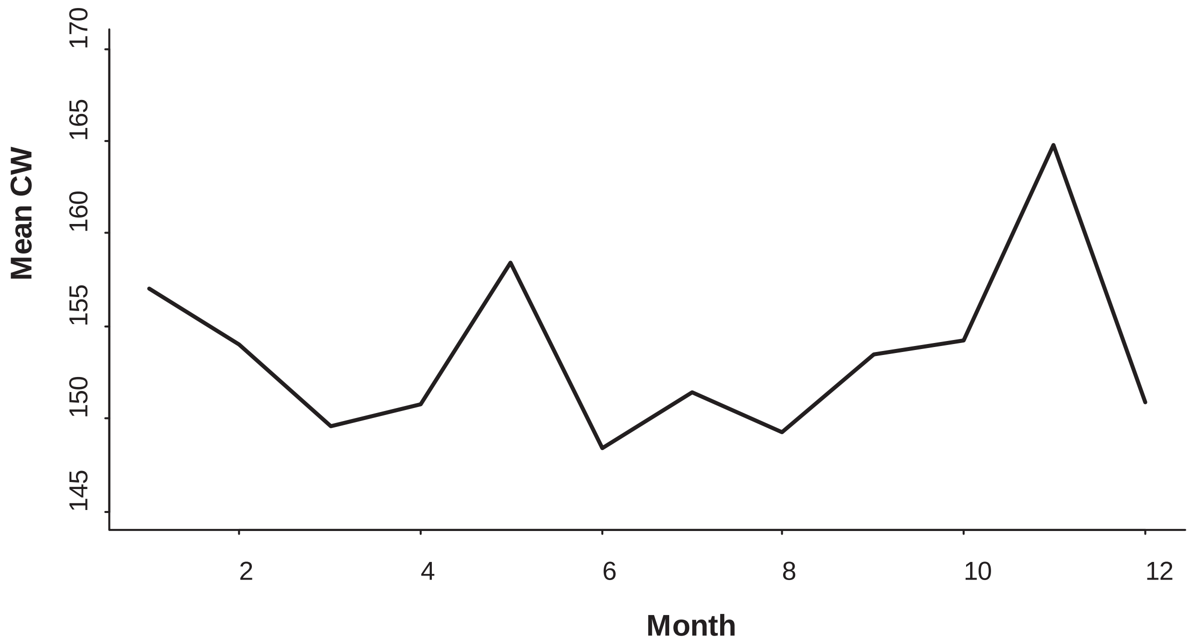

Figure 4.6 Eastern GOM stock mean size of crabs caught per month.

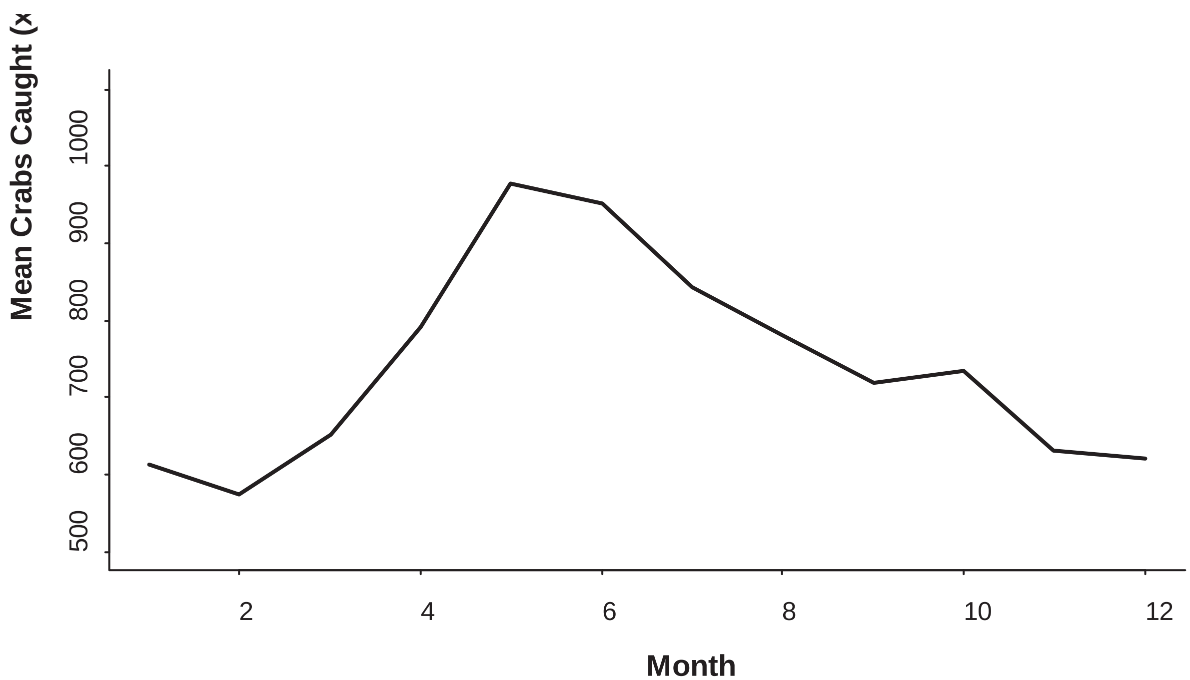

Figure 4.7 Eastern GOM stock mean number of crabs caught per month.

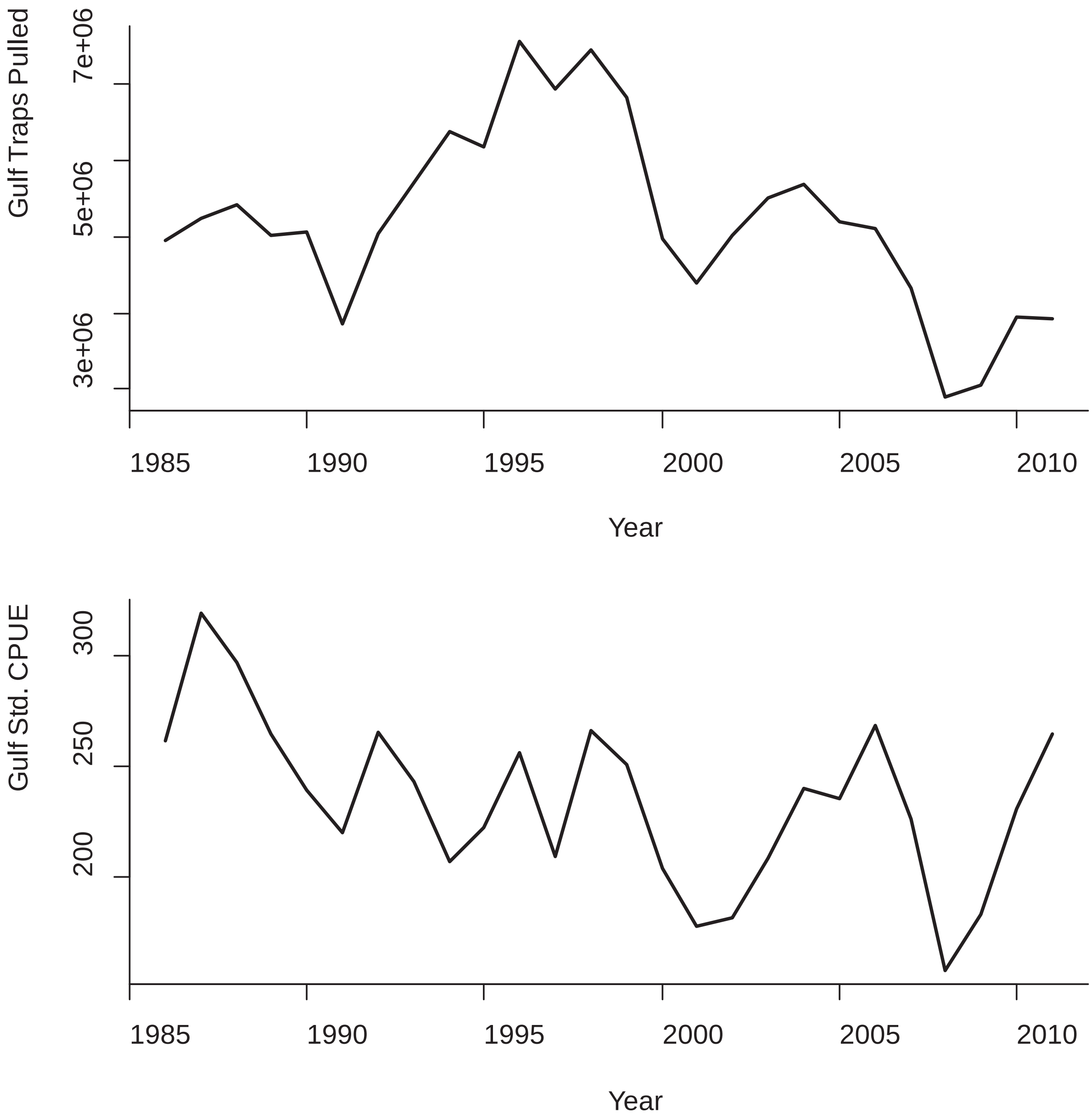

Figure 4.8 Eastern GOM stock nominal effort in units of traps pulled and the standardized CPUE.

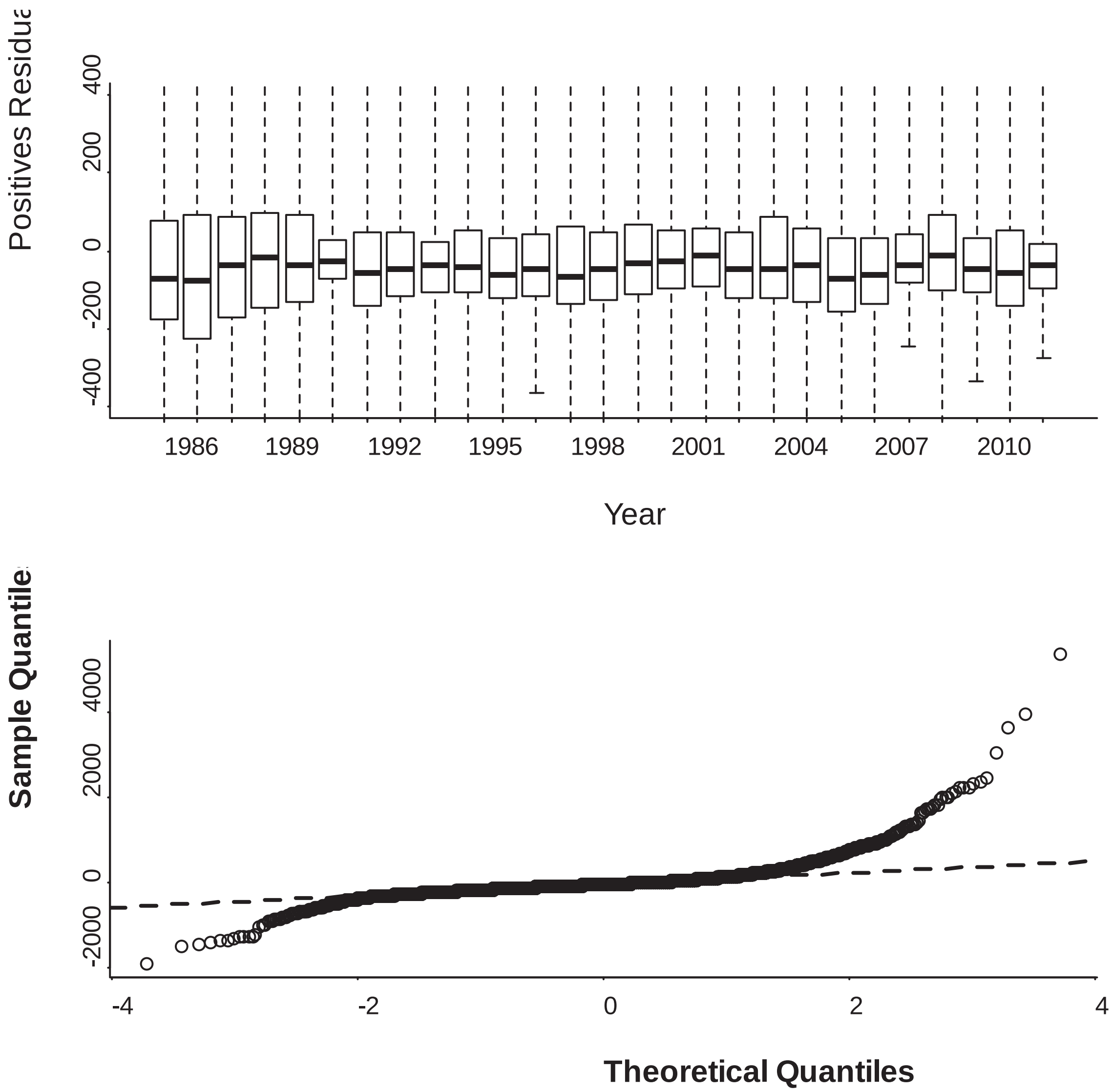

Figure 4.9 Residuals by year from the CPUE standardization procedure for the Eastern stock.

5.0 Fishery-Independent Data

5.1 Data Collection and Treatment

Otter trawl, bag seine and gillnet data collected in Texas, Louisiana, Mississippi, Alabama, and Florida were considered in development of two coast-wide indices of juvenile and adult abundance (See Tables 5.1, 5.2, and 5.3 for specifics on the three gears by state). Each state conducts separate surveys, which collect blue crabs, but blue crabs are not the target species. Below is a brief description of the data for each state. In addition, SEAMAP plankton and trawl data were considered for creation of an index.

5.1.1 Texas

5.1.1.1 Survey Methods

Texas Parks and Wildlife Department (TPWD)'s fishery-independent data are collected as a stratified cluster sampling design; each bay system and Gulf area serves as non-overlapping strata with a fixed number of samples per month (or season, for gill nets; Figure 5.1). A cluster sample is a type of probability sample where each sample unit is a collection, or cluster, of elements. Specifically, locations are sampled and include every organism encountered at that location as part of the sample. Sample locations are drawn independently and without replacement for each combination of gear, stratum, and month (season). Gill net and bag seine sample locations are randomly selected from grids (1-minute latitude by 1-minute longitude) that contains >15.2 m of shoreline. Each selected grid is subdivided into 144 5-second "gridlets". All "gridlets" containing >15.2 m of shoreline are used to randomly choose sample sites. Prior to September 1984, sites were randomly selected from 100 fixed stations in each bay system, with random sites selection since September 1984.

Gill nets, bag seines, and trawls are utilized to determine relative abundance, size, species composition, and temporal and spatial distribution of various life history stages of fish and invertebrates in Texas coastal waters. Brief descriptions of each gear are included in Tables 5.1, 5.2, and 5.3. Gill nets are set perpendicular to shorelines and target subadult and adult finfish. Bag seines are pulled along the shoreline and target juvenile fish and invertebrates. Trawls are towed in open water and target juvenile and subadult fish and invertebrates.

Bag seines and monofilament gill nets are used in each of ten Texas estuarine systems: Sabine Lake, Galveston Bay, Cedar Lakes, East Matagorda Bay, Matagorda Bay, San Antonio Bay, Aransas Bay, Corpus Christi Bay, upper Laguna Madre, and lower Laguna Madre (Figure 5.1). Bag seines have been used in seven Texas bay systems since October 1977; sample collection began in the East Matagorda Bay system in February 1983, Sabine Lake in January 1986, and Cedar Lakes in January 1996. Monofilament gill nets have been systematically used in seven Texas bay systems since November 1975; East Matagorda Bay was added in fall 1976, Sabine Lake in spring 1986 and Cedar Lakes in spring 1995. Bay trawls are used in all estuarine systems except Cedar Lakes. Gulf trawls, identical to those used in the bays, are used in the Texas Territorial Sea (TTS) <16.7 km from shore, in five Gulf areas 24.1 km either side of

Sabine Pass, Bolivar Pass, Matagorda Ship Channel, Aransas Pass, and 48.2 km north from the Texas-Mexico border.

Gill net samples are collected overnight during each spring and fall season. The spring season begins with the 2nd full week in April and extends for 10 weeks. The fall season begins with the 2nd full week in September and extends for 10 weeks. Between three and five nets are set each week in each bay, except in East Matagorda Bay where only two sets are made during each week, and Cedar Lakes, where only one set is made each week. Prior to fall 1981, no more than 18 overnight gill net sets occurred in each season in each bay system. Since fall 1981, 45 gill nets were set during each season in each bay system except East Matagorda Bay. In East Matagorda Bay from fall 1981 to spring 1984, not less than six nor more than 12 gill nets were set each season; since fall 1984, 20 nets were set each season. In Cedar Lakes, 20 nets were set each season until 2000, when 10 nets were set each season. Each sampling week extends from 1 h before sunset on Sunday through 4 h after sunrise the following Sunday. Gill nets are set perpendicular to shore with the smallest mesh shoreward. Nets are set within 1 h before sunset and retrieved within 4 h after the following sunrise. Total fishing time is recorded (nearest 0.1 h).

Bag seines are pulled parallel to the shoreline for 15.2 m. The area swept (0.03 ha) is determined using distance pulled and width of the bag seine. One half of the monthly bag seine samples are collected during each half (days 1-15 and 16-31) of the month to ensure good temporal distribution of samples. No grid is sampled more than once in a month. Prior to October 1981, six bag seine samples were collected each month in each bay system (except during June 1978 when no samples were collected). From October 1981 through March 1988, 10 bag seine samples were collected each month in each bay system, with half of the samples collected during each half of the month. From April 1988 through December 1989, 12 bag seine samples were collected each month in each bay system. Beginning January 1990, 16 bag seine samples were collected each month in each bay system. Beginning January 1992, 20 samples were collected in each bay system each month, except in East Matagorda Bay and Cedar Lakes where 10 samples were collected per month.

Bay trawl sample locations are randomly selected from grids containing water $\geq$1 m deep in at least ⅓ of the grid, and are known to be free of obstructions. Large bays (Galveston, Matagorda, San Antonio, Aransas and Corpus Christi) are stratified into two zones: Zone 1 (upper bay nearest mouths of rivers) and Zone 2 (lower bay farthest from rivers) to ensure good spatial distribution of samples. Smaller bays (Sabine Lake, East Matagorda Bay, upper Laguna Madre and lower Laguna Madre) are not stratified. One half of the monthly trawl samples in each zone in each bay system are collected during each half (days 1-15 and 16-31) of the month to ensure good temporal distribution of samples. Trawls are towed in a circular pattern near the center of each grid. All tow times are 10 minutes in duration. No grid is sampled more than once per month. Trawl samples have been collected in three bays since January 1982 and seven bays since May 1982. Trawl samples commenced in Sabine Lake beginning January 1986, and in East Matagorda Bay beginning April 1987. Since inception, samples size has been 10 trawls/month/zone.

Gulf trawl sample locations are randomly selected from grids in the TTS that contain water $\geq$1.8 m deep in at least ⅓ of the grid, and are known to be free of obstructions. One half of the samples in each area are collected during each half (days 1-15 and 16-31) of the month to ensure good temporal distribution of samples. Trawls are towed linearly, parallel to the fathom curve; direction of tow (north or south) is randomly chosen for the initial tow and alternated on subsequent tows. All tow times are 10 minutes in duration. No grid is sampled more than once per month. Trawl samples have been collected in four Gulf areas within the TTS since August 1985 and five areas since July 1986, with 16 trawls/month/area since inception.

5.1.1.2 Biological and Physical Sampling Methods

All organisms greater than 5 mm total length (carapace width in crabs) caught in seines, trawls, and gill nets are counted and identified to the lowest phylogenetic unit (genus and species are preferred). Up to nineteen individual blue crabs from seines and gill nets, and 35 blue crabs from bay and gulf trawls are randomly selected and measured to the nearest 1 mm. Sex is determined for blue crabs over 50 mm in carapace width in all gears. Maturity stage (immature, mature, developing egg mass, developed egg mass) is recorded for all female blue crabs over 50 mm. Sacculinid barnacle infestation is recorded when present. Captured crabs are returned to the water to minimize mortality.

Surface salinity (‰), water temperature (^{o}C), dissolved oxygen (ppm) and turbidity [Nephelometric Units (NTU)] are measured at the set and pickup for each gill net and prior to each bag seine sample. Bottom salinity, water temperature, dissolved oxygen and turbidity are measured prior to each trawl sample. Latitude/longitude, start and completion times, and shallow and deep water depths are recorded for each sample, as is presence or absence of vegetation.

5.1.1.3 Ageing Methods

TPWD does not age blue crabs samples collected during fishery-independent monitoring.

5.1.1.4 Use for an Index

For use in this assessment, Texas fishery independent monitoring bay trawls were chosen as the most suitable gear to track blue crab recruitment and adult relative abundance within coastal waters. Bay trawls cover an extensive area of bay water habitat and the CV surrounding the mean annual catch rate is relatively low compared to other gears. Gulf trawls were also considered, but not put forth for use in the assessment because they are towed at depths and locations outside the main range of blue crabs. Gill nets catch mainly large adult crabs and relatively few juveniles. Bag seines catch all sizes and are efficient catching small crabs, but only cover the shoreline and have a high CV around the annual mean catch rate.

Seine and gillnet data were considered, but not put forth for use in IOA standardization for the western stock base run. Seine and gillnet data, specifically the size measurements of blue crab, were not consistently collected in all western stock states and precluded development of size-specific IOAs for the Western GOM stock.

Note: only one fishery independent monitoring gear could be chosen from each state that was consistent with the other western stock states in order to create GLM standardized indices of abundance for the Western GOM stock (see section 5.3.3 for more information).

5.1.2 Louisiana

5.1.2.1 Survey Methods

The sampling design for Louisiana data consists of fixed stations selected by coastal study areas to target areas known to have fish/shellfish when the sampling programs started.

> *Coastal Study Area (CSA) 1* is bordered on the east by the Mississippi River state line and on the south by Bayou Terre aux Boeufs, including such major water bodies as Chandeleur and Mississippi Sounds, and Lake Borgne, Pontchartrain, and Maurepas (Figure 5.2).
>
> *CSA 2* is bisected by the Mississippi River with Bay Terre aux Boeufs on the east, extending to Grand Bayou on the west. Some major water bodies found on the eastern side of the Mississippi River include Breton Sound, Black Bay, Bay Gardene, Little Lake, Bay Craba, American Bay, California Bay, Quarantine Bay and Grand Bay. Bay Adams, Bay Jacques, Skipjack Bay, Sandy Point Bay and Bay Lanaux are found on the western side of the Mississippi River.
>
> *CSA 3* includes Barataria and Caminada Bays and Little Lake. Grand Bayou is the eastern boundary and Bayou Lafourche is the western boundary.
>
> *CSA 4* is the Timbalier and Terrebonne Bay complex along with Lake Pelto. It is bounded on the east by Bayou Lafourche and on the west by Bayou Sale.
>
> *CSA 5* is defined by Bayou Sale on the east and Atchafalaya River/Point au Fer Island on the west. Large water bodies in this area are Caillou Bay, Caillou Lake, Lake Mechant, Lake Decade and Four League Bay.
>
> *CSA 6* extends from Atchafalaya River on the east to Freshwater Bayou on the west. Large water bodies in this area include Vermilion Bay, West Cote Blanche Bay, East Cote Blanche Bay and Atchafalaya Bay.
>
> *CSA 7* encompasses the region from Freshwater Bayou, located in Vermilion Parish, westward to the Louisiana/Texas state line. Estuaries located within CSA 7 include the Rockefeller Wildlife Refuge complex, the Mermentau River Basin, Calcasieu Lake, Lake Charles, Prien Lake and Sabine Lake.

At some stations, land loss due to subsidence, storms or anthropogenic activities has forced the station locations to move inland (e.g., shoreline seines, gill nets). In 2010, new stations were added for each gear. These stations were excluded from the analysis because they are not long-term stations.

The survey period for the 16-ft trawl data is 1967-2010, for the seine data it is 1986-2010, and for the gill net data the survey period is 1986-2010. Gear specifications for the trawls, seines, and gillnets can be found in Tables 5.1, 5.2, and 5.3.

The 16-ft flat otter trawl is used to sample penaeid shrimp, blue crabs, finfish (bottomfish), and other marine organisms in the larger inshore bays and in Louisiana's territorial waters. The 50-ft bag seine is used to sample juvenile finfish, shellfish, and other marine organisms to monitor relative abundance, size distribution, and seasonal/long term trends. A 750-ft experimental monofilament gill net is used to sample finfish to obtain indices of abundance, size distribution, and ancillary life history information on selected species.

The 16-ft trawl inshore sampling is conducted semi-monthly during November-February, then weekly during March-October. The offshore trawl samples are taken semi-monthly during November-March and monthly during April-October. The seine samples are carried out monthly during January-August, then semi-monthly during September-December. The gill net sampling is done monthly during October-March, then semi-monthly April-September.

The trawl body is constructed of ¾ in bar mesh No. 9 nylon mesh while the tail is constructed of ¼ in bar mesh knotted 35 lb tensile strength nylon and is 54-60 in long. The trawl is hung on ⅜ in PDP rope with four 3 in by 1½ in spongex floats on the corkline and with a minimum of 3½ ft extra rope on the corkline and leadline. The trawl has 16 ft and 20 ft of webbing along the cork and lead lines, respectively. Trawls are dipped in green plastic nylon net dip. The trawl boards are constructed of ¾ in marine plywood and measure 24 in across the top, 14 in at the back, and 10 in at the front with a 4 in rounded corner. The bridle is constructed of four lengths of galvanized 3⁄16 in chain while the bottom slide consists of a ⅜ in by 2 in, flat iron bar. The 16-ft trawl is attached to a ½ in diameter nylon rope or stainless steel tow line and bridle. The length of the bridle is 2-3 times the trawl width. Tow line length is normally at least 4-5 times the maximum depth of water. The trawl is towed for ten minutes (timed from when the trawl first begins to move forward to when it stops forward movement) at a constant speed and in a weaving or circular track to allow the prop wash to pass on either side of the trawl.

The ends of the seine are held open with 6-ft poles which are attached to the float and lead lines. Seine sampling techniques can be subdivided into two general types: soft bottom and hard bottom. Sampling methodology utilized at each station is identified. The seine is 50 ft in length, 6 ft in depth and has a 6x6 ft bag in the middle of the net. The nylon, tarred ace webbing has a mesh size of ¼ in bar. A lead and float line runs the entire length of the seine. The line is anchored to the shoreline by tying the end to a push pole, paddle, anchor or other structure. The boat is quietly reversed until the line is fully extended. At this point the boat is turned 90^{o} astern (parallel to the shoreline) and the seine is fed out over the boat's bow while making sure the cork line and bag are not tangled. As the end of the seine is placed overboard, the boat proceeds shoreward and is anchored or tied to the bank. The seine is hauled in by the two tow lines, with care being taken to keep the lead line on the bottom. The catch in the wings of the net is shaken down to the bag, and removed.

The experimental gill nets are 750 ft long, 8 ft deep, and comprised of five 150 ft panels of 1, $1\frac{1}{4}$, $1\frac{1}{2}$, $1\frac{3}{4}$, and 2 in bar mesh or 2.0, 2.5, 3, 3.5, and 4.0 in stretch mesh. The float line is $\frac{3}{8}$ in diameter hollow braided polypropylene and the lead line is #60 75 lead core, $\frac{5}{16}$ in diameter lead core line. For the gill nets, large floats and anchor weights are attached to the ends of the float line and lead line, respectively. Gill net deployment begins with the 1 in bar mesh end. After the float and weight are tossed overboard adjacent to or on a shoreline or reef, the gill net is deployed over the transom of the net well. The net may be set parallel to the shoreline or reef or in a crescent shape. Enough room is left on one side of the net to allow the net skiff to enter and then maneuver within the net. Fish are forced to strike the net by running the net skiff around both the inside and outside of the net a minimum of two or three times in gradually tightening circles. The net is then retrieved and pulled aboard from the downwind or down current end.

5.1.2.2 Biological and Physical Sampling Methods

All organisms collected in trawls are identified by species, counted, and up to 50 of each species measured in 5mm intervals. All organisms collected in seine samples are identified to species and counted. Sizes of up to 30 randomly selected individuals of targeted species are measured to the nearest mm total length. More specimens are measured if measurement of 30 (or general inspection of the sample) indicates that there may be more than one mode of length. All organisms captured in the gillnets are removed and placed in baskets corresponding to each mesh size or panel of the net. Organisms are noted as gilled or tangled (i.e., those fish which have not penetrated individual meshes to the back of the operculum). Up to 30 individuals of each target species are individually measured (total length in mm); remaining individuals of these species are counted. Other non-target species are counted and weighed in aggregate. Water temperature and salinity are measured at each station during each sampling event. In addition, information is recorded for blue crabs over 55mm for sex, maturity, and external parasites.

5.1.2.3 Ageing Methods

LDWF does not age blue crabs samples collected during fishery-independent monitoring.

5.1.2.4 Use for an index

Trawl fishery independent data from Louisiana were combined with the data from other states to create indices for use in the base run. Only those long-term fixed stations sampled consistently through time were included in index standardization. See Sections 5.2 and 5.3 for more information.

Gillnet and seine data were considered, but not put forth for use in index standardization due to inconsistencies in size measurements of blue crabs in most years which precluded development of size-specific IOAs for the Western GOM stock.

Note: only one fishery independent monitoring gear could be chosen from each state that was consistent with the other western stock states in order to create GLM standardized indices of abundance for the Western GOM stock (see section 5.3.3 for more information).

5.1.3 Mississippi

5.1.3.1 Survey Methods

Mississippi Department of Marine Resources (MDMR) and the Gulf Coast Research Laboratory (GCRL) collects fishery-independent data using trawls, seines, and beam plankton nets (BPLs). Gear descriptions can be found in Tables 5.1, 5.2, and 5.3. Trawl data have been collected from January 1974 to the present, seine data have been collected from January 1974 to the present, BPL data have been collected from January 1974 to the present, and gillnet data have been collected from October 2005 to the present.

Trawls are run at fixed stations (Figure 5.3) and do not target any specific species. Tows are 10 minutes at each station and no changes in methodology have occurred over time. The trawl has a 16 ft head rope and a 20 ft foot rope. The nets are made of nylon netting of the following size mesh and thread: $1\frac{1}{2}$ in stretch mesh #9 thread body, $1\frac{3}{8}$ in stretch mesh #18 thread cod end (80x100 deep) fully rigged with 2 in O.D. nylon net rings for purse rope, and no lazyline. Head and footropes of $\frac{3}{8}$ in diameter poly-dac net rope with legs extended 3 ft 6 in and rope thimbles spliced in at each end. Six $1\frac{1}{2}$ x $2\frac{1}{2}$ in sponge floats spaced evenly on bosom of headrope with $\frac{1}{8}$ in galvanized chain hung loop style on footrope. Nets treated in latex net dip on completion. Purse rope rigged on nets. Inner liner composed of $\frac{3}{8}$ in stretch mesh #63 knotless nylon netting inserted and hogtied in cod end to hold small specimens.

Seines are sampled at fixed stations (Figure 5.3) and do not target any specific species. Seines are 50 ft bag seines with $\frac{1}{4}$ in bar mesh. Bag seines are set by hand and pulled at various distances from the shoreline depending on the topography of the bottom each station. No changes in methodology have occurred over time.

Beam plankton nets (BPLs) are sampled at fixed stations (Figure 5.3) and do not target any specific species. The wing mesh size is $\frac{1}{16}$ in and the cod-end is 750 microns. An aluminum beam (about 6 feet long) was constructed which the net attaches to. The wings are about 5 ft wide which tapers down like a regular trawl and 28 inches deep, and the cod-end is about 3 ft long tapering down to a PVC tube with screened holes at the bottom. The net is pulled by hand for 50 m parallel to the shoreline, then turning around and pulling the net outside the previous track to the starting point. No changes in methodology have occurred over time.

5.1.3.2 Biological and Physical Sampling Methods

All organisms sampled in trawls, seines, and beam plankton nets (BPLs) are brought back to the lab for processing. All species are sorted, measured, and weighed. A minimum aliquot of 50 specimens, including the minimum and maximum sizes, are measured when the total number of a species exceeds 50. When 50 or fewer animals of a species are present, all are measured and weighed. In January 2009, the minimum aliquot was reduced to 20 specimens per species. Blue crabs are measured for carapace width (CW) recorded in mm. Weights were recorded in grams. Additional data collected on blue crabs includes missing parts (legs, broken spines, etc.), sex (for individuals > 20 mm), maturity, growth (hard, buster, soft, or paper), and presence of common parasites and epizoans. Temperature, salinity, and dissolved oxygen were sampled at each sampling location during each sample.

5.1.3.3 Ageing Methods

The MDMR and the GCRL do not age blue crab samples collected during fishery-independent monitoring.

5.1.3.4 Use for an Index

Trawl fishery-independent data from Mississippi were combined with the data from other states to create indices for use in the base run. See Sections 5.2 and 5.3 for more information.

Fishery-independent BPL data were considered, but not put forth for use in IOA standardization because most states did not collect this type of data consistently.

Seine data also were considered, but not put forth for use in IOA standardization for the western stock base run. Seine data, specifically the size measurements of blue crab, were not consistently collected in all western Gulf States and precluded development of size-specific IOAs.

Note: only one fishery independent monitoring gear could be chosen from each state that was consistent with the other western stock states in order to create GLM standardized indices of abundance for the Western GOM stock (see section 5.3.3 for more information).

5.1.4 Alabama

5.1.4.1 Survey Methods (Including Coverage, Intensity)

Trawls have been towed at fixed stations by the Alabama Marine Resources Division (AMRD) from 1981 to the present (Figure 5.4). The trawl gear has not changed over time. Trawls are 16 ft, flat two seam with 1.25 in stretch mesh (front) and 1.5 in stretch mesh (bag) with a 3/16 in liner. Trawls are towed for 10 minutes. Changes in the stations sampled have occurred over time with some stations being added and others dropped. Gear descriptions can be found in Tables 5.1, 5.2, and 5.3.

Seines have been used at fixed stations from 1981 to the present. The seine gear has not changed over time. Seines are 4 ft by 50 ft bag seines with bag dimension of 4 ft cubed. The mesh is knotless $^{3}/_{16}$ in mesh. Seines are pulled 60 ft toward shore, which means all pulls are perpendicular to shore. Stations are fixed, and numerous stations have been added or dropped over time, although some long running stations are consistent throughout the time series. The target species for the seine survey was juvenile mullet for two specific stations, otherwise no particular species was targeted.

Beam plankton and larvae (BPL) nets have been implemented from 1981 to the present. The BPL gear has not changed over time. BPL nets have a 1.8 m aluminum beam with 0.5 mm mesh. The opening is 150 cm by 83.8 cm, and the back of the net is 40 cm in diameter. Net depth is 100 cm in the center and 116 cm on the sides. The bag is detachable and has a 40 cm diameter opening. The bag is 100 cm deep and has a 9 cm opening for the cod end. The cod end is 3 in PVC with a 3 in cap with 16 holes of 0.5 mm screen. The BPL net is towed perpendicular to shore for 426 ft, and sampling does not target any specific species. Sampling occurs at fixed stations. Some stations have been added or dropped from sampling over time, but some long running stations are consistent throughout the time series.

A gillnet survey has been implemented from 2001 to the present. Gillnets used for sampling in Alabama were either small mesh gillnets or large mesh gillnets. The small mesh gillnet is composed of five panels (8 by 150 ft) of graduated mesh sizes (750 ft total). Mesh sizes begin with a 2 in stretch mesh and increase by ½ inch increments up to 4 in. Each mesh is color coded by a corresponding float (blue = 2, red =2.5, white = 3, green = 3.5, and gold = 4). Each large mesh gillnet is composed of four panels (8 by 150 ft) of graduated mesh sizes (600 ft total). Mesh sizes begin with a 4.5 in stretch mesh and increase by ½ inch increments up to 6 in. Meshes are color coded by a corresponding float (blue = 4.5, red =5, white = 5.5, and green = 6). The configuration of the large mesh net was changed in 2005 when a 4 in mesh was dropped. Nets are soaked for a period of one hour and do not target any specific species. Stations are selected using stratified random sampling with sampling sites being allocated based on variation in samples. Essentially this minimized samples in cold months and areas that did not catch fish, while maintaining a target of 240 sets per year.

5.1.4.2 Biological Sampling Methods (including coverage, intensity)

Prior to 2007 trawl samples were preserved in 10% formalin, and after 2007 samples were frozen until processing. Large adults if caught were measured for appropriate length, weighed using a spring scale, and released. Lab processing entails measuring up to 50 individuals in mm SL and obtaining the weight of the entire species catch on a bench scale. Water temperature, salinity, and dissolved oxygen were sampled at each station during each sample taken.

Samples taken during seine sampling are preserved in 5% formalin solution until processing. Large adults if caught are measured for appropriate length, weighed using a spring scale, and released. Lab processing entails measuring up to 50 individuals in mm SL and obtaining the weight of the entire species catch on a bench scale. Water temperature, salinity, and dissolved oxygen are sampled at each station during each sample taken.

Samples taken during beam plankton and larvae sampling are preserved in 5% formalin solution until processing. Lab processing entails measuring up to 50 individuals in mm SL and obtaining the weight of the entire species catch on a bench scale. Water temperature, salinity, and dissolved oxygen are sampled at each station during each sample taken.

Samples taken during gillnet sampling are placed on ice until processing. Field processing entails measuring up to 10 individuals in mm FL from each mesh size per species and obtaining a total count by mesh size. Species of interest are bagged, labeled, and are returned for lab processing. Lab processing includes measuring length, weight, and ovary weight; sexing; and otolith extraction. Water temperature, salinity, and dissolved oxygen are sampled at each station during each sample taken.

Finally, blue crabs collected in independent samples are examined for sex, health, and lifestage.

5.1.4.3 Ageing Methods

The AMRD does not age blue crabs samples collected during fishery-independent monitoring.

5.1.4.4 Use for an Index

Trawl fishery-independent data from Alabama were combined with the data from other states to create indices for use in the base run. See Sections 5.2 and 5.3 for more information.

Fishery independent BPL data were considered, but not put forth for use in the assessment model. BPL data are not consistently collected in all states and thus were thought not be as useful as other data sources.

Seine and gillnet data were considered, but not put forth for use in IOA standardization for the western stock base run. Seine and gillnet data, specifically the size measurements of blue crab, were not consistently collected in all western Gulf States and precluded development of size-specific IOAs.

Note: only one fishery independent monitoring gear could be chosen from each state that was consistent with the other western stock states in order to create GLM standardized indices of abundance for the Western GOM stock (see section 5.3.3 for more information).

5.1.5 Florida

5.1.5.1 Survey Methods (Including Coverage, Intensity)

Two sampling designs (stratified-random and fixed-station) were initially employed by the Florida Fish and Wildlife Conservation Commission's (FFWCC) Fisheries-Independent Monitoring (FIM) program to assess the status of fishery stocks in Florida estuaries. Fixed-station samples, however, cannot be statistically expanded to describe the fishery stocks beyond the actual sampling sites, while stratified-random samples can be extrapolated to describe an entire estuary. Monthly fixed-station sampling, therefore, was terminated in 1996. Monthly stratified-random sampling is currently conducted year-round using seines and trawls. A number of gears and locations have been sampled in the FIM program but not all are continuous. Figure 5.5 indicates the location and duration of the various collections in Florida. The primary sampling areas since 1997 along the west Florida coast are Apalachicola, Cedar Key, Charlotte Harbor, and Tampa Bay.

For stratified random sampling, estuarine systems are subdivided into zones delineated primarily on geographic and logistical criteria but which also define areas of greater biological and hydrographic homogeneity than the system as a whole. Zones are identified as being either bay or riverine. Both bay and riverine zones are subdivided into grids based upon a 1 x 1 minute cartographic grid that is overlaid on the entire system. Grids are further subdivided into microgrids using a 10 x 10 cell grid overlay.

In bay zones, grids have been stratified by depth and may be further stratified by habitat type. Depth identifies the gear types (trawl and/or seine) that can be used to sample each grid. Habitat stratification is gear and field lab specific. At field labs that stratify offshore seines by habitat, stratification is by the presence/absence of submerged aquatic vegetation and by the occurrence of a shoreline within the grid. At field labs that stratify the haul seines by habitat, stratification is based on the presence/absence of overhanging vegetation within the grid.

In riverine zones, microgrids are stratified by depth and may be further stratified by habitat type and salinity gradient. As with bay zones, depth identifies the gear types (trawls and/or seines) that can be used to sample each microgrid. At some field labs, the seines are further stratified by the presence/absence of overhanging vegetation within the microgrid. Rivers may also be stratified into subzones to ensure that the river's entire salinity gradient is sampled each month.

Differences in the scale of stratification between bay and riverine zones results in slightly different definitions of the primary sampling unit (sampling site) between the two zone types. Bay zone stratification has only been taken to the grid level, so the grid is randomly selected based upon strata, but the microgrid is simply a random number between 0 and 99. Therefore, the primary sampling unit in bay zones is a randomly selected microgrid within a randomly selected grid. In riverine zones, where stratification has been taken to the microgrid level, microgrids are randomly selected based on strata; the primary sampling unit, therefore, is a randomly selected microgrid. The number of sites to be sampled each month, for each gear and stratum within a given zone, is proportional to the total number of sampling sites that can be sampled within a particular stratum by a gear in an estuarine system. All sampling sites are selected and sampled without replacement each month. After site selections have been made for a month, zone boundaries are removed and sample sites are grouped to optimize sampling logistics. Once sampling groups have been identified, the order in which these groups are sampled during a given month is randomized.

Seines have been used for fishery-independent sampling from 1989 to the present and include both a 21.3-m beach seine and a 183-m haul seine. Sampling with the 21.3-m seine began in both Tampa Bay and Charlotte Harbor in 1989 for four and eight months of the year, respectively (CH: April, May, October and November; TB: March, April, May, June, September, October, November, and December). In 1992, sampling was expanded to include March and September in Charlotte Harbor. In 1996, the 183-m haul seine was instituted to target adult species, and monthly sampling was expanded to the focal estuaries along with the addition of other sampling locations. By 1997, monthly sampling was occurring at all of the sampling estuaries on the Gulf coast (including Cedar Key and Apalachicola Bay). Gear descriptions can be found in Table 5.1, 5.2, and 5.3.

The beach seine is a 21.3-m (~69 ft), 1.8-m deep center bag seine used to collect juvenile and small adult fish and macrocrustaceans along bay edges, river banks, shallow tidal flats and most areas where water depth is less than 1.5 m (1.8 m in rivers). Two techniques are currently employed by the FIM program to cover specific habitats. The bay technique samples areas where the water depth is less than 1.5 m, such as tidal flats, mangrove fringes, sea wall habitats, sloping beaches, and banks. The river technique samples riverine areas and tidal creeks where water depth typically increases rapidly (to not more than 1.8 m) from the shoreline, making it impossible to use the bay technique. The beach seine technique sampled shallow sloping beaches and banks and was discontinued in all areas by February 2001. The shoreline stratum was implemented January 1998 and replaced the beach seine technique in all areas by February 2001.

The 183-m center bag haul seine is used to catch larger sub-adult and adult crabs. The seine is 3.0-m deep with 38-mm stretch knotted nylon mesh. The seine is set in a rectangular shape along the shoreline from a small, shallow draft mullet skiff. Sampling is stratified in some bay systems into two habitat types (with and without overhanging shoreline vegetation). The gear is deployed from the rear of the boat near the shoreline. A sampler stays with the shore end of the net and boat moves away to deploy the remaining net in a box pattern, returning to shore where a second sampler takes the other end to shore. The shore-based samplers retrieve the net by hand until all the animals inside are funneled into the center bag removing any gilled fish along the way. The entire catch is then placed into a sample tub for work-up.

Trawls have been used for fishery independent sampling from 1989 to the present at a similar sampling frequency (bay and month) as the 21.3-m seine. A 6.1-m otter trawl with 38-mm stretch mesh and 3-mm mesh liner is used in the FIM program to sample areas of the estuarine system between 1.8 m and 7.6 m in depth. In addition to sampling areas of the bay not accessible to seines, trawls tend to collect epibenthic fish and macrocrustaceans that are larger than those typically collected in seines. Trawl tows last five to ten minutes based on the type of tow. The trawls are conical in shape with a wide elliptical mouth opening which gradually tapers backwards toward a narrow bag. Each side of the trawl mouth has lines attached to weighted doors. A tow line is tethered to each of these doors and is used to pull the net through the water. The trawl mouth is leaded at the base and floated on top. Running from the base of the doors is a long chain that is pulled just ahead of the mouth of the trawl. This is called a tickler chain and serves the purpose of scaring bottom organisms into the water column where they can be collected by the trawl. When the net is fishing, the doors are spread apart by the forward motion of the boat. This forward action opens the mouth of the trawl. Organisms on the bottom stirred up by the tickler chain and those already present in the water column are funneled down the trawl toward the bag where they are trapped. The bag is lined with a small-mesh liner and tied off at the end to prevent escapement of organisms.

5.1.5.2 Biological and Physical Sampling Methods

Temperature, dissolved oxygen, salinity, and multiple habitat descriptors (e.g., bottom vegetation, shoreline habitat) are sampled at each site, and all fishery samples collected by the collected by the FFWCC’s FIM program are processed following a standard set of protocols. All species of fish and select macroinvertebrates are worked up for each sample. Specimens are separated by species, selected randomly to be measured, and counted. The type, amount, and ratio of by-catch are recorded. If samples contain large numbers of specimens (>1000) sub-sampling may be used.

Crabs are identified and carapace width (CW) is measured in mm. Randomly select up to 10 individuals for each species <150 mm SL and up to 20 individuals for each species <150 mm SL (40 individuals prior to October 1997). If multiple size classes of a particular species exist, then 40 specimens from each size class should be measured. More than 40 specimens should be measured when a large size range exists with no clear size classes. If a sample has been sub-sampled and the species is present in both the split and unsplit portions, up to 40 specimens will be measured from each size class within both the split and unsplit portions. Count all individuals that were not measured. If different size classes were measured, then the number collected within each size class must be counted separately. In addition, blue crabs are examined and information is recorded on sex, health, and maturity in females.

5.1.5.3 Ageing Methods

FFWCC does not age blue crabs samples collected during fishery-independent monitoring.

5.1.5.4 Use for an Index

The 21.3m seine was instituted as a young-of-year sampling gear, and primarily catches young juvenile crabs (<50mm). The 6.1m otter trawl additionally catches juvenile crabs, but the magnitude of juvenile crabs caught per tow is substantially less than the 21.3m seine. As such, only the 21.3m seine was used for constructing the juvenile index. The 183-m haul seine and 6.1m otter trawl both catch adult crabs within the same order of magnitude, so both were used in developing the adult index. Given the relatively short time frame for which all sampling locations, months, and gear types were implemented in Florida (1997-present), effort was placed on developing juvenile and adult indices from the beginning of the FIM program (1989) when select gears and locations were first initiated. Indices for both stages were constructed starting in 1989 and in 1996 when monthly sampling began, and these were compared to determine the appropriateness of using the longer time frame index despite the unbalanced sampling frequency. Comparisons of the indices found the longer time frame had nearly identical relative indices of abundance to the shorter time frame, and was therefore used for the assessment. Although the variability for these initial years was greater due to the lower sampling frequencies, year-specific estimates of the index variability were incorporated into the assessment models to account for this discrepancy in sampling frequency.

5.1.6 SEAMAP Trawl Survey

5.1.6.1 Survey Methods (Including Coverage and Intensity)

SEAMAP (South East Area Monitoring and Assessment Program) surveys use trawl gear to collect fishery independent data (i.e. finfish, shrimp, and other invertebrates). The Summer and Fall Shrimp/Groundfish use the same survey design that has been used from 1987 to 2009. National Marine Fisheries Service (NMFS) in 2009 changed protocol from stations that were collected across a fathom stratum to a 30 minute fixed tow time; additionally, the designation of “day” and “night” stations was removed. State partners made this switch in 2010. Currently all SEAMAP trawls follow the same 30-minute tow time survey design. State and federal agencies collaboratively coordinate the scheduling of cruise dates and the selection of stations to be sampled by each agency, which results in a coordinated and cost-efficient program. Texas participates in the trawl survey; see Section 5.1.1.1 for more information on their gear.

SEAMAP sampling stations are chosen using a random design with proportional allocation by bottom area within shrimp statistical zones (Figure 5.6). Stations are sampled 24-hours a day, with a tow time (bottom time) of 30 minutes per station. A 42-foot SEAMAP trawl with $1\frac{5}{8}$ in stretched mesh is lowered to depth at each station and the towline is set at a 5:1 cable length water depth ratio. The desired vessel speed while towing is 2.5-3.0 knots.

5.1.6.2 Biological and Physical Sampling Methods

Temperature (air and water) was collected for each sampling station. Weight of the catch was recorded for individual species and for the catch as a whole. The number of individuals per species is also recorded. Up to 20 individuals of a species are measured for length with the appropriate measurement being used depending upon the species. Blue crabs are also examined for sex and maturity.

5.1.6.3 Ageing Methods

SEAMAP does not age blue crabs samples collected during fishery-independent monitoring.

5.1.6.4 Use for an Index

SEAMAP trawl data were not used for an index of abundance because data workshop participants thought that the samples were not representative of the range of blue crabs given the depth at which most samples had been taken and the blue crabs that were collected were primarily mature females. In the early data, there was some question as to the validity of small crabs identified as *Callinectes sapidus* in samples taken that far offshore. The possibility of confusion with the lesser blue crab, *C. similis*, precluded use of those data.

5.1.7 Environmental Data

Due to the relationship between blue crabs and freshwater inflow, data were collected on both precipitation and streamflow along the Gulf coast. Precipitation data were obtained by Gulf coast state from the National Climatic Data Center (http://www.ncdc.noaa.gov/) on a monthly basis from 1950-2012. Streamflow data were obtained from United States Geologic Survey (USGS) gauges (http://waterdata.usgs.gov/nwis/). To select appropriate streamflow gauges, GIS analyses were used to select all gauges within each hydrologic sub-basin unit near the coast (http://water.usgs.gov/GIS/huc.html) (Figure 5.7). Within each sub-basin, the gauges were then sorted to select a single gauge from each sub-basin with the highest average flow for the longest period of time spanning 1980-present. Gauges were restricted to a single gauge within each sub-basin in order to evenly distribute the signal along the stock distribution. The environmental data are presented in Figure 5.8.

5.2 Data Compilation for Use in an Index

Survey data were used to construct a recruit and adult index of abundance (IOA) for both the Western and Eastern GOM stock separately. Recruit and adult IOAs were also constructed for each of the Western GOM stock states separately and for only the northern GOM states (Louisiana, Mississippi, and Alabama) for use in sensitivity runs. Recruits were considered those individuals <=80mm carapace width (CW) sampled from October through March, which were the sizes and proportion of the survey year determined to best represent juvenile blue crab abundance. Juvenile blue crab catches in the months of January-March are considered previous year's catches. The midpoint of the juvenile indices (January 1st) corresponds with observed peaks in juvenile survey catches. Peaks in megalopae abundance are typically observed three months earlier (Rabalais et al. 1995). Adults were considered those individuals >=125mm (*i.e.*, harvestable size), sampled from April through September, which was the size and proportion of the survey year determined to best represent adult blue crab abundance. The midpoint of the adult indices (July 1st) corresponds with the average observed spawning peak reported for Texas (Daugherty 1952) and other regions along the northern GOM.

5.3 Methods

5.3.1 Standardization Approach

Standardized indices of abundance were calculated using a generalized linear modeling procedure (PROC GENMOD; SAS 1994) that combined the analysis of the binomial information on presence/absence with the lognormal-distributed positive catch data (a delta model, Lo et al. 1992) as:

$$I_y = c_y p_y \quad [1]$$

where c_y are estimated annual mean CPUEs of non-zero catches modeled as lognormal distributions and p_y are estimated annual mean probabilities of capture modeled as binomial distributions. The lognormal submodel considers only samples in which either adult or juvenile blue crab were captured (*i.e*., non-zero catches). The binomial model considers all samples (*i.e.*, the proportion of samples that captured juvenile or adult blue crab).

To determine the most appropriate models, factors were selected using a forward step-wise approach where each factor was added to each submodel individually and the resulting reduction in deviance per degree of freedom (Dev/DF) analyzed. The factor causing the greatest reduction in Dev/DF was then added to the base model. We assume that there are no significant interaction terms with year in this model and consider only the main effects. Criteria for model inclusion also include a reduction in Dev/DF$\geq$1% and a Chi-square significance test $\leq$0.05. This process was then repeated until no factor met criteria for model inclusion. Final year-specific least-square means estimates and standard errors were used to generate distributions from a Monte Carlo simulation (5000 Student's t distributed realizations), which were in turn used to determine the median catch rates and year-specific CVs for each IOA. Due to differences in the fisheries independent sampling programs among states, different gears and predictor variables were used in constructing the IOAs for each stock, while the standardization approach was the same among stocks.

5.3.2 Eastern GOM Stock

Data sampling with the recruit gear type (21.3m seines) began in FL in 1989 for select regions, leading to a juvenile IOA time series from 1989-2011. For the adult gear types, the 183m haul seines began in 1996, while the 6.1m otter trawls began in 1989 (Table 5.4). Typically the Florida Fisheries Independent Monitoring program uses the 183m seine as the preferred method for indexing blue crab abundance. Different combinations of gear types and years for the adult IOAs were compared (haul seine 1996-2011, otter trawl 1989-2011, and both seine and trawl 1989-2011), and found to be markedly similar in trends; therefore, the combined gear IOA was utilized to extend the adult IOA across the longest time period (Table 5.5).

5.3.2.1 Juvenile Index (Eastern)

For the Florida FIM program, a host of environmental variables were collected at each set location, including standard measurements (temperature, salinity, depth), and categorical measures of the habitat (bottom type, vegetation cover, shore structures, etc). A number of these variables were collapsed into a few general categories and included in the IOA standardization.

Response Variable:

CPUE **–** Catch per unit effort (CPUE) has units of catch/effort, where effort is calculated based on the area sampled per soak-time per set, and catch are the number of crabs caught per set.

Continuous Predictor Variables:

Temperature (natural logarithm of temperature)
Salinity (natural logarithm of salinity + 1.0)
Depth (natural logarithm of depth + 1.0)

Categorical Predictor Variables:

Year (must be included in each submodel to develop an annual IOA)
Bottom Type (collapsed to Mud versus Sand)
Vegetation Type (collapsed to SAV versus Unknown)
Shoreline Type (collapsed to Emergent versus Terrestrial)
Bay Zone (unique sampling locations broken down into multiple regions per bay system)
Gear (sub-categories within 21.3m seines, including boat versus beach)

Resulting submodels for the Eastern GOM stock juvenile IOA are as follows:

$$c \sim Year + Bay\ Zone + Gear + Bottom\ Type \qquad [2]$$

$$p \sim Year + Bay\ Zone + Gear \qquad [3]$$

Standard diagnostics for each submodel are presented **(**Figure 5.9).

5.3.2.2 Adult Index (Eastern)

The response and predictor variables for the Eastern GOM stock adult IOA were the same as the Eastern GOM stock juvenile IOA (section 5.3.2.1). The only exception from the juvenile IOA was in the "Gear" categorical predictor variable, which included the 183m haul seines and 6.1m otter trawls.

Resulting submodels for the Eastern GOM stock adult IOA are as follows:

$$c \sim Year + Gear + Salinity \quad [4]$$

$$p \sim Year + Bay\ Zone + Gear \quad [5]$$

Standard diagnostics for each submodel are presented (Figure 5.10).

5.3.3 Western GOM Stock

Different states have different survey gears and numbers of years of survey data available. To remain consistent with the available time-series of monthly blue crab landings used in the base run of the Western GOM stock, only the years 1985-2011 were used in index standardization. Due to inconsistencies in blue crab size measurements in seine and gillnet survey catches in these years, only blue crab catches from each states otter trawl gear were used in Western GOM stock IOA development. Sample sizes, number of positive samples, and blue crab catches used in juvenile and adult IOA development are presented (Tables 5.6 and 5.7).

5.3.3.1 Juvenile Index (Western)

Response Variable:

CPUE – Catch per unit effort (CPUE) has units of catch/effort, where effort is trawl tow time, and catch are the number of crabs caught per tow.

Continuous Predictor Variables:

Temperature (natural logarithm of temperature)
Salinity (natural logarithm of salinity + 1.0)
Depth (natural logarithm of depth + 1.0)

If values were missing for any of the factors listed above, then the arithmetic average of that factor by state, month, and bay/area was substituted.

Categorical Predictor Variables:

Year (must be included in each submodel to develop an annual IOA)
State (Only included in Western Stock IOAs; excluded from state-specific standardization)
Month

Bay/Area (only included in state-specific IOAs)

Resulting submodels for the Western GOM stock juvenile IOA are as follows:

Western GOM stock:

$$c \sim Year + State + Month + Salinity \quad [6]$$

$$p \sim Year + State + Month + Salinity \quad [7]$$

Standard diagnostics for each submodel are presented (Figure 5.11).

5.3.3.2 Adult Index (Western)

The response and predictor variables for the Western GOM stock adult IOAs were the same as the Western GOM stock juvenile IOAs (section 5.3.3.1).

Resulting submodels for the Western GOM stock adult IOA are as follows:

Western GOM stock:

$$c \sim Year + State + Month \quad [8]$$

$$p \sim Year + Month \quad [9]$$

Standard diagnostics for each submodel are presented (Figure 5.12).

5.4 Indices of Abundance

5.4.1 Eastern GOM Stock

5.4.1.1 Juvenile Index (Eastern)

The Eastern GOM stock juvenile index has been relatively stable from 1989-2011 without any observable long-term trend, but marked with significantly large fluctuations from year to year (Table 5.5, Figure 5.13). Years with high juveniles abundances often correspond to years with high adult abundances, and these years often follow a year with higher than average rainfall (Figure 5.14). The uncertainty surrounding this index has decreased over time as the sampling frequency was expanded through to 1997.

5.4.1.1 Adult Index (Eastern)

Similar to the juvenile index, the adult index has shown substantial year-to-year variability, often peaking on similar years with the juvenile index and one year following peaks in rainfall. However, the adult index is suggestive of a general decline in abundance over the full time frame, while the juvenile index has remained relatively flat (Figure 5.13). The uncertainty surrounding this index has decreased over time as with the juvenile index.

5.4.2.1 Juvenile Index (Western)

The juvenile IOA for the Western GOM stock showed an overall declining trend over time with large year classes observed in 1987, 1990, 1993 and 1997 and smaller peaks in 1999, 2005 and 2011 (Table 5.8, Figure 5.15). The uncertainty surrounding this index has remained stable over time. State-specific juvenile IOAs of the Western GOM stock are also presented. State-specific juvenile IOAs were positively correlated with each other (Table 5.10).

5.4.2.2 Adult Index (Western)

The adult IOA for the Western GOM stock showed a declining trend in earlier years of the time-series (1985-1995), but has remained relatively flat in recent years (1996-2011) with a substantial peak occurring in 2006 (Table 5.9, Figure 5.16). The uncertainty surrounding this index has remained stable over time. State-specific adult IOAs of the Western GOM stock are also presented. State-specific adult IOAs were positively correlated with each other with the exception of Louisiana and Mississippi (Table 5.10).

5.5 Length Compositions

5.5.1 Eastern GOM Stock

Size-frequency distributions for different size bins, gear types, and month of sampling are presented in Figures 5.17 and 5.18. Generally, juvenile crabs (<80mm) were caught in the highest frequency during the winter months (November through March), while adult crabs (>125mm) were caught in the greatest frequency during the summer months (April through October).

5.5.2 Western GOM Stock

Size-frequency distributions for different size bins and month of sampling for the 16’ trawl survey gear are presented in Figures 5.19 and 5.20. Generally, juvenile crabs (<80mm) were caught in the highest frequency during the winter months (November through March), while adult crabs (>125mm) were caught in the greatest frequency during the summer months (April through October).

Table 5.1 Fishery-independent gear descriptions by state for gillnets.

	Texas	Louisiana	Mississippi	Alabama	Florida
Length (ft)	600	750	750	750(1), 600 (2)	NA
Mesh size (in)/type	3,4,5,6	2,2.5,3,3.5,4	2,2.5,3,3.5,4	(1)2,2.5,3,3.5,4 (2) 4.5,5,5.5,6	
	stretch	stretch	stretch	stretch	
Net height (ft)	4	8	6	8	
Effort	hours	strike net	1 hour	1 hour	
Rough size ranges	243-289	100-200	180-220	95-241	
Length units	TL	TL	TL	FL	

**Note that the rough size ranges are in the length units specified.

Table 5.2. Fishery-independent gear descriptions by state for seines.

	Texas	Louisiana	Mississippi	Alabama	Florida	
Gear length	60-ft bag seine	50-ft bag seine	50-ft bag seine	50-ft bag seine	21.3 m bag seine	183-m haul seine
Gear height (ft)				4		
Legs length (ft)	60	50	50	50		
Bag dimensions	1.8 m wide	6 X 6ft	1.5 m^3	4 x 4 x 4ft	1.8 m^3	3 x 3 x 3m
Mesh size	1/2in	1/4in bar mesh	1/4 in bar mesh	3/16in knotless	3.1mm	38.1mm
Effort	3,229 ft^2	982 ft^2	3,432 ft^2	2,400 ft^2	1,507 and 723 ft^2	4,120 m^2
Rough size ranges	38-74	25-44	21-54	45	22-55	
length units	TL	TL	SL	SL	SL	

**Note that the rough size ranges are in the length units specified.

Table 5.3. Fishery-independent gear descriptions by state for trawls.

State	Texas	Louisiana	Mississippi	Alabama	Florida
Gear name	20-ft trawl	16-ft flat trawl	16-ft trawl	16-ft flat 2-seam trawl	20-ft trawl
Door Length (in)	48	24	36	24	36
Door Height (in)	18	14	18	12.5	18
Leg length (ft)	1.5	1		6	4
Net Footrope (ft)			20	17.8	21.5
Net Headrope (ft)	20	16	16	14.2	20
Bag Length (ft)		4.9		2	7
Mesh Body (in)/Front	1.5 stretch	1.5 stretch	1.5 stretch	1.37 stretch	1.5 stretch
Mesh Cod/Bag (in)	1.5 stretch	0.5 stretch	1 3/8 stretch and 3/8 stretch liner	1.75 cover and 3/16 knotless bar liner	1/8 knotless bar
No. of weights	1 per foot	1/4in chain along the footrope webbing	1/8 in chain hung loop style on footrope	3/16in chain, 17 links = 1 chain, 7 chains along footrope	1/4in chain along the footrope webbing
Weight size	2 oz/ weight			7 chains=4 lbs	
No. of Floats		4	6	2	4
Float Dimensions		2.5 x 1in	1.5 x 2.5 in	3 x 3in	2.5 x 1in
Tickler Length	none	none	none	none	24ft of ¼in chain
Effort	10 minute tow	10 minute tow	10 minute tow	10 minute tow	timed tow
Rough size range	116-151 67-123	20-85	37-85	50-70	21-64
length measurement	TL	TL	SL	SL	SL

**Note that the rough size ranges are in the length units specified.

Table 5.4 Florida fisheries independent monitoring sampling for the three gears used in the index of abundance calculations. The 21.3-m seines were used for juveniles, while the 183-m seines and 6.1m otter trawls were combined for adults. Note: these data include all samples recorded, while some samples were removed from the IOA calculations due to missing fields.

Year	21.3-m Seines			183-m Seines			6.1-m Otter Trawls		
	Total Trips	Positive Trips	Total Crabs	Total Trips	Positive Trips	Total Crabs	Total Trips	Positive Trips	Total Crabs
1989	186	48	237				161	73	688
1990	218	47	256				190	88	437
1991	241	65	335				193	65	260
1992	249	90	408				184	104	431
1993	245	67	226				182	80	452
1994	262	52	210				192	68	397
1995	592	164	575				460	146	738
1996	1,542	414	1,488	312	121	769	732	354	1,836
1997	1,680	388	2,143	836	179	672	830	290	1,231
1998	1,332	502	3,508	1,077	432	3,978	313	226	2,135
1999	1,404	505	3,039	1,414	419	2,266	372	197	1,694
2000	1,446	430	2,039	1,442	281	915	414	185	747
2001	1,769	500	2,336	1,402	245	776	669	262	1,166
2002	1,776	356	1,161	1,342	259	805	684	230	1,058
2003	1,852	550	2,480	1,344	326	939	720	271	1,133
2004	2,304	763	3,420	1,354	488	1,782	899	473	2,685
2005	2,412	648	2,224	923	293	1,100	1,260	598	2,999
2006	2,411	707	3,463	924	386	2,255	1,260	754	4,704
2007	2,411	658	3,948	924	292	1,169	1,260	648	3,759
2008	2,171	418	1,652	924	184	387	1,164	371	1,442
2009	2,172	377	1,799	887	187	478	1,163	266	975
2010	2,040	536	2,576	852	307	1,452	1,098	434	2,120
2011	2,039	648	3,538	852	272	1,394	1,104	446	3,055

Table 5.5 Indices of abundance (IOAs) for the Florida Gulf coast. For the recruits, the IOA was limited to 21.3m seines. For adults, IOAs were calculated separately for both gears, and using both gears combined. Although the combined IOA had an unbalanced design with years, the results were near identical to an IOA where the years were restricted to all full years (1996-2011); therefore, the full time series was used to fit the base model.

Year	Juveniles		Adults					
	21.3m Seine		183m Seine		6.1m Otter Trawl		Both Gears	
	CPUE	CV	CPUE	CV	CPUE	CV	CPUE	CV
1989	1.00	36.66			2.20	38.86	2.80	37.44
1990	0.28	44.07			0.84	39.49	1.09	40.08
1991	1.14	28.83			0.58	41.64	0.79	40.65
1992	0.93	29.76			1.84	34.16	2.13	33.99
1993	0.79	27.79			0.49	44.67	0.64	44.52
1994	0.64	24.27			0.74	49.71	0.99	50.85
1995	0.83	13.04			0.43	34.60	0.60	33.49
1996	0.71	11.52	1.75	20.81	1.64	21.07	1.45	14.49
1997	0.97	11.95	0.57	20.32	0.41	31.05	0.46	16.69
1998	2.01	10.93	2.04	11.93	3.64	53.87	1.92	11.62
1999	1.30	11.38	0.84	12.82	0.88	71.74	0.79	12.20
2000	1.08	10.80	0.44	16.20	0.17	163.63	0.41	15.76
2001	0.77	11.29	0.29	18.58	0.35	50.47	0.28	17.13
2002	0.64	11.36	0.44	15.66	0.36	82.93	0.39	15.20
2003	1.78	9.16	0.82	13.12	0.32	89.46	0.67	12.76
2004	1.11	9.32	1.11	11.73	1.77	23.05	1.14	10.34
2005	0.85	9.36	1.22	13.74	0.88	17.34	1.02	10.67
2006	1.60	9.17	2.38	12.47	2.65	13.01	2.30	9.45
2007	0.83	10.13	0.77	16.00	0.95	16.39	0.74	11.50
2008	0.57	10.67	0.22	25.84	0.22	35.68	0.19	20.75
2009	0.73	10.62	0.43	18.79	0.06	67.72	0.24	17.80
2010	1.67	9.82	1.59	13.52	0.92	19.26	1.17	11.01
2011	0.77	14.92	1.08	14.52	0.66	19.51	0.78	11.83

Table 5.6 Western Gulf Coast state's fisheries independent monitoring sampling for otter trawls used in juvenile IOA calculations (1985-2011). *Note:* Year reflects timing year used in assessment stage model where recruits are measured from October to December in $year_x$ and January to March in $year_x + 1$.

Year	Alabama			Louisiana			Mississippi			Texas		
	6.1-m Otter Trawls			6.1-m Otter Trawls			6.1-m Otter Trawls			6.1-m Otter Trawls		
	Total Trips	Positive Trips	Total Crabs	Total Trips	Positive Trips	Total Crabs	Total Trips	Positive Trips	Total Crabs	Total Trips	Positive Trips	Total Crabs
1985	115	53	2,577	401	227	6,730	48	20	390	780	250	1,731
1986	124	66	2,223	320	173	5,613	48	22	575	840	202	954
1987	158	84	3,145	329	186	9,379	47	23	261	898	269	3,616
1988	88	25	868	414	175	5,035	48	25	216	900	238	2,680
1989	96	34	1,133	369	183	8,317	23	14	303	870	285	2,644
1990	107	47	2,406	411	252	15,647	24	10	213	837	230	3,586
1991	113	41	605	409	211	7,472	24	8	42	838	278	5,531
1992	117	31	388	381	165	5,721	23	5	14	838	261	3,818
1993	98	32	523	378	228	14,170	23	5	16	837	247	2,360
1994	109	37	1,149	417	219	8,496	24	12	153	840	245	2,030
1995	97	30	364	423	212	7,095	24	8	110	840	202	781
1996	112	47	1,450	394	201	5,236	24	14	140	840	171	573
1997	113	49	1,920	501	318	16,372	23	14	172	840	224	1,406
1998	75	22	232	541	235	3,431	24	6	12	840	236	1,441
1999	91	23	223	526	257	9,146	23	4	9	840	178	647
2000	123	24	142	507	235	5,499	21	3	3	840	125	275
2001	129	27	187	533	247	4,964	21	6	36	840	142	425
2002	129	23	150	505	211	3,378	23	8	42	840	189	895
2003	132	55	2,732	510	250	6,824	24	9	43	840	145	443
2004	149	35	350	551	324	15,213	24	2	1	840	178	503
2005	140	38	668	506	298	8,906	24	9	70	840	146	273
2006	141	37	608	545	267	6,181	22	3	3	840	118	195
2007	148	28	218	530	261	7,888	24	7	35	840	132	216
2008	134	19	69	542	255	4,838	27	3	2	840	161	478
2009	139	24	194	525	251	4,311	24	1	0	840	86	97
2010	126	22	262	420	153	3,685	24	1	0	840	156	811
2011	68	15	312	417	177	7,205	16	1	0	420	34	35

Table 5.7 Western Gulf Coast state's fisheries independent monitoring sampling for otter trawls used in adult IOA calculations (1985-2011). *Note:* Year reflects timing year used in assessment stage model where adults are measured from April to September of each year.

Year	Alabama			Louisiana			Mississippi			Texas		
	6.1-m Otter Trawls			6.1-m Otter Trawls			6.1-m Otter Trawls			6.1-m Otter Trawls		
	Total Trips	Positive Trips	Total Crabs	Total Trips	Positive Trips	Total Crabs	Total Trips	Positive Trips	Total Crabs	Total Trips	Positive Trips	Total Crabs
1985	101	45	527	652	322	2,874	48	6	11	720	324	1,813
1986	141	72	818	534	267	2,351	48	12	27	840	360	1,975
1987	155	28	108	645	256	1,505	47	7	10	900	380	2,858
1988	112	28	146	613	200	729	48	11	22	900	286	1,445
1989	103	36	568	551	158	645	48	15	86	900	227	787
1990	107	37	305	663	285	2,568	24	5	14	840	273	1,342
1991	107	35	259	666	277	2,298	24	1	0	840	285	1,250
1992	128	35	322	614	167	503	24	2	1	839	234	1,181
1993	119	31	206	608	166	614	23	4	4	840	353	2,675
1994	125	22	116	597	133	333	24	5	8	840	241	1,171
1995	112	27	116	669	89	92	24	4	9	840	138	240
1996	112	20	102	647	104	186	24	9	41	840	180	450
1997	115	25	124	669	159	400	24	8	28	840	215	619
1998	110	26	142	661	152	482	24	3	4	840	272	1,133
1999	80	16	55	676	160	579	24	3	3	840	167	322
2000	90	18	86	671	175	571	24	5	6	840	128	233
2001	159	44	252	692	137	246	24	7	23	840	169	409
2002	155	31	137	705	172	675	24	3	3	840	191	452
2003	159	46	434	688	125	276	24	4	4	840	204	595
2004	172	66	776	655	141	392	24	4	4	840	193	485
2005	141	19	43	603	181	1,166	24	2	1	840	122	170
2006	142	26	114	666	391	4,715	24	2	2	840	123	163
2007	147	13	21	632	220	1,223	24	4	4	839	207	631
2008	145	12	20	694	170	670	23	1	0	840	190	459
2009	137	16	36	667	244	1,652	24	2	2	839	159	373
2010	135	24	179	604	157	574	24	6	15	840	157	320
2011	134	23	119	650	195	1,336	24	1	0	840	132	203

Table 5.8 Juvenile IOAs for each state and one standardized index for the Western GOM stock (1985-2011).

Year	Alabama 6.1-m Otter Trawls		Louisiana 6.1-m Otter Trawls		Mississippi 6.1-m Otter Trawls		Texas 6.1-m Otter Trawls		Western Gulf All trawls	
	CPUE	CV	CPUE	CV	CPUE	CV	CPUE	CV	CPUE	CV
1985	25.46	27.10	14.22	14.80	9.72	42.10	3.72	9.97	8.03	8.38
1986	15.35	25.78	15.16	16.69	8.30	41.16	2.24	10.96	6.01	8.47
1987	25.85	22.51	20.13	16.69	7.72	41.44	4.81	9.57	10.52	8.30
1988	13.84	34.14	12.54	14.51	7.27	40.99	5.30	10.21	8.52	8.66
1989	11.80	30.98	16.27	15.45	12.26	66.91	5.02	9.68	9.68	8.73
1990	22.97	27.83	24.66	14.78	16.72	66.49	5.31	10.41	11.82	8.32
1991	9.87	28.22	14.56	14.68	5.94	72.91	4.80	9.88	7.93	8.46
1992	5.74	30.06	10.74	15.12	2.44	94.17	4.81	10.14	7.16	8.76
1993	12.59	31.57	22.51	15.19	2.42	91.71	4.11	10.03	9.50	8.71
1994	13.10	29.38	16.31	14.29	9.48	61.10	3.63	10.22	7.71	8.50
1995	5.94	32.82	14.80	14.09	9.68	71.29	2.73	10.72	6.22	8.65
1996	14.44	27.34	12.26	15.21	9.18	60.06	2.08	11.49	5.53	8.91
1997	19.10	27.60	23.44	13.69	10.03	67.70	2.88	10.51	8.71	8.05
1998	7.25	38.04	6.85	12.69	2.36	85.40	2.80	10.07	4.12	8.42
1999	9.43	37.39	18.22	13.26	4.51	124.04	2.79	11.47	7.09	8.62
2000	3.07	34.91	12.23	13.39	1.55	153.80	1.41	12.74	4.00	9.17
2001	5.71	32.43	9.07	12.81	4.02	82.80	1.45	12.31	3.49	8.65
2002	3.02	34.83	6.73	13.00	4.00	67.99	1.68	11.13	3.06	8.86
2003	21.38	25.52	10.67	13.46	3.69	62.90	1.54	12.20	4.52	8.36
2004	4.91	28.30	16.11	12.31	1.55	510.48	1.46	11.38	4.97	8.11
2005	7.73	28.40	15.98	13.24	7.93	65.40	1.62	12.36	5.57	8.47
2006	10.49	28.54	10.00	12.84	1.79	147.96	1.17	13.29	3.74	8.88
2007	6.08	31.01	11.78	12.63	4.08	77.37	1.09	12.78	3.84	8.74
2008	2.73	36.90	10.28	12.82	1.33	157.70	2.32	11.63	4.49	8.78
2009	2.66	33.16	6.77	12.55	0.44	226.94	0.72	15.59	2.32	9.28
2010	8.38	34.68	9.03	15.09	0.65	143.37	2.13	12.08	4.20	9.60
2011	15.38	45.31	14.48	14.54	1.44	161.12	1.98	24.74	6.11	11.72

Table 5.9 Adult IOAs for each state and one standardized index for the Western GOM stock (1985-2011).

Year	Alabama		Louisiana		Mississippi		Texas		Western Gulf	
	6.1-m Otter Trawls		6.1-m Otter Trawls		6.1-m Otter Trawls		6.1-m Otter Trawls		All trawls	
	CPUE	CV	CPUE	CV	CPUE	CV	CPUE	CV	CPUE	CV
1985	9.47	24.07	6.43	10.00	1.79	54.88	3.95	9.19	5.46	6.44
1986	9.33	20.98	6.03	11.00	2.49	41.04	4.40	8.36	5.47	6.52
1987	3.19	25.59	4.41	9.83	1.33	50.30	5.00	8.36	4.95	6.21
1988	4.15	26.40	2.93	10.69	2.07	41.84	3.21	8.69	3.42	6.66
1989	9.37	25.37	2.95	11.75	4.21	37.73	2.28	9.15	3.10	6.92
1990	6.22	24.92	5.61	9.72	2.26	70.67	3.42	8.86	4.72	6.45
1991	5.48	24.78	5.32	9.65	0.37	174.19	3.19	8.73	4.41	6.44
1992	6.52	24.11	2.43	11.13	0.88	230.97	3.16	9.37	3.22	6.83
1993	5.47	25.59	2.53	11.01	1.16	82.54	5.38	8.45	4.54	6.51
1994	3.46	28.76	1.90	12.09	1.43	68.44	3.12	9.09	2.91	7.17
1995	3.95	27.34	0.89	13.96	1.70	87.33	1.31	11.34	1.35	8.35
1996	4.37	30.90	1.34	13.20	3.79	53.54	1.77	10.10	1.90	7.73
1997	3.95	27.90	1.98	11.05	3.27	57.69	2.23	9.44	2.44	7.05
1998	4.38	27.43	2.15	11.20	1.39	90.22	3.06	8.86	2.98	6.92
1999	3.23	35.08	2.32	11.08	1.28	92.93	1.54	10.35	2.14	7.51
2000	3.95	32.90	2.48	10.68	1.70	70.84	1.19	11.25	1.98	7.58
2001	4.83	20.94	1.53	11.82	2.70	60.23	1.72	10.38	1.97	7.25
2002	3.96	24.49	2.63	10.83	1.19	92.50	1.82	9.85	2.43	7.03
2003	7.73	21.49	1.61	12.02	1.07	85.32	2.08	9.52	2.33	7.12
2004	8.45	19.10	1.95	11.42	1.13	82.80	1.90	9.77	2.44	7.11
2005	1.99	30.73	3.95	11.13	0.70	151.69	1.05	11.68	2.29	7.61
2006	3.62	26.85	8.37	10.07	1.37	162.49	1.05	11.78	4.21	6.47
2007	1.61	36.89	3.78	10.39	1.42	77.97	2.27	9.49	3.01	6.93
2008	1.54	38.11	2.41	10.76	0.44	204.58	1.88	9.88	2.25	7.30
2009	2.12	33.12	3.90	9.77	1.28	222.57	1.61	10.47	2.75	6.95
2010	5.43	27.07	2.77	11.28	2.49	64.25	1.65	10.50	2.44	7.52
2011	4.41	28.68	3.73	10.47	0.47	207.80	1.22	11.23	2.48	7.35

Table 5.10 Correlation analysis (Pearson correlation coefficients) of each Western GOM stock by state for each juvenile and adult IOA.

Juveniles	LA	TX	MS	AL
LA	--			
TX	0.52	--		
MS	0.61	0.56	--	
AL	0.58	0.89	0.59	--

Adults	LA	TX	MS	AL
LA	--			
TX	0.24	--		
MS	-0.14	0.01	--	
AL	0.16	0.36	0.34	--

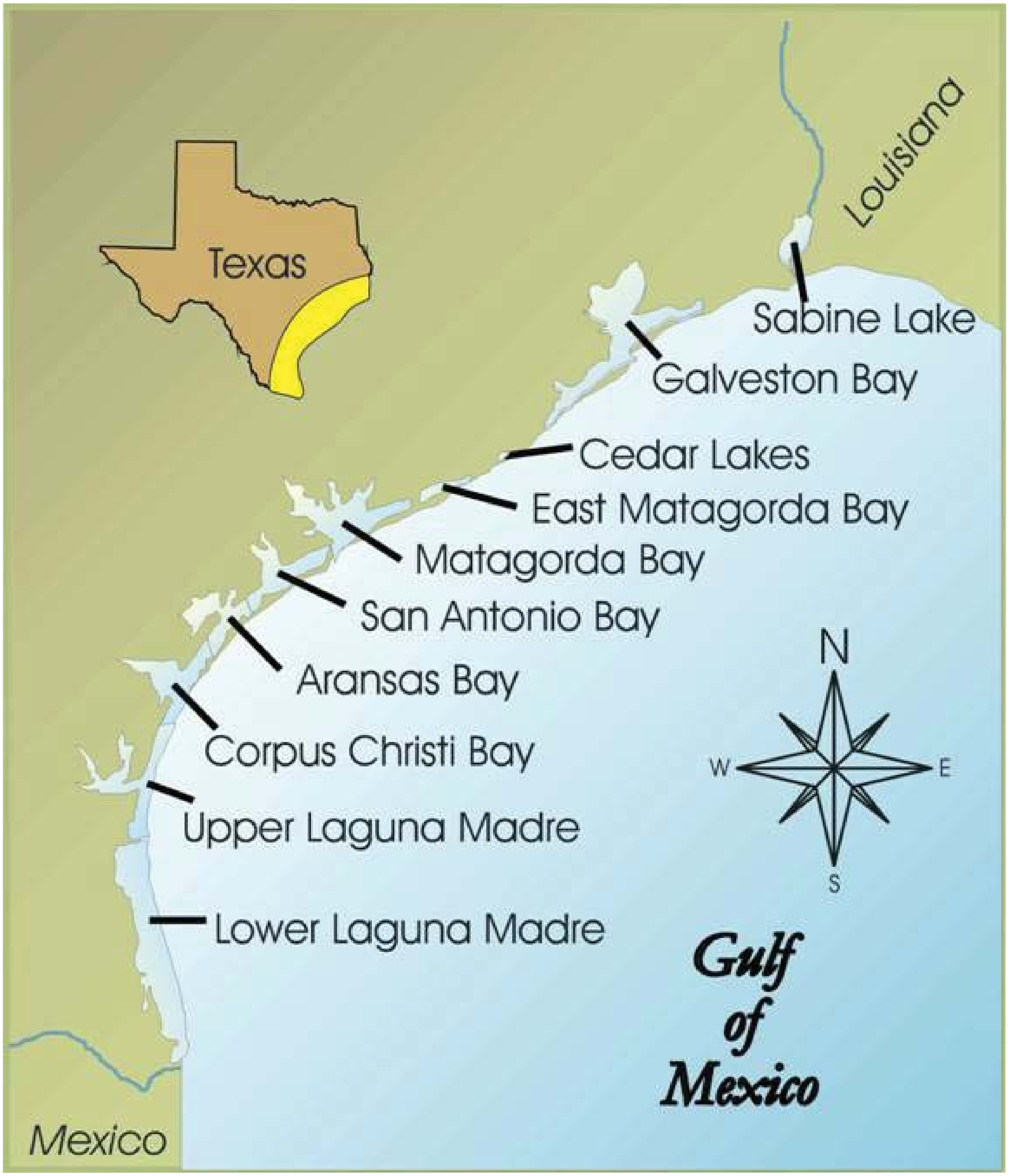

Figure 5.1 Map of Texas bay systems.

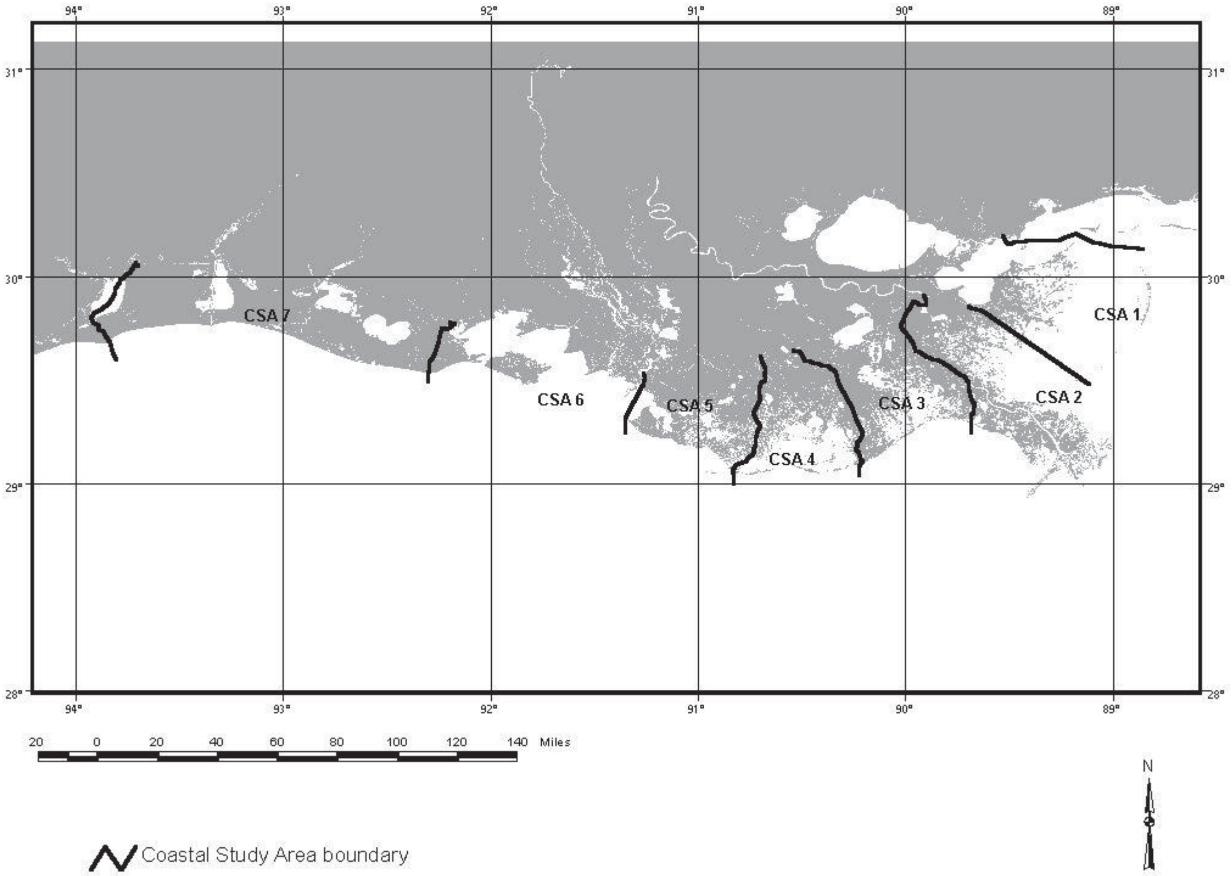

Figure 5.2 Map showing the boundaries of the 7 coastal study areas (i.e., management units) for Louisiana Department of Wildlife and Fisheries. The boundaries are generally delineated by river basins.

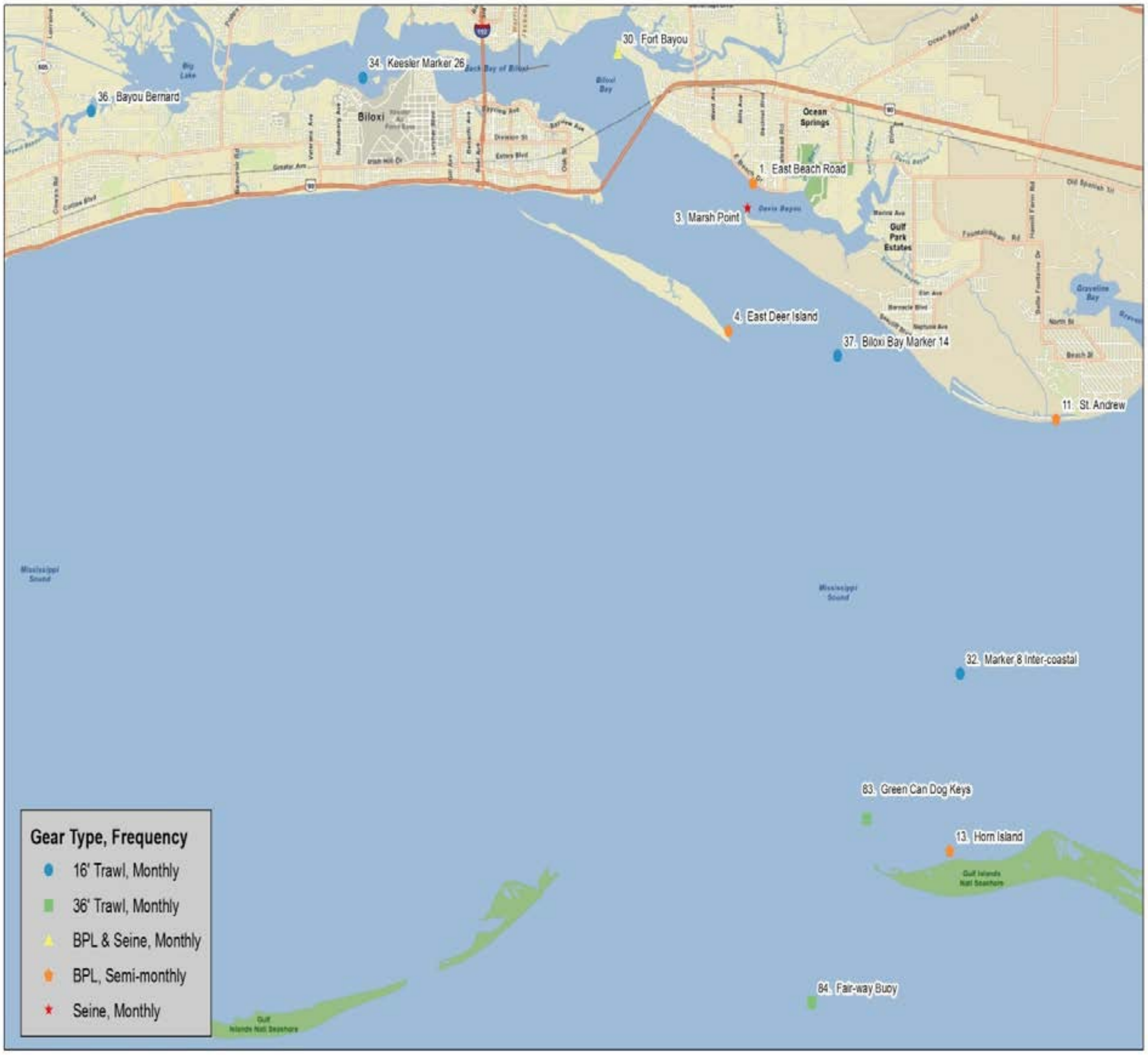

Figure 5.3 Fixed seine, trawl, and beam plankton net (BPL) stations for fishery-independent sampling conducted by Mississippi Department of Marine Resources and the Gulf Coast Research Laboratory. Seines are pulled at stations 3 and 30. 16ft trawls are pulled at stations 32, 37, 34, and 36. BPLs are pulled at stations 11 and 1.

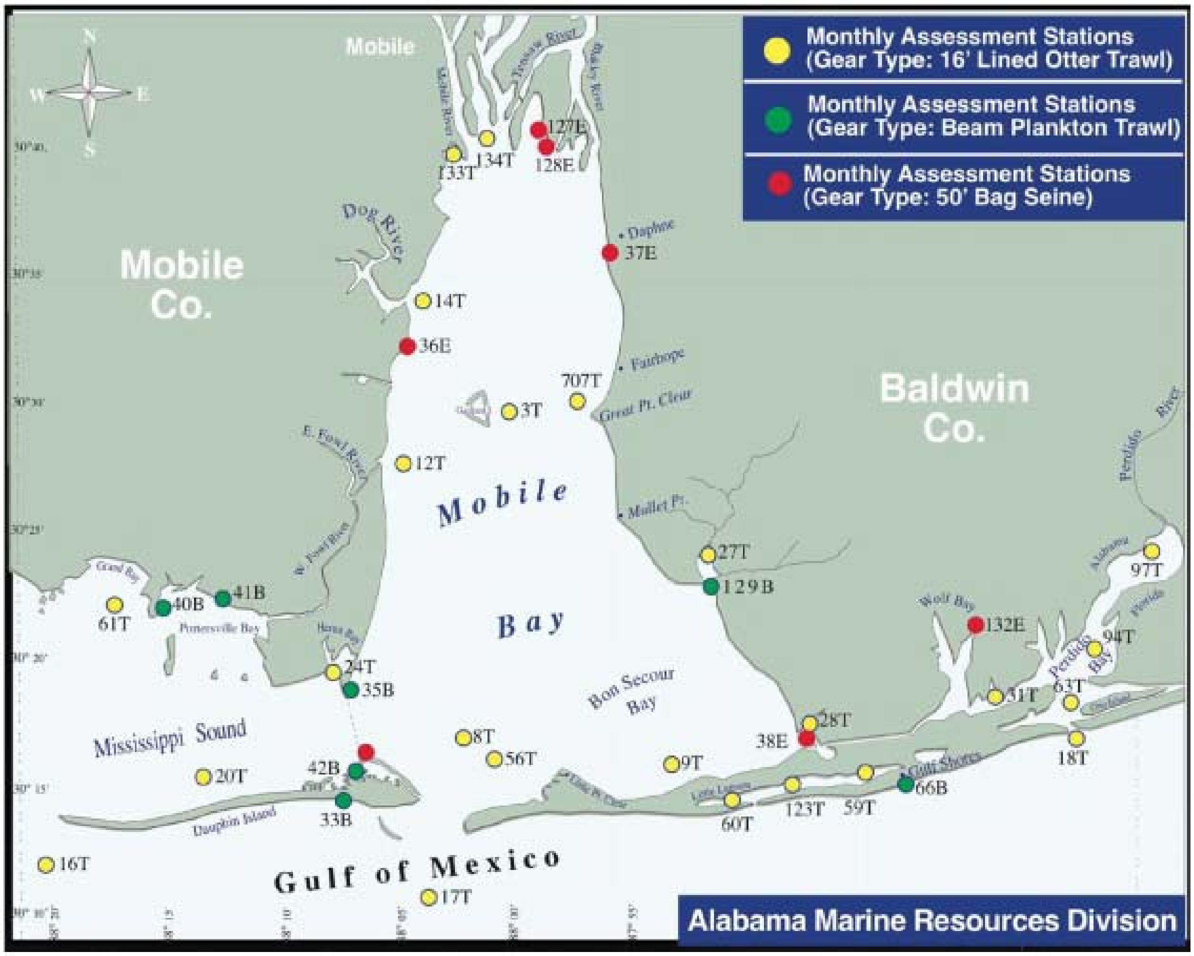

Figure 5.4 Fixed seine, trawl, and beam plankton trawl (BPL) stations for fishery-independent sampling conducted by Alabama Marine Resources Division.

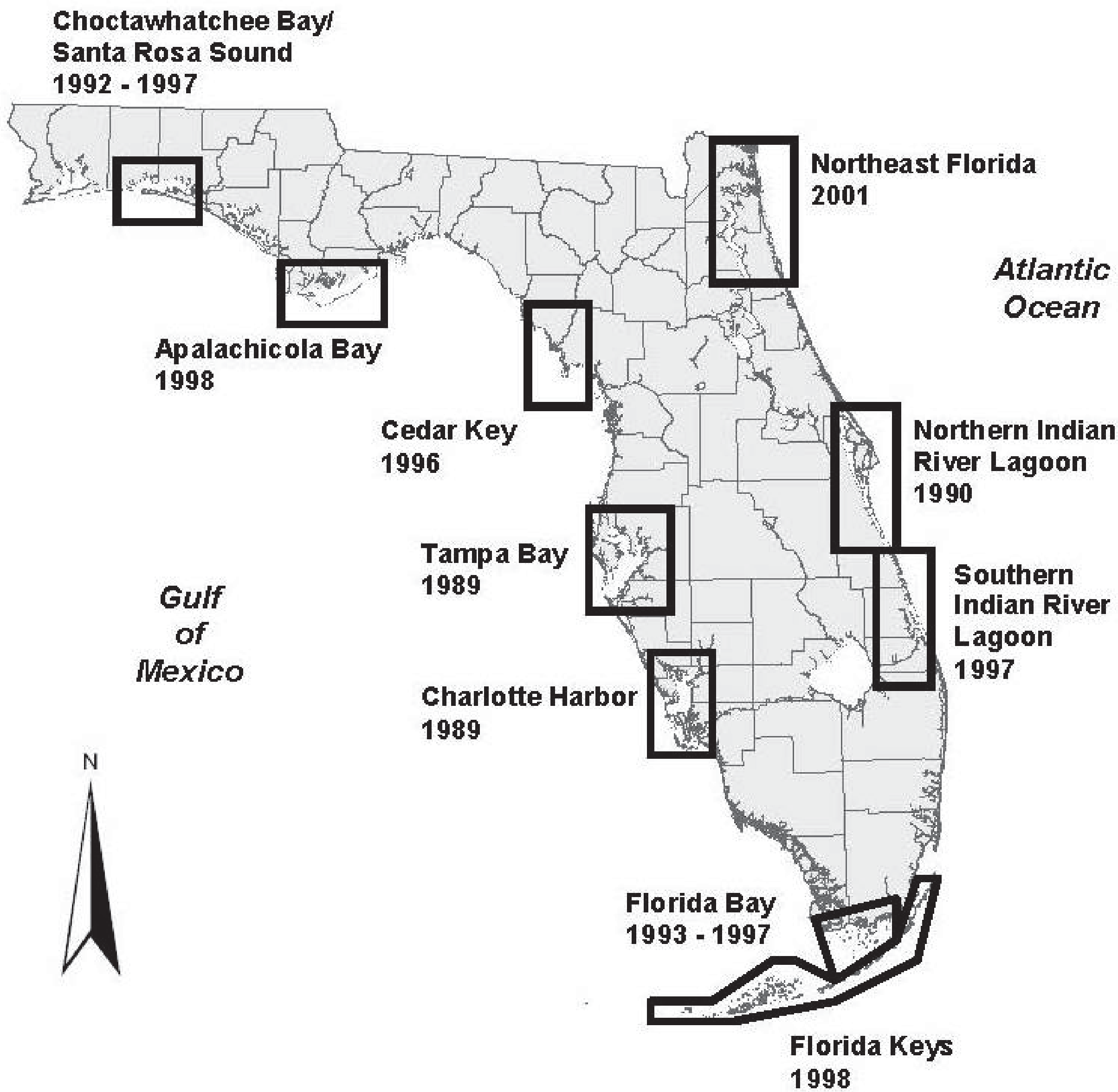

Figure 5.5 Locations of Fisheries-Independent Monitoring (FIM) program field laboratories for FWC. Years indicate initiation of sampling. If sampling was discontinued at a field lab, the last year of sampling is also provided.

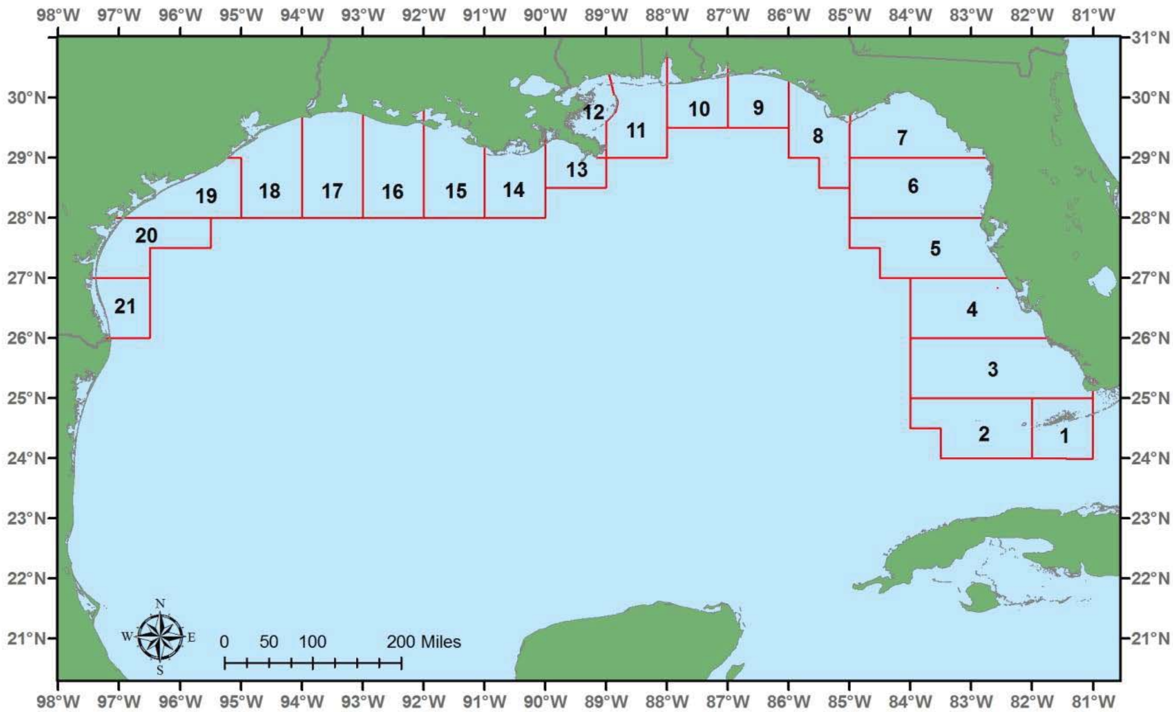

Figure 5.6 NMFS Gulf Shrimp Landing Statistical Zones.

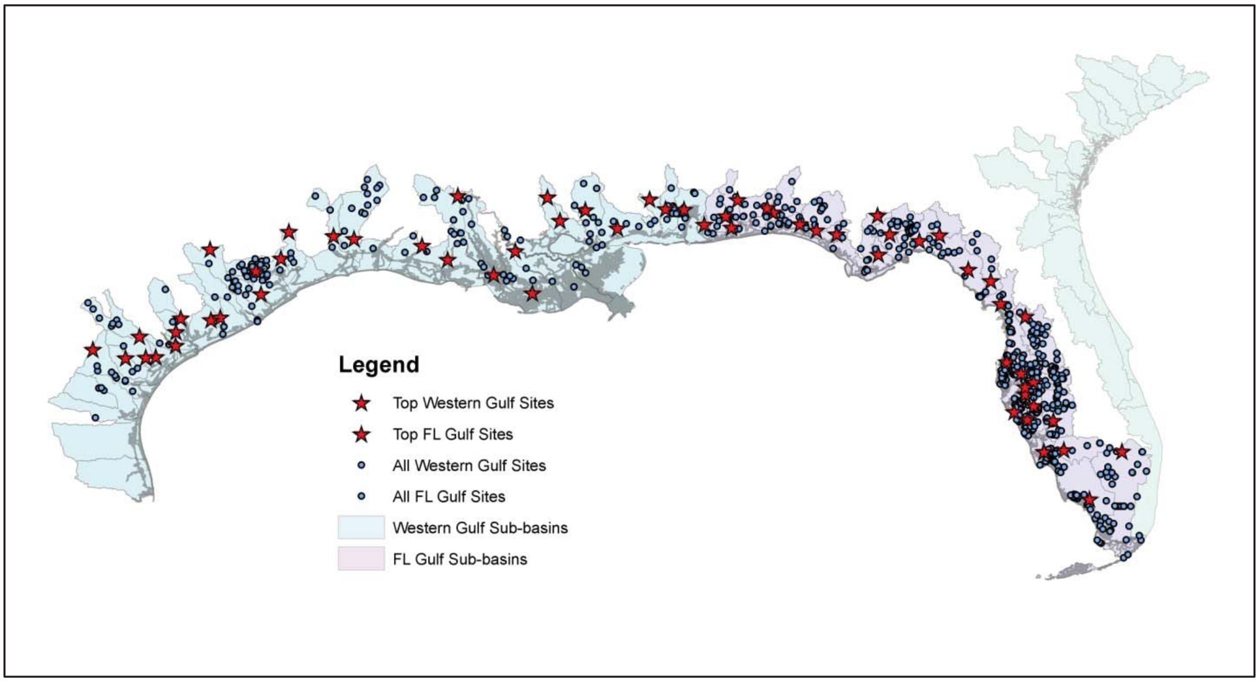

Figure 5.7 United States Geologic Service gauges used to extract streamflow data. For each hydrologic sub-basin (blue and pink polygons for the Western and Eastern GOM stock, respectively), a single gauge was selected that had the highest average flow and the longest period of data collection from 1980-2011.

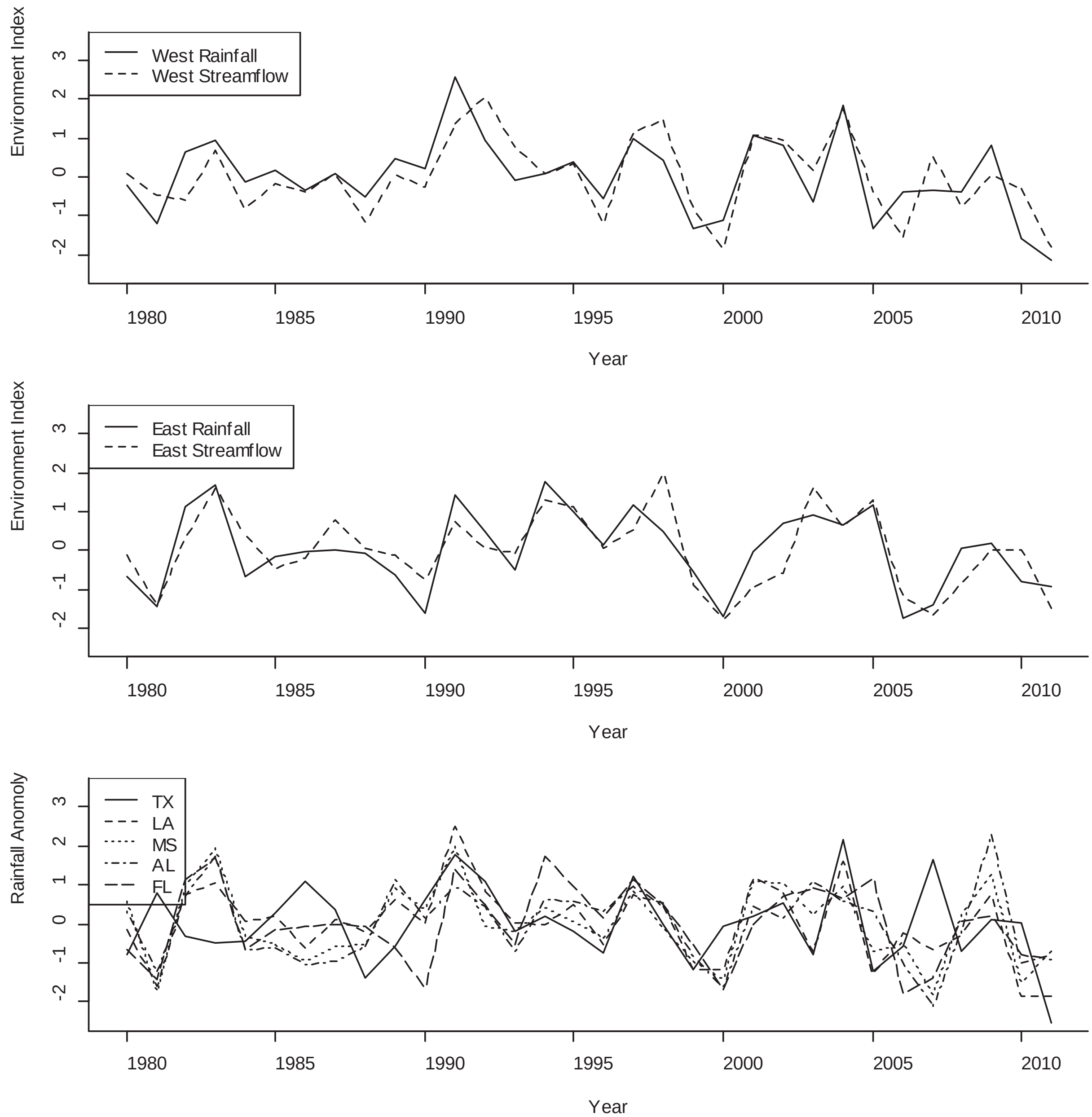

Figure 5.8 Environmental time series for both rainfall and United States Geologic Service stream flow gauges for the Western and Eastern GOM stocks (top and middle panel, respectively). The bottom panel is the rainfall anomalies for the different states.

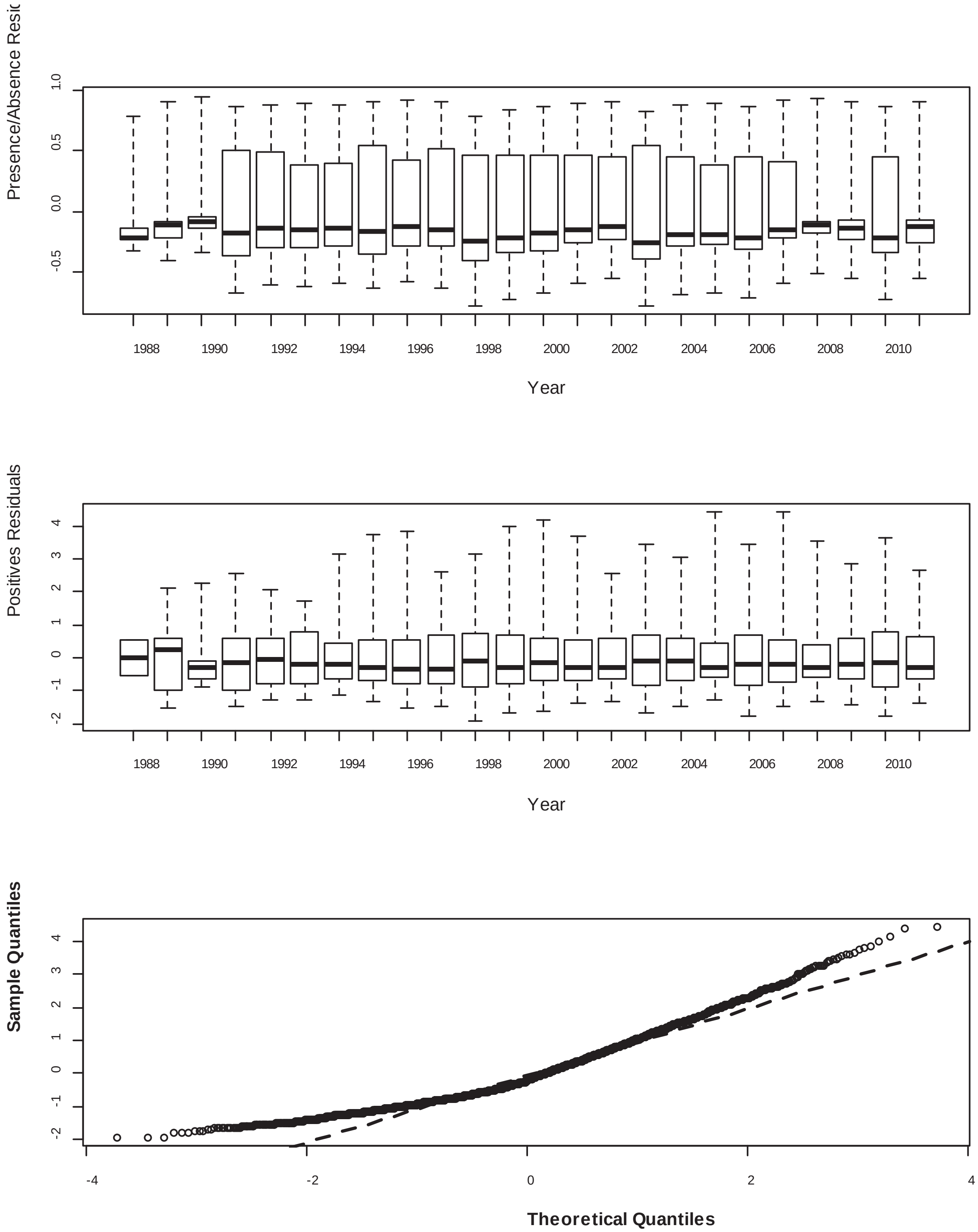

Figure 5.9 Diagnostics plots for the Eastern GOM stock juvenile IOA.

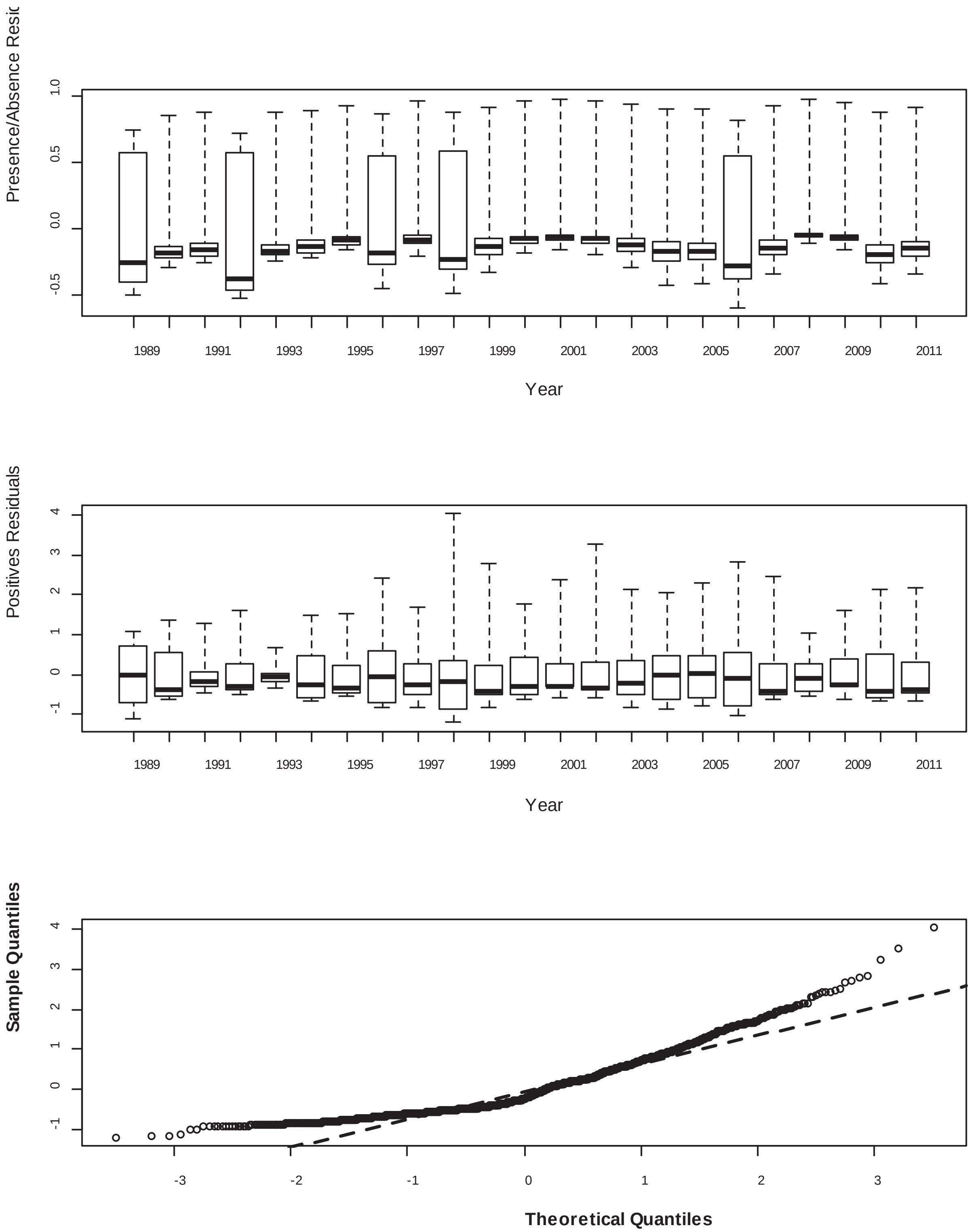

Figure 5.10 Diagnostics plots for the Eastern GOM stock adult IOA

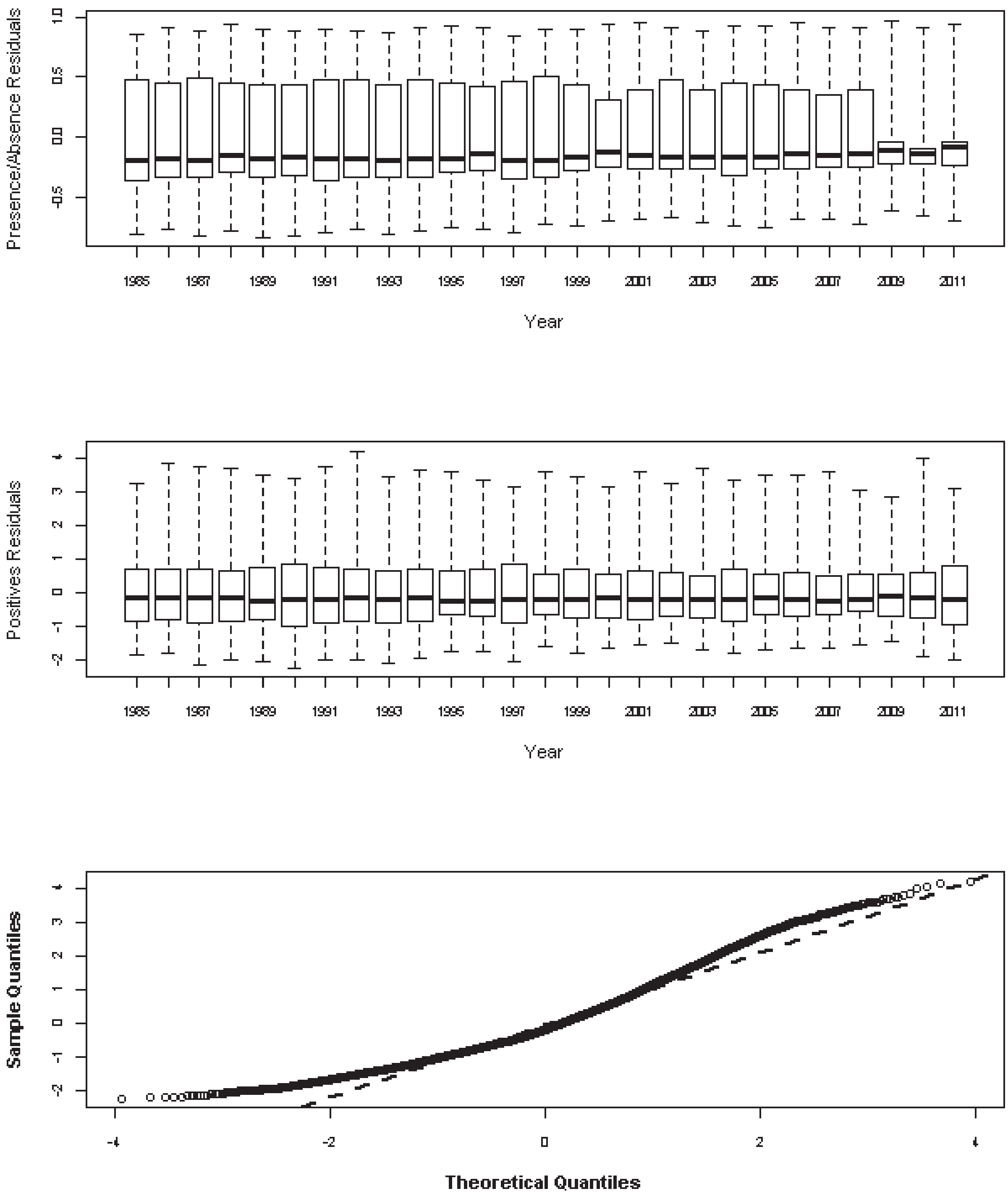

Figure 5.11 Diagnostics plots for the Western GOM stock juvenile IOA.

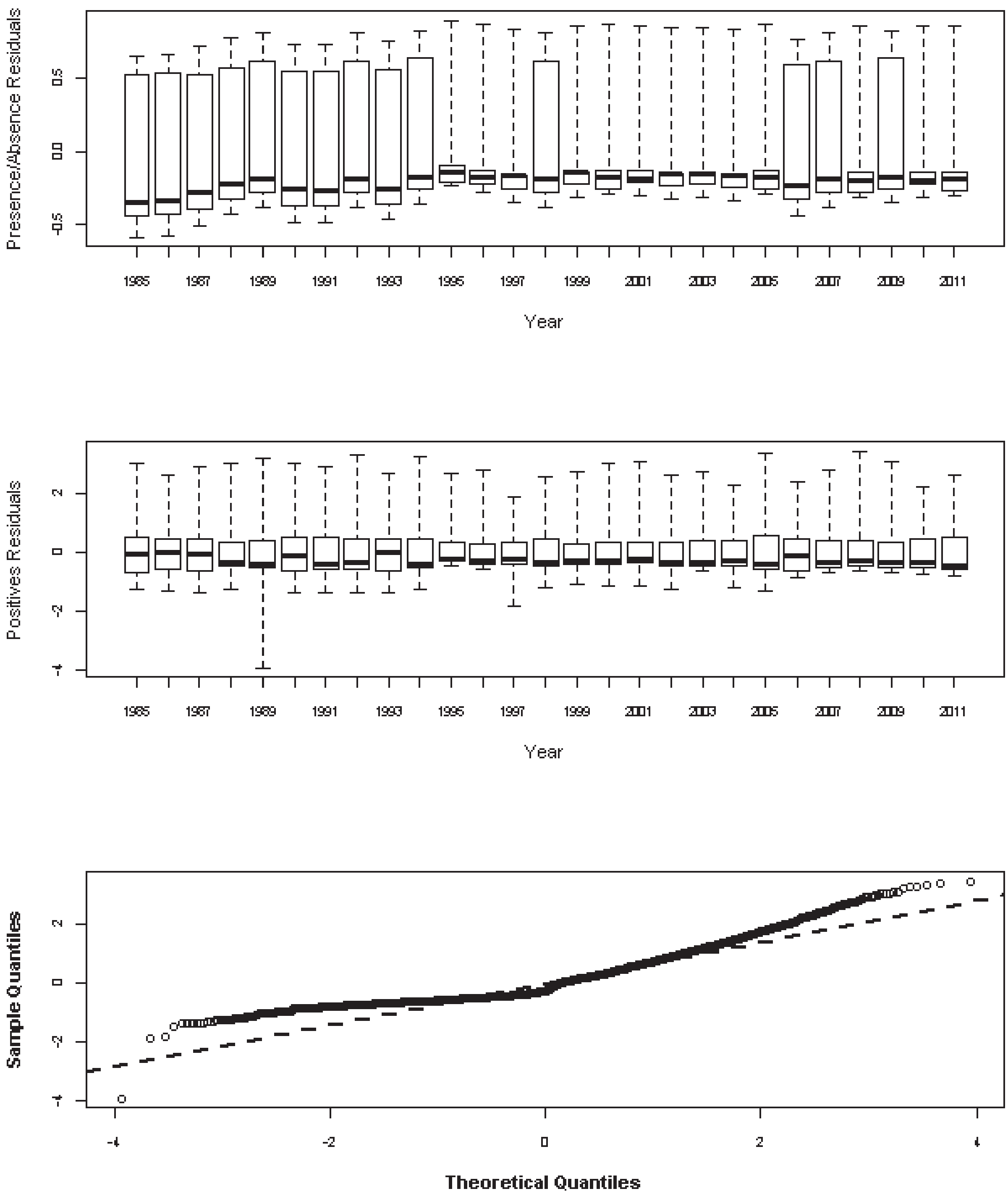

Figure 5.12 Diagnostics plots for the Western GOM stock adult IOA.

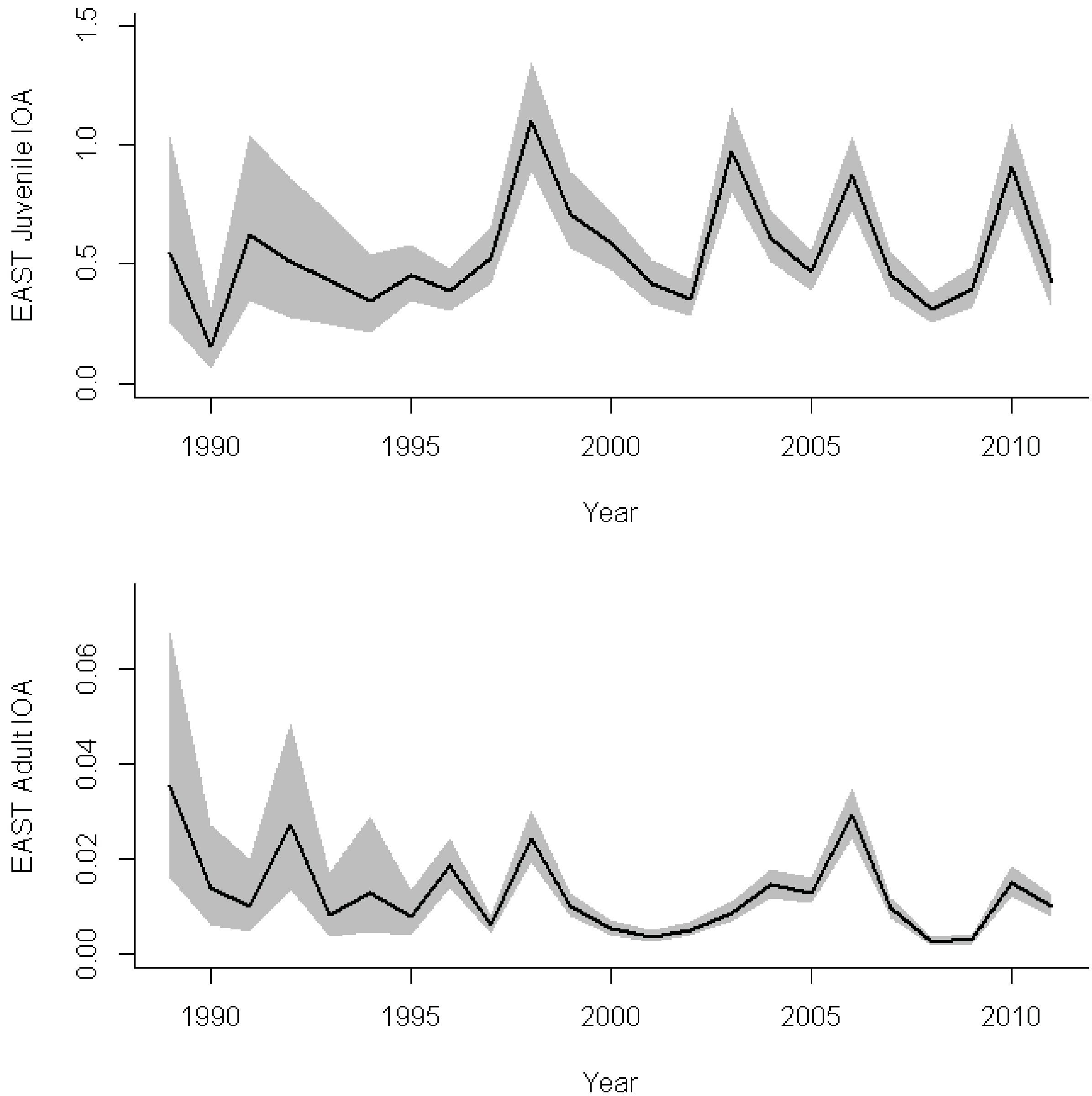

Figure 5.13 Indices of abundance for recruits and adults for the Eastern GOM stock. Solid line represents the mean (un-scaled), while the shaded region represents the 95% confidence interval.

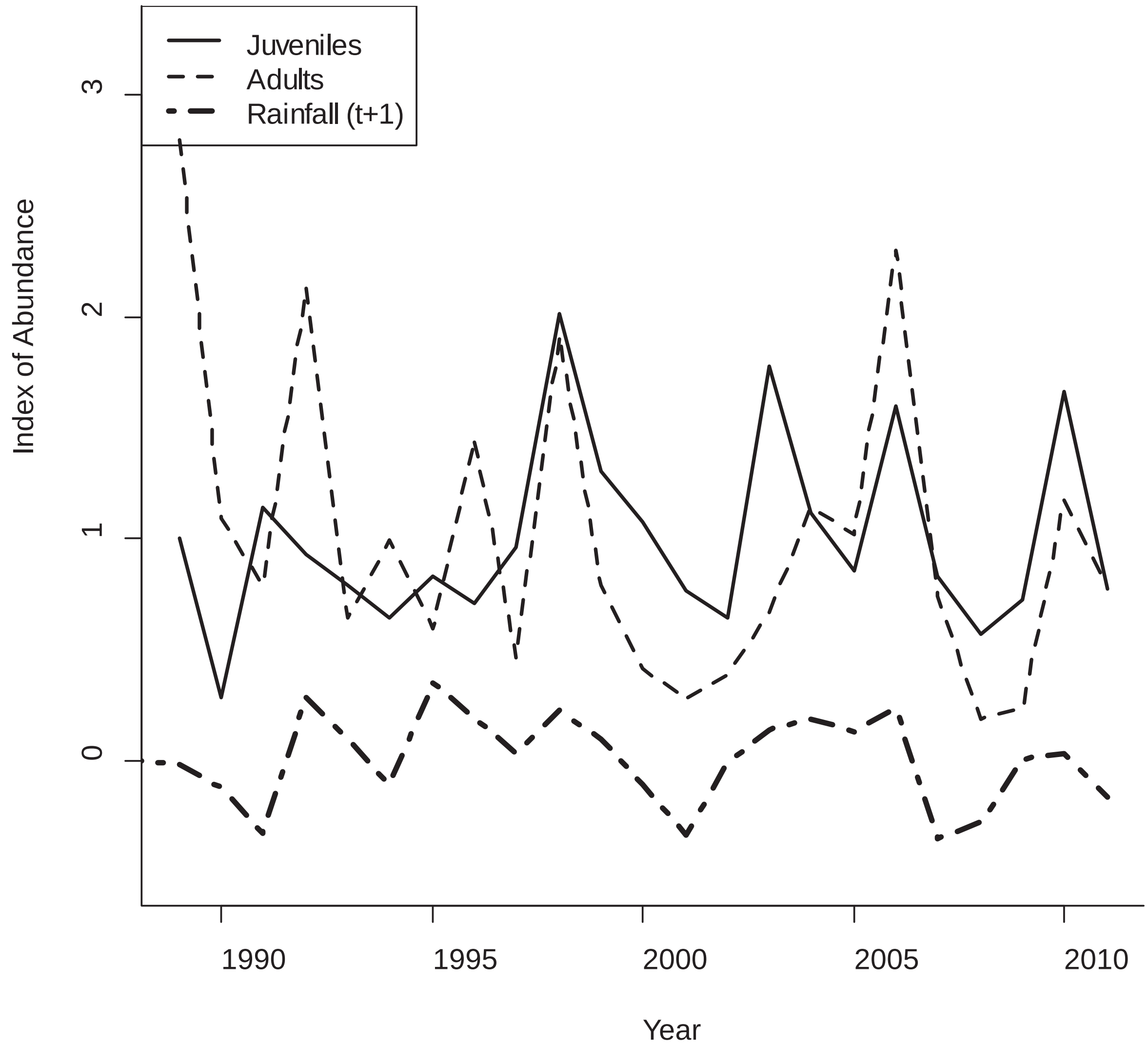

Figure 5.14 Eastern GOM stock juvenile and adult IOAs superimposed with the precipitation index, where the precipitation index is lagged one year (t+1) to demonstrate the relationship between the IOAs and the rainfall in the previous year.

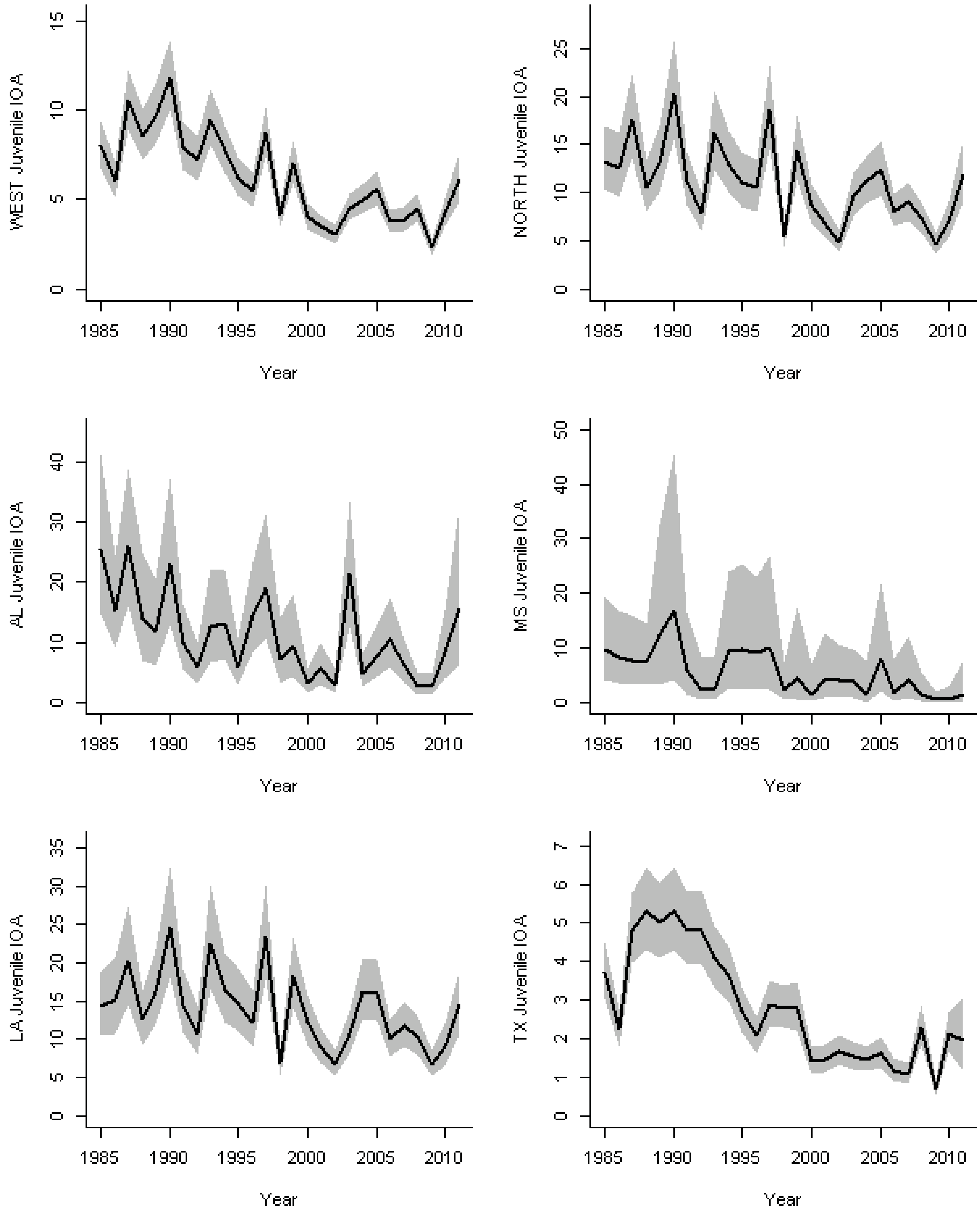

Figure 5.15 Indices of abundance for juveniles for the Western GOM stock, broken down by all states (WEST), the northern Gulf states (NORTH; LA, MS, AL), and each individual state. Solid line represents the un-scaled mean, while the shaded region represents the 95% confidence interval.

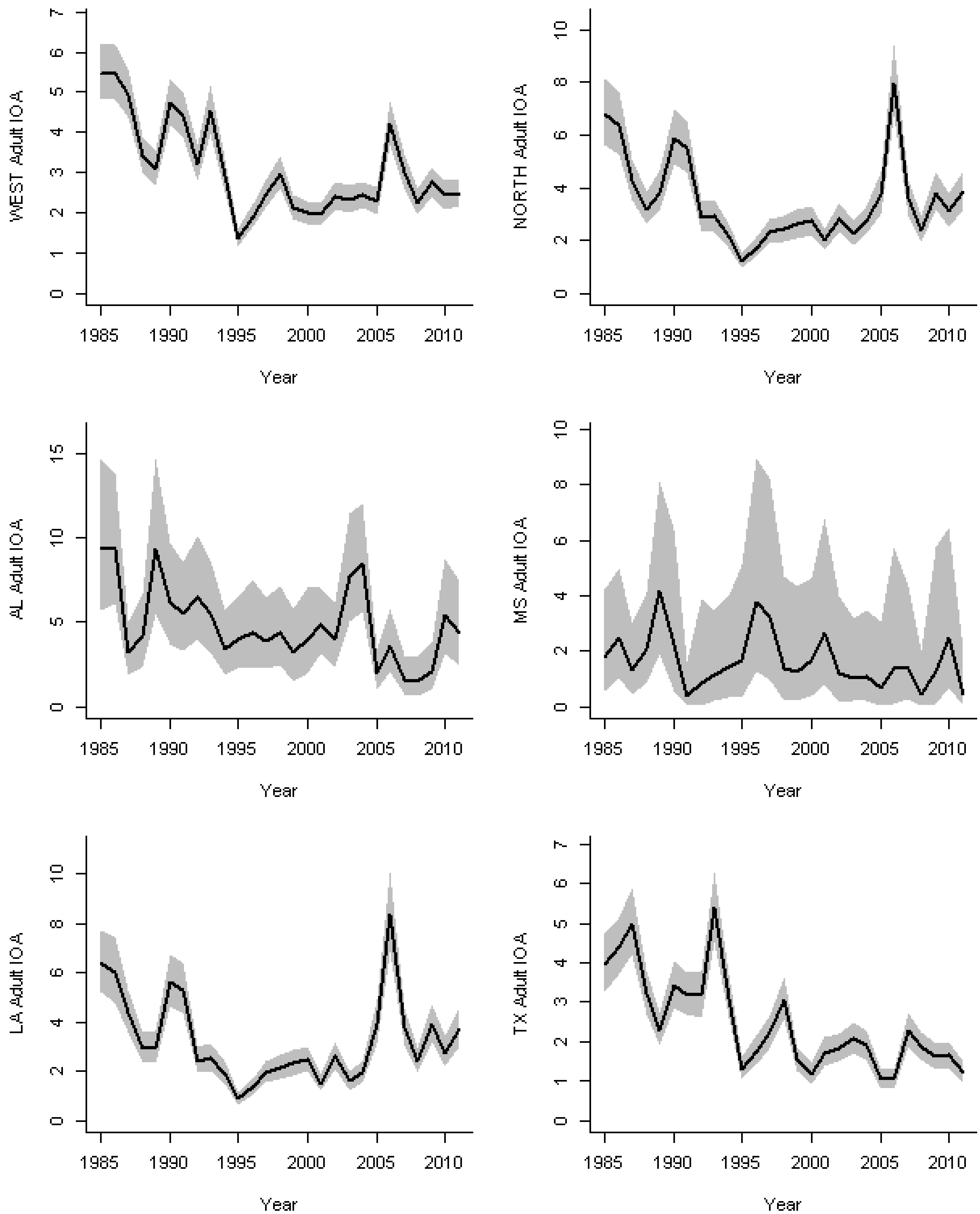

Figure 5.16 Indices of abundance for adults for the Western GOM stock, broken down by all states (WEST), the northern Gulf states (NORTH: LA, MS, AL), and each individual state. Solid line represents the un-scaled mean, while the shaded region represents the 95% confidence interval.

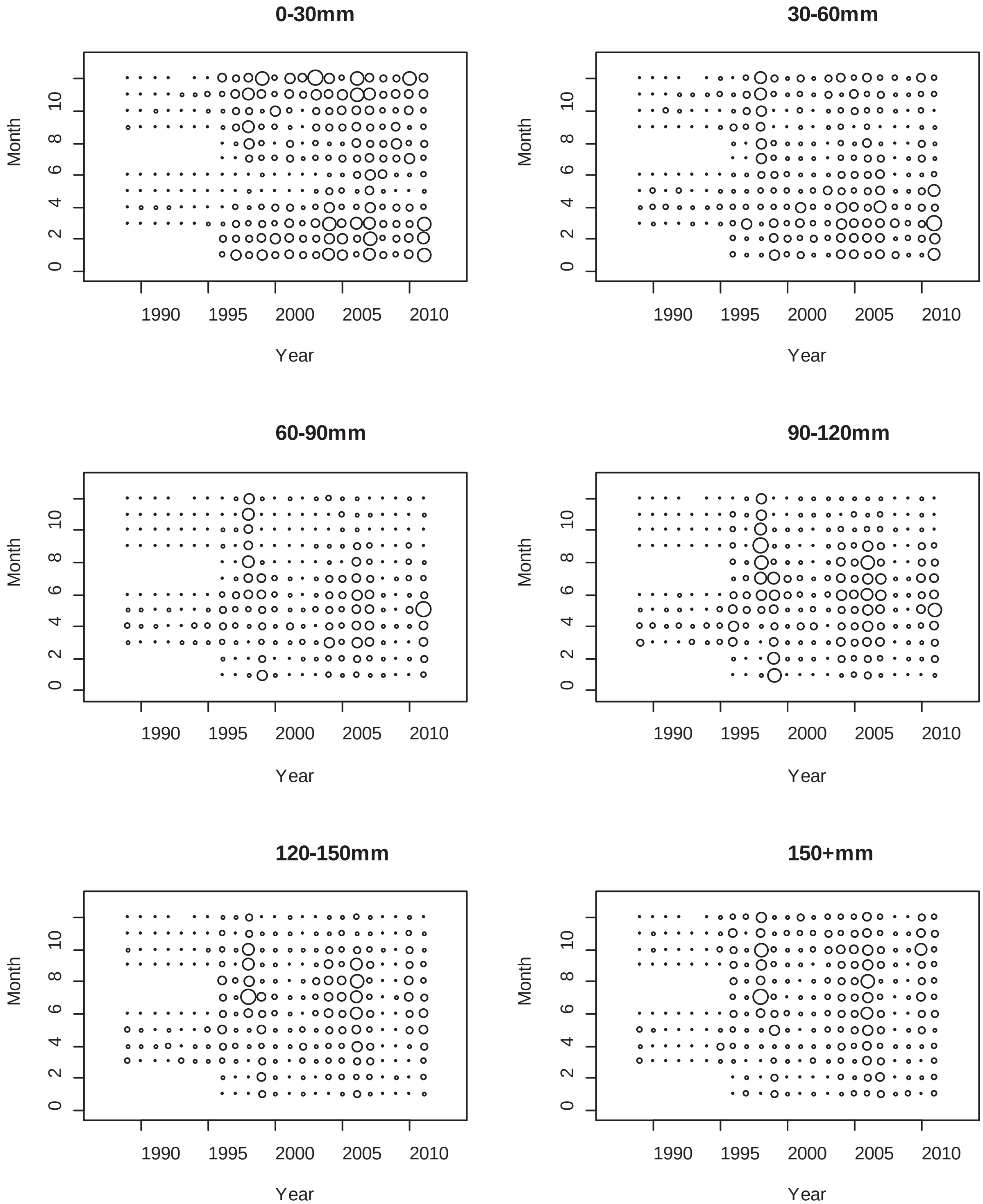

Figure 5.17 Size frequency distributions of crabs caught by month and year in the Eastern GOM stock from the Florida Fishery Independent Monitoring program, summed across gears (21.3-m seines, 183-m seines, and 6.1m otter trawls).

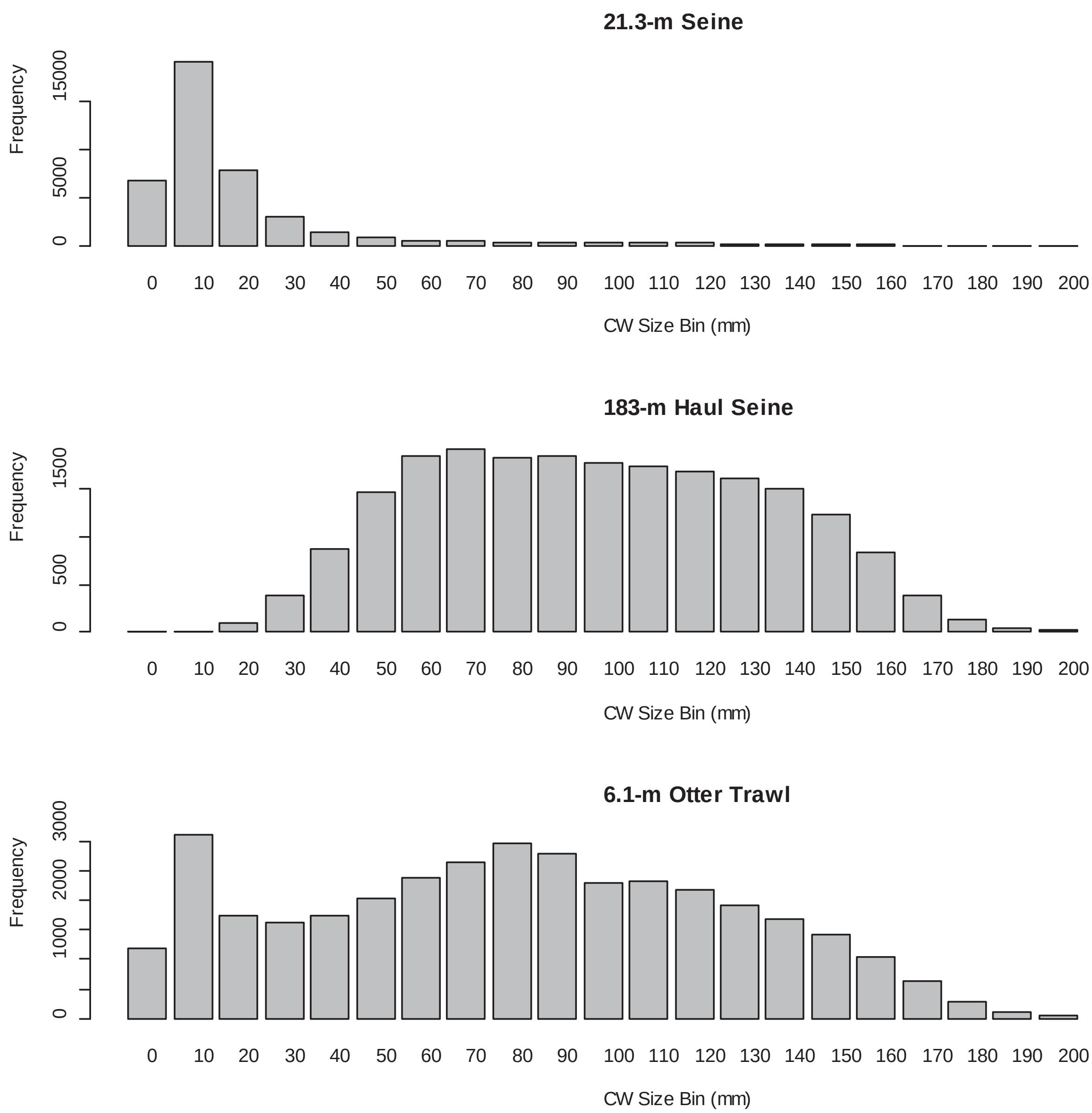

Figure 5.18 Size frequency distributions of crabs caught by gear across all years in the Eastern GOM stock from the Florida Fishery Independent Monitoring program.

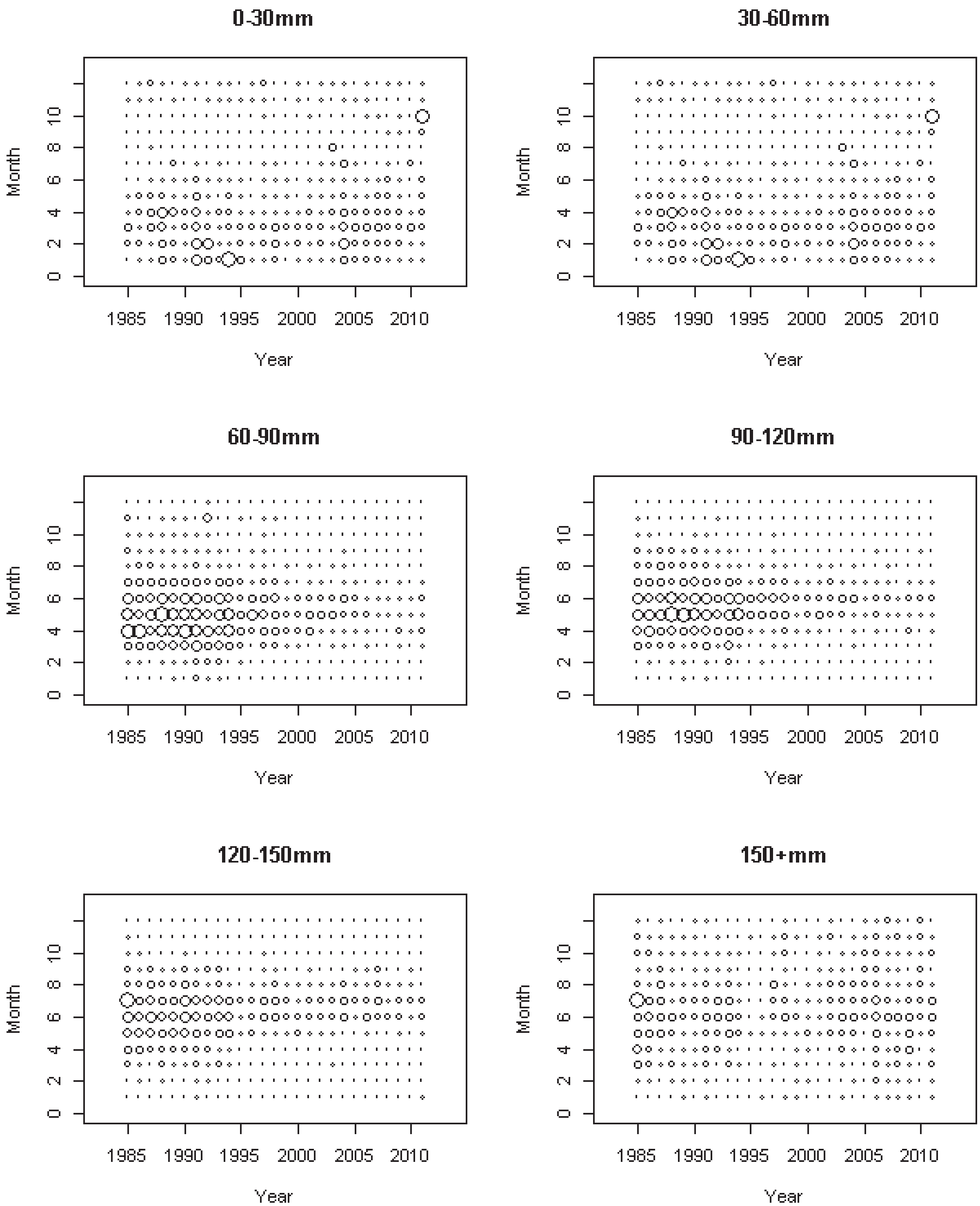

Figure 5.19 Size frequency distributions of crabs caught by month and year from the Western GOM stock fishery-independent monitoring programs for the trawl gear.

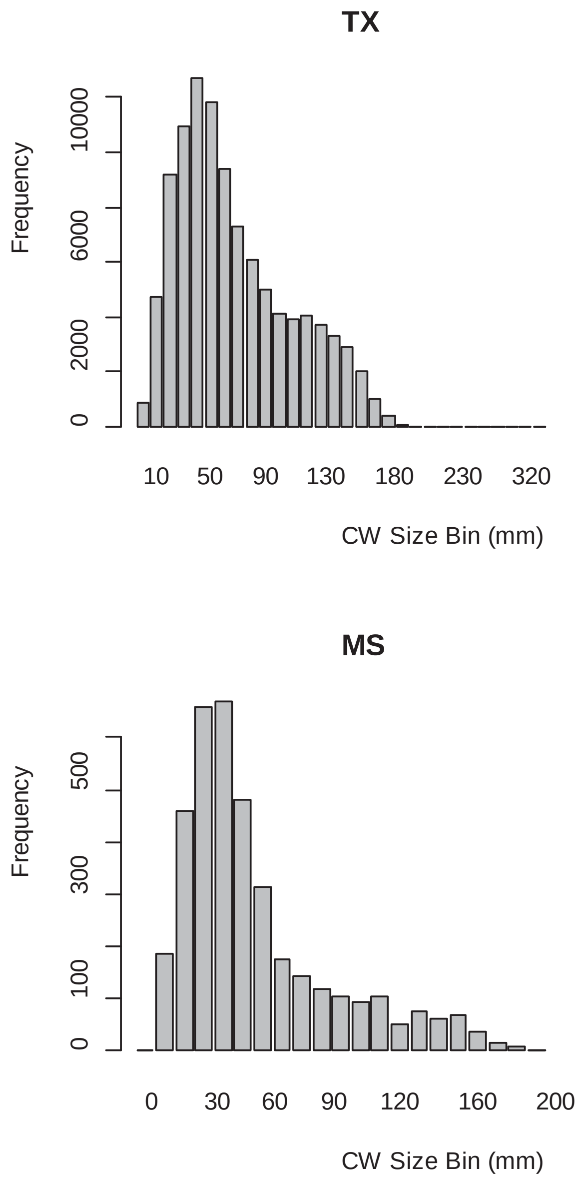

Figure 5.20 Size frequency distributions of crabs caught in trawls all years from the Western GOM stock fishery-independent monitoring programs.

6.0 Methods

6.1 Assessment Model Descriptions

Two modeling approaches were identified as potential models during the Data Workshop (DW) and Assessment Workshop (AW). These modeling approaches include: (1) a two-stage model (catch-survey analysis/modified Delury model) adapted from the 2011 Chesapeake blue crab assessment, and (2) a surplus production model (ASPIC). The two-stage model was selected as the base model, due to the preference for this modeling approach from previous blue crab assessments (Twilley et al. 2001, Louisiana, Florida, Delaware), while ASPIC was used as a supporting model. Stochastic Stock Reduction Analysis (SSRA) was also discussed at the DW and explored between the DW and AW. However, it was decided at the AW to not use SSRA as another supporting model for two primary reasons: (1) exploratory analyses led to high uncertainty in the reference point estimates from SSRA; and (2) given the dynamics of blue crabs in the Gulf (spawn mid-summer; reach maturity and legal size within 9 mo of being spawned; annual crop fishery) using an adjusted year time step (July 1st-June 30th, computed from monthly landings) is more conducive to their life history in a multi-stage model, and these monthly landings were not available for the historic landings used in SRA.

6.1.1 Two-Stage Model

The two-stage model was a forward-projecting model, similar to a statistical catch-at-age but with only two stages represented: juveniles and adults. This model was adapted from the 2011 Chesapeake blue crab assessment model (Miller et al. 2011), hereafter termed "Chesapeake model", using the ADMB code available online (http://hjort.cbl.umces.edu/crabs/Assessment.html). The Chesapeake model is similar to a catch-survey analysis (CSA), also known as a modified Delury model, but is not conditioned on catch (i.e., assuming no error in catch statistics), as it typically done in these models. Instead, the expected catch is predicted from estimated fishing mortality rates in the model, and compared to observed catches, while accounting for an input level of error in landings data. In addition, this model utilizes a built-in stock recruitment relationship, providing for MSY-based reference points. Finally, by using an ADMB model, we were able to access the built-in capabilities for uncertainty analyses (asymptotic error, likelihood profiles, MCMC).

A number of important modifications were made to the Chesapeake model for this assessment, in order to more accurately represent the GOM blue crab dynamics and data limitations. First, we did not have suitable biostatistical sampling of landings data over time to infer the sex composition of landings, so all of the sex-specific dynamics in the Chesapeake model were removed from our model. As a result, the stock-recruitment relationship used in the Chesapeake model, formulated specifically to account for different sexes, was changed to a standard Ricker formulation, with Beverton-Holt available as a sensitivity option. Second, stage-specific natural mortality rates, using a Lorenzen approach, were included in our model, thereby requiring updates to both the population dynamics and reference point calculations in the model. This provided for more accurate representations of natural mortality rate differences between juveniles and adults. Third, the parameters controlling fishing rates (F) in the Chesapeake model (mean F, and F deviations with a mean of zero) were changed to a 'q' parameter estimate for the first year (where F=q*Effort), with subsequent year F deviations freely varying (i.e., not restricted to a mean of zero). These changes were done to provide an option to include an input effort time-series (not used in the final base model, but as a sensitivity for the Eastern GOM stock), and to allow F rates to trend more freely over time, especially for the Gulf where effort has generally been decreasing due to management regulations. Forth, after exploration of the model dynamics through simulated data, it was discovered that the model produced high F estimates and low initial abundance and recruitment estimates across a range of simulated natural variability. This resulted from lack of contrast in the model to estimate these parameters independently. The Chesapeake model may not have experienced this problem because they used the winter dredge survey as an absolute estimate of abundance, which allowed them to anchor the absolute values for abundance and fishing mortality in the model estimates. To address this issue in our model, we included a prior for the average total mortality rate (Z) of fully-selected adults across all years in the model, thereby providing guidance to the absolute F rates, and consequently the initial abundance and recruitment estimates. If this was not done, the absolute F estimates would be set by an input value for maximum F, where the highest predicted F year would be scaled to the maximum F input to the model. As such, setting the maximum F in effect served as a strong prior, but without any data to support the choice of maximum F. While inclusion of the Z prior did not significantly influence some reference points (e.g., MSY), it did influence others, such as (SPR, F_{MSY}, U_{MSY}) that were governed by the absolute fishing rate. Limited data exist by which to independently estimate F or Z (i.e., few tagging studies in the Gulf region); therefore, a linearized catch curve analysis on the fisheries independent size frequency data of fully-selected adults was used to compute an average Z estimate. Finally, due to the relationships between blue crabs and freshwater inflow, options for environmental influences on both the recruitment and mortality processes were included. These were formulated as deviations following an environmental time series from an average value, as is typically done in other assessment models (SS3, BAM).

6.2 Model Configuration for Base and Alternate Approaches

6.2.1 Assessment Model – Base model: Two-Stage Model

The two-stage model is adapted from the Chesapeake model, and implemented with the AD Model Builder software (http://admb-project.org/). A summary of the model equations can be found in Table 6.1-6.4.

6.2.1.1 Spatial and Temporal Coverage

The two-stage model is not a spatially-explicit model, and assumes a single population for the area of interest. Because two stocks were modeled in the GOM (Eastern and Western), separate models for the two stocks were run. Although it would have been possible to combine the stocks in a single model using a spatial framework and estimate only a single parameter for those that are theoretically similar or shared among stocks (e.g., stock-recruitment parameters), enough potential differences exist between the stocks that they were modeled separately for all parameters.

The model uses annual time steps for the years, modeling the years beginning with the earliest index of abundance for each stock (1985 and 1989 for western and eastern, respectively), through 2011. Due to the fast growth rates of blue crabs in the GOM (e.g., 7-9 months to reach a legal size of 127mm), the model time step was begun on July 1st, corresponding to the peak of the spawning season. Early difficulties with fitting the model using a calendar year time frame resulting in the adjustment of the model time step to begin at the time of spawning. This allowed us to model the juvenile stage as starting at the time of entry into the population from spawning through their first reproductive period (12-mo of age). Attempting to start the model on the calendar year would potentially negate the usefulness of a two-stage model under this fast growth in the GOM, since the juvenile stage would be those individuals from 6-mo – 18-mo, with spawning occurring at 12-mo. If the primary component of landings are juvenile crabs entering the fishery in their first year (i.e., 12-mo at age, representing an annual crop), then the majority of the dynamics would occur in only the juvenile stage, with few individuals remaining to the adult stage.

6.2.1.2 Selection and Treatment of Indices

The juvenile and adult indices were developed from trawl data in the west, and a combination of trawl and seine data in the east (see Section 5.2). CPUE indices were not generated from the landings data, due to quality accuracy issues of effort data for this fishery. For the Eastern GOM stock, only a single index was created for each of juveniles and adults, and these were used in the base model configuration. For the Western GOM stock, juvenile and adult indices were generated for all the states combined as the base model configuration, and sensitivies were performed for each state separately, and for Texas versus the northern Gulf States (Louisiana, Mississippi, and Alabama). Texas was split out as a separate component due to potential differences in climate, leading to differential environmental influences than the northern Gulf States. An effort index was also developed for the Eastern GOM stock using the methods of Murphy et al. (2007).

6.2.1.3 Parameterization

The ADMB model code and input data files for the base runs are attached as Appendices A.1, A.2 (Eastern GOM stock data file), and A.3 (Western GOM stock data file). The formulation's major characteristics were as follows:

- *Natural mortality*: The stage-specific natural mortality rate was assumed constant. A Lorenzen curve was scaled such that the total natural mortality rate was based on a maximum life-span of 3 years.
- *Stock dynamics*: The standard Baranov catch equation was applied. This assumes exponential decay in population size because of fishing and natural mortality processes.
- *Sex Ratio/Maturity/Fecundity*: The ratio of males to females was assumed to be 1:1, and only influenced the parameter estimates for the stock-recruitment relationship, reflecting spawning by only females. The maturity was fixed with 100% of juveniles being mature by 12mo of age when spawning occurs at the end of the model time step (i.e., all surviving juveniles spawn at the end of the time step). Fecundity was fixed for both juvenile and adult spawners.

- *Recruitment:* Recruitment to age-0 was estimated in the assessment model for each year with a set of annual deviation parameters centered on the bias-corrected average recruitment in a Ricker stock recruitment curve, estimated in log-space.
- *Biological benchmarks*: The maximum sustainable yield (MSY) benchmarks were used for the blue crab assessment. A default control rule was used from federal guidelines to assign the overfishing and overfished limits (see Table 6.4 and section 8.0 for details). Once these limits were established, overfishing was defined as F/F_{Limit} greater than one, where the geometric mean of the estimated F rate in 2009 and 2010 was used as the current F estimate (note: the 2011 terminal year F was not used, as there were no 2012 survey data on which to tune the terminal year F estimate in the model). Overfished was defined as N/N_{Limit} less than one, where the geometric mean of the estimated N in 2009-2011 was uses as the current N estimate.
- *Fishing*: The commercial trap fishery was the only fishery explicitly modeled. Recreational fishing pressure, currently unmonitored, was set at 5% of the commercial catch per year. Fishing mortality rates were estimated for each year. Juveniles were assumed to have a vulnerability to the fishery of 30%, representing the proportion of the year at which they are vulnerable to fishing (roughly, reaching a legal size of 127mm by 7-9 months). This vulnerability was set based on simulation runs from an individual-based molt-process model, adapted from Bunnell and Miller (2005) and fit to pond growth data from Florida and Mississippi, which suggest growth to legal size within 7-9 mo, dependent on temperature. This parameter was also included in sensitivity runs to assess the model’s response to varying degrees of vulnerability of juveniles to the fishery.
- *Abundance indices*: The model used two indices of abundance that were modeled separately: a juvenile (age-0) index series and an adult index series (1985-2011 for both indices in the Western GOM stock; 1989-2011 for both indices in the Eastern GOM stock).
- *Fitting criterion*: The fitting criterion was a total likelihood approach in which total catch and the patterns of the abundance indices for both juveniles and adults were fit based on a log-normal error distribution. A 5% CV was assumed for total catch measurement error, and year-specific estimates of measurement error were used for the indices of. In addition to the primary data sources, a prior on the average Z estimate was included in the model fit in order to anchor the initial abundance and recruitment estimates in the model (see Model testing below).
- *Model testing*: To test the ability of the model to fit the data, a simulation was constructed with different levels of process error (recruitment deviations, F and M deviations and trends, landings deviations and trends, environmental deviations and trends) and measurement error (juvenile and adult abundances). Simulations were done using the same basic population dynamics model as in the assessment model, and found to recover the parameters estimated from the assessment model under limited variability scenarios (e.g., 1-5% CVs). The parameter estimates became more variable, relative to the known values, as the simulation variability increased (e.g., up to 10-50% CVs for different processes). Under all simulation variability scenarios however, the median parameter estimates were centered on their known simulated values, indicating that the model performs well. The model produces unbiased estimates only when an absolute measurement of F or abundance is included as a prior in the model, in order to anchor the estimates in place. This combination of testing and verification procedures suggests that

the assessment model has been implemented correctly and provides an accurate assessment of blue crab dynamics, conditional on the quality of the data.

6.2.1.4 Weighting of Likelihoods

The likelihood components in the model include landings, the juvenile IOA, the adult IOA, recruitment process error (i.e., recruit deviations from the expected value), and the average Z prior. For each parameter, a lognormal error distribution was assumed, with the following error levels:

Likelihood Component	Error Levels
Landings	Constant CV value equal to 0.05
Juvenile IOA (western)	Annual CV value from 0.08 to 0.12
Adult IOA (western)	Annual CV value from 0.06 to 0.08
Juvenile IOA (eastern)	Annual CV value from 0.09 to 0.44
Adult IOA (eastern)	Annual CV value from 0.09 to 0.51
Recruitment deviations	Constant CV value equal to 0.5
Average Z prior	Constant CV value equal to 0.05

The error on the average Z prior was set to a low level to ensure that the model anchored the mortality rates near the observed estimate of Z, while providing some flexibility in the estimates.

6.2.1.5 Estimating Precision

The precision of each estimated parameter and a number of year-specific derived parameters (juvenile abundance, adult abundance, full F rates) were obtained from the built-in asymptotic standard error estimates using the inverse Hessian (delta-method) in ADMB. In addition, the MCMC posterior distribution of the parameters and primary reference points (MSY, F_{MSY}, N_{MSY}, F_{Limit}, N_{Limit}) were obtained using the built-in ADMB capabilities. MCMC runs were started at the base model best fit parameter estimates with 2,000,000 iterations, a burn-in time of 1000 iterations, and a thinning rate of 1000 iterations.

6.2.1.6 Sensitivity Analyses

A total of 24 sensitivity runs were completed with the two-stage model. These sensitivity runs are represented by those involving input data and those involving changes to the model configuration.

6.2.1.6.1 Sensitivity to Input Data

Several sensitivity runs were conducted to examine various effects to changes in the input data. The following is a list of these sensitivity runs. The sensitivities are run for both the Western GOM stock and the Eastern GOM stock unless otherwise noted, using the notation ‘bc-xx-west’ or ‘bc-xx-east’.

Run Number	Sensitivity Examined
bc-00	None (base model)
bc-01	Juvenile fishing selectivity set to 0.2
bc-02	Juvenile fishing selectivity set to 0.4
bc-03	Juvenile fishing selectivity set to 0.6
bc-04	Natural mortality as Lorenzen curve with maximum age of 2yr
bc-05	Natural mortality as constant with maximum age of 3yr
bc-06	Average Z estimate times 0.7 (30% less)
bc-07	Average Z estimate times 1.3 (30% greater)
bc-08	Maximum F and M set to 3.0 in the model (versus default of 4.0)
bc-09	Maximum F and M set to 5.0 in the model
bc-10	Precipitation influence on natural mortality
bc-11	USGS stream flow influence on natural mortality
bc-12	Precipitation influence on stock recruitment process (lagged one year)
bc-13	USGS stream flow influence on stock recruitment process (lagged one year)

The vulnerability of juveniles to fishing, also referred to as partial recruitment in similar models, is difficult to ascertain for blue crabs given their high variability in growth rates, temperature-dependent growth, and seasonal fishing effort. We used a value of 0.3 in the base model, given that crabs typically reach legal size within 7-9 months of birth in the Gulf, and would therefore be susceptible to fishing for 3-5 months of their first year. This derivation assumes that fishing pressure is evenly spread throughout the year. To explore the sensitivity of the estimates to this parameter choice, we included sensitivities using 0.2, 0.4, and 0.6. Although higher values are not biological feasible if fishing pressure is evenly distributed throughout the year, these values could be obtained if effort is higher during the time frame when juveniles become legal size (e.g., late spring/early summer).

Given uncertainty in mortality estimates, we explored various options as sensitivities. First we modeled natural mortality using a Lorenzen curve with a 2-yr maximum age, where this maximum age may be more typical of females in the Gulf since they can reach their terminal molt within 1-yr. Constant natural mortality across stages using the 3-yr maximum age (M=1.0 for juveniles and adults) was also assessed. We also looked at the sensitivity to our average Z estimate from the length-based catch curve analyses on the fisheries independent data. For these, we increased and decreased the estimate by 30% as two separate sensitivity runs. Related to the Z estimate, which was necessary to anchor the absolute F estimates in the model, we also adjusted our estimates of the maximum F and M allowed. This would not be expected to have a large sensitivity, given that the average Z estimate should be driving the absolute estimates, but it was explored anyways to check for any possible interactions. Finally, a time-dynamic natural mortality rate as a result of bottom-up forcing through freshwater input was assessed using both streamflow and precipitation data. This was added to the model due to the often strong relationships seen between blue crabs and freshwater input.

The influence of precipitation and streamflow was also assessed on the stock-recruitment process as added sensitivities. Exploratory analyses with the model found that lack of contrast in the data leads to difficulties in independently estimating a freshwater effect on both recruitment and mortality simultaneously. Therefore, the recruitment effect was modeled as a separate set of sensitivities from the mortality effect.

6.2.1.6.1 Sensitivity to Model Configuration

Several sensitivity runs were conducted to examine various effects to changes in the model configuration. The following is a list of these sensitivity runs, where bc-12 through bc-19 are specific to the Western GOM stock (differences in stock spatial structure):

Run Number	Sensitivity Examined
bc-14	Use of Beverton-Holt stock recruit relationship
bc-15	No stock-recruit relationship (steepness=.99 for B-H)
bc-16	Inclusion of an effort time series (east stock only)
bc-17	TX IOAs and landings with using base parameters (independent TX assessment)
bc-18	LA IOAs and landings with using base parameters (independent LA assessment)
bc-19	MS IOAs and landings with using base parameters (independent MS assessment)
bc-20	AL IOAs and landings with base parameters (independent AL assessment)
bc-21	Western subregion (TX) IOAs and landings with base parameters (same as bc-12)
bc-22	Central subregion (LA, MS, AL) IOAs and landings with base parameters
bc-23	Western subregion IOAs and landings with streamflow influence on M
bc-24	Central subregion IOAs and landings with streamflow influence on M

Although a Ricker stock-recruitment relationship has often been used for blue crab assessments (Chesapeake, Delaware), we explored the use of a Beverton-Holt relationship. Lack of a stock-recruitment relationship was also assessed by forcing the model to a steepness value of 0.99 (using a Beverton-Holt relationship).

For the Eastern GOM stock, where effort data are available from the trip ticket program going back to 1986, an effort time series using the number of traps pulled per trip was computed as in Murphy et al. (2006). This was included as a sensitivity (bc-16) for the east stock only, to see how well the estimated effort from the base model corresponded to the input effort data.

The final set of sensitivity runs for input data had to deal with the stock spatial differentiation for the Western GOM stock only. Sensitivities were done by running the model for each state independently[1] (i.e., four spatial zones within the Western GOM stock; bc-17 through bc-20); and by splitting the Western GOM stock into a western subregion (Texas; bc-21) and central subregion (Louisiana, Mississippi, and Alabama; bc-22) based on ecological and climatic zonation differences (Twilley et al. 2001). Note: bc-21 (western subregion) is the same as bc-17 (Texas independent), but was presented as a separate run to improve clarity in the results. The state-independent sensitivities were not conducted to represent realistic stock structures and

[1] To ascertain the stock status of individual states, which may not be appropriate given the stock structure, the models would have to be configured for each state independently and run with a full uncertainty analysis. Most importantly, sensitivity runs bc-17 through bc-20 use a combined four states Western GOM stock parameterization of juvenile vulnerability, M, and Z, which could be different for each individual state.

should not be viewed as such, but were intended to provide information to the states regarding an independent assessment if this information is desirable.

At the data workshop, it was decided to model the Western GOM stock, including Texas, Louisiana, Mississippi, and Alabama, based on genetic stock structure. Due to the presence of strong environmental regulation in blue crabs and the strong differences in ecological zones across the Western GOM stock (Twilley et al. 2001), the two subregion sensitivities (western versus central subregions) were performed to test a different spatial structure than the base model. A more suitable approach would be to run both subregions in a single model using a spatial framework, where the subregions are linked via movement and larval dispersal processes in the model. However, this would have involved significant re-programming of the model to add in a spatial structure, in addition to added data requirements on movement and larval dispersal pathways that were not available at the time. As such, we only present the gradation in fishery status across the Western GOM stock as independent model runs.

Because streamflow on mortality was found to have a strong influence on the model runs (see section 6.0), two additional sensitivities were added to test the streamflow influence on mortality for both the western and central subregions (bc-23, bc-24).

6.2.1.7 Retrospective Analyses

Retrospective analyses were completed by running the model in a series of runs sequentially omitting years 2011 to 2007, as indicated below:

Run Number	Sensitivity Examined
bc-25	Retrospective analysis with modeling ending in 2010
bc-26	Retrospective analysis with modeling ending in 2009
bc-27	Retrospective analysis with modeling ending in 2008
bc-28	Retrospective analysis with modeling ending in 2007
bc-29	Retrospective analysis with modeling ending in 2006

6.2.1.8 Reference Point Estimation – Parameterization, Uncertainty, and Sensitivity Analysis

This assessment presents maximum sustainable yield (MSY) based benchmarks using a Ricker stock recruitment model with a bias correction. This approach was chosen because it conforms to the federal fisheries guidelines, and was successfully implemented for the Chesapeake model. The quantities F_{MSY}, U_{MSY}, N_{MSY}, and MSY were estimated by the method of Shepherd (1982). MSY based benchmarks are commonly used in the federal management system and maximize equilibrium landings. Although the GSMFC's Blue Crab Advisory Committee (BCAC) has the ability to recommend reference points to the Gulf States, they are not constrained to the Magnuson-Stevens Act. The assessment workshop panel chose to present the de facto MSY based benchmarks since a specific reference point system has not been identified or requested to date. In addition to the MSY based reference points, the spawning potential ratio (SPR) was additionally calculated.

6.2.2 Surplus Production Model (ASPIC)

Surplus production models describe the dynamics of exploited populations and do not distinguish between recruitment, individual growth, and mortality patterns as contributing factors to changes in abundance. Instead, the aggregate effects of these factors are modeled as a single function of the population size. Population growth is a function of stock size and is zero when the stock is at maximum biomass and is maximized at an intermediate level of biomass. Blue crab fishery independent indices and harvest data were analyzed with a logistic (Schaefer) functional model form (Schaefer 1954) using the ASPIC production model software package (version. 5.34, Prager 1994 and 2004). The software provides formulation of the Schaefer production model and alternative model shapes: the Fox (1970) and Pella–Tomlinson (Pella 1967) models. The use of surplus production model analysis of blue crab is intended as an alternative/validation approach to the results of the stage-structured model presented in this report. Surplus production models of blue crab have been used previously for this purpose, notably for the Chesapeake stock (Miller 2011). In that assessment the authors used a production model to provide support for the reference point MSY.

6.2.2.1 Spatial and Temporal Coverage

The surplus production model is not spatially-explicit. Thus a Western GOM stock surplus production model (Texas, Louisiana, Mississippi, and Alabama) and Eastern GOM stock (Florida) production model are presented.

The temporal range of the fishery-independent indices for the Western GOM stock is 1985 to 2011. The temporal range of the fishery-independent abundance index for the Eastern GOM stock is 1989 to 2011. The time steps for model analysis were the calendar year and this is coincident with the estimated landings data and adult abundance indices. Models were run for the entire time-series starting at 1950, the date with which landings data are available.

6.2.2.2 Selection and Treatment of Indices

The adult IOAs were developed from trawl and seine data collected by the GOM states' fisheries management agencies. For the Eastern GOM stock, the adult IOA was derived from trawl and seine data (Section 1.1.5). An additional IOA, Florida standardized commercial CPUE (fishery-dependent, 1986 to 2011) was included in a sensitivity run. For the Western GOM stock, adult IOAs were derived primarily from trawl data. Separate indices were created for each of the western GOM states (Texas [trawl, section 5.1.1], Louisiana [trawl, section 5.1.2], Mississippi [trawl, section 5.1.3], and Alabama [trawl, section 5.1.4]). These state-specific indices were combined into a single adult IOA (adults were considered those individuals >=125mm (i.e., harvestable size), and this was used in the base model configuration for the Western GOM stock (section 5.3.3.2).

6.2.2.3 Parameterization

The input file (.INP) for each stock (Western and Eastern) are included as appendices (Appendix B.1 and Appendix B.2). The parameterization of the base model runs, for each stock, is described below.

- *Model structure:* The ASPIC software implements a forward-projecting population model, and thus provides annual estimates of biomass, fishing mortality rate, etc. We report these relative to their corresponding benchmarks (Prager 1994).
- *Stock dynamics*: Population growth is a function of population size and the rate of increase follows a logistic function (Schaefer 1954).
- *Fitting criterion*: We assume that the magnitude of catch has a greater precision than the IOAs. Therefore, fitting of parameters in all runs was conditioned on catch. The objective function was weighted sum of squared residuals. Weights for each IOA were calculated as the inverse of the squared coefficient of variation. In the case when a unique solution was not found (detailed below) model fit was achieved with a sum of squared residuals objective function.
- *Abundance indices*: The model used the adult index series (1985-2011 for the Western GOM stock; 1989-2011 for the Eastern GOM stock). These indices of abundance were converted to biomass by assuming that each crab weighs 0.41 lbs.
- *Initial biomass*: The fraction of year one biomass, B_1, of the carrying capacity was estimated in most model runs. The state of the stock at the initiation of the model (1985 in the Western GOM stock, and 1989 in the Eastern GOM stock) was not known so we initialized year one biomass in the base configuration (B_1 = 0.75K) to reflect the reduction of biomass, relative to carrying capacity, in the fishery.
- *Estimated parameters*: The leading parameters of the ASPIC formulation are K (the carrying capacity), B_1/K (starting biomass relative to K), *MSY* (maximum sustainable yield), and a series of catchability coefficients qi, i = 1…m, where m is the number of abundance indices used. From the leading parameters, quantities of management interest can be computed (Prager 1994).
- *Determination of a unique solution*: Monte Carlo searching was enabled for some model runs when a repeatable solution was not found. Prager (2004) recommends only using this approach only when needed.

6.2.2.4 Weighting of Likelihoods

Annual inverse-variance weighting was used, based on the *CV*s of indices described above. The error in each index was assumed log-normally distributed.

6.2.2.5 Estimating Precision

A bootstrap with 1,000 realizations was used to quantify uncertainty in model estimates for the base runs. From the bootstrap, it is possible to obtain bias-corrected confidence intervals (Efron and Gong 1983) on each model parameter and on functions of parameters.

In the bootstrapping method employed by ASPIC, estimated IOAs and residuals from the original fit are saved (Prager 2004). The saved residuals are then increased by an adjustment factor (Stine 1990), which is generally slightly more than unity and is reported in the ASPIC output file. Then, once for each bootstrap realization, the residuals are randomly added (with replacement) to the estimated values to arrive at a synthetic data set, and the model is refit. Adjustments are made in saving and applying the residuals to account for the original variance structure of the data as specified in the data-input file.

6.2.2.6 Sensitivity Analyses

Sensitivity run configurations and estimates are summarized in 6.2.2.6.1. These configurations are described in the balance of Section 6.2.2.6. Results are summarized in Section 7.2.3.1.

6.2.2.6.1 Sensitivity to Input Data

Analysis of model sensitivity to the choice of adult IOAs was performed. For the Western GOM stock, sensitivity runs were performed using the adult IOA for each state separately and the regional (TX, LA, MS, AL) combined landings. We also performed a sensitivity analysis by removing Texas from the central-northern Gulf States (Louisiana, Mississippi, and Alabama). In this model run, Texas was removed to evaluate the potential differences in climate from this state relative to the other northern Gulf States.

Several sensitivity runs were conducted to examine various effects to changes in the input data. The following is a list of these sensitivity runs. The sensitivities are run for both the Western GOM stock and the Eastern GOM stock unless otherwise noted, using the notation sp-##-west or sp-##-east.

Western GOM stock model runs:

Run Number	Sensitivity Examined
sp-01-west	None (Western GOM stock base model, “Combined” adult IOA)
sp-02-west	“Central” GOM state adult IOA (LA, MS, AL)
sp-03-west	TX adult IOA only
sp-04-west	AL adult IOA only
sp-05-west	LA adult IOA only
sp-06-west	MS adult IOA only

Eastern GOM stock model runs:

Run Number	Sensitivity Examined
sp-01-east	None (Eastern GOM stock base model)
sp-02-east	FL adult IOA and FIMS IOA

6.2.2.6.2 Sensitivity to Model Configuration

Several sensitivity runs were conducted to examine various effects to changes in the model configuration. In each case, the sensitivity runs are identical to the base model configuration detailed above, and the model shape or initial biomass was changed.

Model runs were configured to examine sensitivity to the assumption B_1 = 0.50K used in the base run. Both runs were similar to the base production model run, except that one assumed B_1 = 0.50K and the other assumed B_1 = 0.25K. Additional model runs were configured to evaluate sensitivity to model shape and the Fox (1970) model shape was used.

Western GOM stock model runs:

Run Number	Sensitivity Examined
sp-07-west	sp-01-west formulation, B_1 = 0.25K
sp-08-west	sp-01-west formulation, B_1 = 0.50K
sp-09-west	sp-01-west formulation, Fox Model

Eastern GOM stock model runs:

Run Number	Sensitivity Examined
sp-03-east	sp-01-east formulation, B_1 = 0.25K
sp-04-east	sp-01-east formulation, B_1 = 0.50K
sp-05-east	sp-01-east formulation, Fox Model

6.2.2.7 Retrospective Analyses

A retrospective analysis (runs sp-10-west to sp-14-west and sp-06-east to sp-10-east) compared the base run to runs with 1, 2, 3, 4, or 5 years of data omitted from the end of the data.

Western GOM stock model runs:

Run Number	Sensitivity Examined
sp-10-west	sp-01-west formulation, exclude 2011
sp-11-west	sp-01-west formulation, exclude 2010, 2011
sp-12-west	sp-01-west formulation, exclude 2009 to 2011
sp-13-west	sp-01-west formulation, exclude 2008 to 2011
sp-14-west	sp-01-west formulation, exclude 2007 to 2011

Eastern GOM stock model runs:

Run Number	Sensitivity Examined
sp-06-east	sp-01- east formulation, exclude 2011
sp-07- east	sp-01- east formulation, exclude 2010, 2011
sp-08- east	sp-01- east formulation, exclude 2009 to 2011
sp-09- east	sp-01- east formulation, exclude 2008 to 2011
sp-10- east	sp-01- east formulation, exclude 2007 to 2011

6.2.2.8 Reference Point Estimation – Parameterization, Uncertainty, and Sensitivity Analysis

Reference-point estimation is inherent in production model analysis. Uncertainty in reference points was estimated through the bootstrap, as described above for each base model. Each sensitivity analysis was also a sensitivity analyses on estimated reference points.

Table 6.1 Population model equations of the two-stage assessment model for Gulf blue crab. Estimated parameters are denoted using hat (^) notation, and predicted values are denoted using breve (˘) notation.

Population Model	Symbol	Description/Definition
Fishing mortality	$F_{a,y}$	$F_{a,0} = s_a \hat{q} E f_0$; $\hat{q}$ estimated for the initial year; $F_{a,y} = s_a \hat{q} E f_0 e^{\hat{\delta}_{F,y}}$; $\hat{\delta}_{F,y}$ are year specific deviations for all years after the initial year
Natural mortality	$M_{a,y}$	$M_{a,y} = M_a e^{\hat{\beta}_{M,a} E_y - 0.5\sigma_M^2}$; M_a is the stage-specific estimate of M from a Lorenzen curve; $\sigma_M = \sqrt{\log(1 + c_M{}^2)}$; $\hat{\beta}_{M,a}$ is an estimated scaling parameter to link the environment to mortality for each stage
Total mortality	$Z_{a,y}$	$Z_{a,y} = M_{a,y} + F_{a,y}$
Number of female spawners	SP_y	$SP_y = \omega \rho_a N_{a,y} e^{-\kappa(M_{a,y} + F_{a,y})}$
Number of juveniles	$N_{0,y}$	$N_{0,0} = \hat{N}_{0,0}$ is estimated for the initial year; $N_{0,y+1} = \alpha SP_y e^{-\beta SP_y} e^{\hat{\beta}_R E_y} e^{\hat{\delta}_{R,y} - 0.5\sigma_R^2}$; $\hat{\delta}_{R,y} \sim N(0, \sigma_R^2)$; $\alpha = \frac{e^{\frac{5\log(5\hat{h})}{4}} R_0}{\hat{S}_0}$; $\beta = \frac{\log(5\hat{h})}{.8\hat{S}_0}$; $R_0 = \frac{\hat{S}_0}{SR_0}$; $SR_0 = \omega \rho_0 e^{-\kappa M_0} + \omega \rho_1 \frac{e^{-(M_0 + \kappa M_1)}}{1 - e^{-M_1}}$; $\sigma_R = \sqrt{\log(1 + c_R^2)}$; $\hat{\beta}_R$ is an estimated scaling parameter to link the environment to recruitment
Number of adults	$N_{1+,y}$	$N_{1,0} = \hat{N}_{1,0}$ is estimated for the initial year; $N_{1,y+1} = N_{a,y} e^{-(M_{a,y} + F_{a,y})}$
Predicted catch-at-stage	$\breve{C}_{a,y}$	$\breve{C}_{a,y} = \frac{F_{a,y}}{Z_{a,y}} N_{a,y} [1 - e^{-Z_{a,y}}]$
Predicted landings	$\breve{L}_y$	$\breve{L}_y = \sum_{a=0}^{1} \breve{C}_{a,y}$
Predicted juvenile IOA	$\breve{I}_{0,y}$	$\breve{I}_{0,y} = q_0 (N_{0,y} e^{-\tau_0 M_{0,y}})$ [assumes survey before vulnerable] $\log(q_0) = \frac{\sum_y \log(\breve{I}_{0,y}) - \log(N_{0,y})}{k_{I,0}}$;
Predicted adult IOA	$\breve{I}_{1,y}$	$\breve{I}_{1,y} = q_1 (N_{1,y} e^{-\tau_1 (M_{1,y} + F_{1,y})})$; $\log(q_1) = \frac{\sum_y \log(\breve{I}_{1,y}) - \log(N_{1,y})}{k_{I,1}}$;

Table 6.2 General definitions and input data of the two-stage assessment model for Gulf blue crab.

General Definitions	Symbol	Description/Definition
Year index: y = {1985,..,2011}	y	
Stage index: a = {0,1+}	a	
Total years in model	k_m	
Total years for each survey	$k_{I,a}$	
Total years of landings data	k_L	
Input Data	**Symbol**	**Description/Definition**
Observed IOAs	$I_{a,y}$	Based on numbers of juvenile or adult crabs from state-specific surveys (selected at Data Workshop)
Observed fishery landings	L_y	Reported landings in numbers for each year (y)
Observed average total mortality of fully-selected adults	Z	Estimated from linearized length-based catch curve analysis of fisheries independent size frequency data, using growth parameters estimated from individual-based molt-process model.
Coefficient of variation for $I_{a,y}$	$c_{I,a,y}$	Based on annual estimates from samples for I_0 and I_1
Fishery selectivity	s_a	Fixed at 0.3 for juveniles and 1.0 for adults, based on time to reach legal size (7-9 months) from individual-based molt-process model.
Probability of spawning	ρ_a	Fixed at 1.0 for both juveniles and adults, contingent on spawning occurring at the end of the model time step.
Spawn time	κ	Fixed at 1.0 to coincide with spawning at the end of the model time step.
Survey time	τ_a	Fixed at 0.5 for juveniles (winter) and 0.0 for adults (summer).
Sex ratio	ω	Fixed at 0.5.
Fishery effort	Ef_y	Fixed at 1.0 for all years in base model run (effort data incomplete for Western GOM stock as determined at Data Workshop); input as sensitivity for Eastern GOM stock.
Environment	E_y	Environmental time series (precipitation, USGS streamflow), scaled to a mean of 0.
Coefficient of variation for L_y	c_L	Fixed at 0.05
Coefficient of variation for R_y	c_R	Fixed at 0.5
Coefficient of variation for M_a	c_M	Fixed at 0.1
Coefficient of variation for Ef_y	c_{Ef}	Fixed at 0.2
Coefficient of variation for Z	c_Z	Fixed at 0.05

Table 6.3 Likelihood components of the two-stage assessment model for Gulf blue crab. Predicted values are denoted using breve (˘) notation.

Negative Log-Likelihood	Symbol	Description/Definition
Lognormal indices	$\Lambda_{I,a}$	$\Lambda_{I,a} = \lambda_{I,a} \sum_{y} [0.5 \log(2pi) + 0.5 \log(\sigma_{I,a,y}^2) + \log(\mathrm{I}_{a,y}) + \frac{[\log(\mathrm{I}_{a,y} + \chi) - \log(\breve{\mathrm{I}}_{a,y} + \chi)]^2}{2\sigma_{I,a,y}^2}]$ $\sigma_{I,a,y} = \sqrt{\log (1 + c_{I,a,y}^2)}$; $\lambda_{I,a}$ is a preset weight factor set to 1.0; χ is fixed at an arbitrary value of 0.000001 for numerical stability.
Lognormal landings	Λ_L	$\Lambda_L = \lambda_L \sum_{y} [0.5 \log(2pi) + 0.5 \log(\sigma_L^2) + \log(\mathrm{L}_y) + \frac{[\log(\mathrm{L}_y + \chi) - \log(\breve{\mathrm{L}}_y + \chi)]^2}{2\sigma_L^2}]$ $\sigma_L = \sqrt{\log (1 + c_L^2)}$; λ_L is a preset weight factor set to 1.0; χ is fixed at an arbitrary value of 0.000001
Lognormal effort deviations	Λ_{Ef}	$\Lambda_{Ef} = \lambda_{Ef} \sum_{y} [0.5 \log(2pi) + 0.5 \log(\sigma_{Ef}^2) + \log(Ef_y) + \frac{[\log(Ef_y) - \log(\mathrm{F}_y) - \log(\hat{\mathrm{q}})]^2}{2\sigma_L^2}]$ $\sigma_{Ef} = \sqrt{\log (1 + c_{Ef}^2)}$; λ_{Ef} is a preset weight factor set to 0.0 if an effort series is not used (base), and 1.0 if the effort series is used (sensitivity bc-16)
Lognormal recruitment deviations	Λ_R	$\Lambda_R = \lambda_R \sum_{y} [0.5 \log(2pi) + 0.5 \log(\sigma_R^2) + \log(\hat{\delta}_{R,y}) + \frac{\log(\hat{\delta}_{R,y})^2}{2\sigma_R^2}]$ $\sigma_R = \sqrt{\log (1 + c_R^2)}$; λ_R is a preset weight factor set to 1.0
Prior distribution for Z	Λ_Z	$\Lambda_Z = \lambda_Z [0.5 \log(2pi) + 0.5 \log(\sigma_Z^2) + \log(z) + \frac{[\log(z) - \log(\overline{Z_{1,y}})]^2}{2\sigma_Z^2}]$ $\sigma_Z = \sqrt{\log (1 + c_Z^2)}$; $\overline{Z_{1,y}}$ is the mean adult Z across all model years except terminal year; λ_Z is a preset weight factor set to 1.0

Table 6.4 Reference point calculations.

Reference Point Components	Symbol	Description/Definition
Fishing rate value: F={0, ….6}	F	F is incremented from 0.0 to 6.0 by 0.01, and the reference point calculations are performed at each F value. All final MSY-based reference points are set at the F that maximizes equilibrium catch (Ceq), while the spawning potential ratio F targets (FSPR) are each set at the F that produces the SPR closest to an input set of targets (SPR={.05,.1,.2,.3,.4})
Virgin spawners per recruit	SR_0	$SR_0 = \omega\rho_0 e^{-\kappa M_0} + \omega\rho_1 \frac{e^{-(M_0+\kappa M_1)}}{1-e^{-M_1}}$
Spawners per recruit	SR	$SR = \omega\rho_0 e^{-\kappa(M_0+s_0\mathrm{F})} + \omega\rho_1 \frac{e^{-(M_0+s_0\mathrm{F}+\kappa M_1+\kappa s_1\mathrm{F})}}{1-e^{-\kappa(M_1+s_1\mathrm{F})}}$
Number per recruit	NR	$NR = \frac{e^{-(M_0+s_0\mathrm{F})}}{1-e^{-\kappa(M_1+s_1\mathrm{F})}}$
Yield per recruit	YR	$YR = \frac{s_0\mathrm{F}}{M_0+s_0\mathrm{F}}\left[1-e^{-(M_0+s_0\mathrm{F})}\right] + \frac{s_1\mathrm{F}}{M_1+s_1\mathrm{F}}\left[1-e^{-(M_1+s_1\mathrm{F})}\right]$*NR
Equilibrium recruitment (Ricker)	Req	$Req = \frac{\log(\alpha)+\log(SR)}{\beta * SR}$
Equilibrium number	Neq	$Neq = NR * Req$
Equilibrium catch	Ceq	$Ceq = YR * Req$
Equilibrium exploitation rate	Ueq	$Ueq = \frac{Ceq}{Neq + Req * \frac{1-e^{-s_0\mathrm{F}}}{1-e^{-s_1\mathrm{F}}}}$
Maximum sustainable yield	MSY	$MSY = \max(Ceq)$ across all F values
Number at MSY	N_{MSY}	Neq at MSY
Fishing rate at MSY	F_{MSY}	F at MSY
Exploitation rate at MSY	u_{MSY}	Ueq at MSY
Overfished limit	N_{limit}	$N_{limit} = cN_{MSY}$; $c = \max(1-M, 0.5)$
Overfishing limit	F_{limit}	$F_{limit} = \frac{F_{MSY}N}{cN_{MSY}}\ for\ all\ N \le N_{limit}$ $F_{limit} = F_{MSY}\ for\ all\ N > N_{limit}$
Spawning potential ratio	SPR	$SPR = \frac{SR}{SR_0}$

7.0 Base and Alternate Assessment Model Results

7.1 Results of Base Two-Stage Model

7.1.1 Goodness of Fit

Goodness-of-fit was governed by the likelihood components in the objective function of the model (Table 6.3), which in turn were governed by the error input data (measured and assumed for various levels). Goodness of fit was primarily judged through examination of the model residuals for landings and indices of abundance.

7.1.1.1 Western GOM stock

Overall, the Western GOM stock base fit the observed data well for landings and adults, but not as well for juveniles. There was also obvious patterning in the residuals, where landings and the adult IOA were underestimated and the juvenile IOA overestimated in the latter half of the model run period (2000-2011; Figures 7.1 and 7.2). This pattern is suggestive of an additional process not captured in the model (e.g., large-scale regulatory change, environmental change, spatial processes). Although effort has slowly been declining due to effort-management plans initiated during this period, the model should capture this general trend in effort. As configured in the base run, the model would not be able to detect trends in environmental degradation that could cause such a pattern (e.g., habitat loss, persistent drought conditions; but see Sensitivity Analyses for the influence of precipitation/stream flow). In addition, subregional differences within the Western GOM stock could also have influenced the poor residual fits, which were not assessed in the base configuration.

Despite this pattern, the base model fit both the landings and adult IOA observed data relatively well (Figure 7.3). This would be expected for the case of the landings, where the assumed CV was low at 5%. For the adult IOA, the model did a good job at fitting the major peaks and general decline in abundance for the first half of the time series (1985-1995). The model did a relatively poor job at fitting to the observed juvenile IOA data, which has declined substantially over the model time period. Although the model was able to simulate the decline, it underestimated the magnitude of the decline, leading to the residual pattern.

7.1.1.2 Eastern GOM stock

For the Eastern GOM stock, the model fit the landings data well without any clear patterning in the residuals (Figure 7.4). Although residual patterns were similarly not evident in either the juvenile or adult IOA fits, the model did a relatively poor job at capturing the large fluctuations in abundance, particularly the joint peaks in abundance of both juveniles and adults that occurred on some years (1998, 2003, 2006, and 2010; Figures 7.5 and 7.6). This was likely due to lack of a mechanism in the base model configuration that would allow for juveniles and adults to increase or decrease rapidly in abundance during the same year, given an expected cyclical lag in abundance between juveniles and adults. External perturbations relative to the inherent population dynamics (e.g., environmental forcing), could provide for the large and simultaneous deviations in abundance, and this issue was addressed with the sensitivity runs using environmental forcing, which had a strong influence on the model fit for the Eastern GOM stock (see Sensitivity Analyses below).

Another issue with the Eastern GOM stock goodness of fit was the overestimated abundance of adults in the initial year, corresponding to the lowest estimated F rate in the initial year, and underestimates for all subsequent large peaks in abundance of adults. This issue was partly addressed with the sensitivity run including an effort time series, which lead to a lower estimate of abundance during the initial year (on scale with the other peaks in abundance), but still with underestimates for all peaks in abundance.

7.1.2 Parameter Estimates

7.1.2.1 Western GOM stock

The main model parameters and their corresponding precision estimates (ADMB delta-method estimate of standard deviations, and MCMC confidence intervals) are presented in Table 7.1. Derived parameters (juvenile/adult abundances, full F) and precision estimates (delta-method SDs, MCMC confidence interval) are presented in Table 7.2 and Figure 7.4.

Overall, landings were generally constant throughout the first half of the model time period (1985-2000), but marked with two years with the highest landings (1987, 1999). After 2000, landings have generally declined. Although the vulnerability of juveniles to fishing pressure was set to 0.3 in the base model runs (i.e., vulnerable for 0.3 of the year in the late spring / early summer before spawning in mid-summer), the majority of the landings were composed of juveniles (Figure 7.8). During the initial years, fishing mortality increased to peak in 1999, after which it has steadily declined along with landings, but still at a level above those F rates experienced in the mid-1980s. The effect of this changing fishing pressure can be seen directly in the observed and estimated juvenile and adult abundances, which declined sharply through to 2000 concurrently with increasing F, but remained relatively constant since then despite the continual decline in both F and landings (Figure 7.7).

Due to the short lifespan of blue crabs and subsequent resiliency, one would expect their populations to track fishing pressure relatively well, in the absence of additional external forces driving their dynamics. Given the lack of increase in juvenile and adult abundances as fishing pressures and landings have decreased suggest forces other than fishing pressure may be currently limiting population growth. Additional drivers (e.g., habitat degradation, drought) could be driving this lack of population growth during the last decade as fishing rates have declined, and this is partly addressed in the Sensitivity Analyses using environmental forcing.

The base model fit a stock-recruitment relationship relatively well, without any clear patterning in the residuals during the first half of the time span, but with generally lower than average recruitment during the latter half of the time frame (2000-present; Figure 7.9). This result mirrors the residual patterns as discussed above (Section 7.1.1), and is suggestive of additional external processes influencing the population dynamics during the latter half of the time frame. It should be noted that since the recruitment was lower than average during the latter half of the model period, reference point estimates, which are calculated at equilibrium or "average" conditions, will generally be biased during long time periods marked with non-average conditions, particularly if serial autocorrelation in the residuals exist.

7.1.2.2 Eastern GOM stock

The main model parameters and their corresponding precision estimates (ADMB delta-method estimate of standard deviations, and MCMC confidence intervals) are presented in Table 7.3. Derived parameters (juvenile/adult abundances, full F) and precision estimates (delta-method SDs, MCMC confidence interval) are presented in Table 7.4 and Figure 7.10.

Overall, landings increased substantially from 1989 to a peak of 39 million crabs in 1998, but then dropped rapidly in 2000 to an average landings of around 10-15 million crabs (Figure 7.11). This increase in landings was marked by a higher estimated proportion of juveniles caught (i.e., those individuals in late spring/early summer before their first spawning event), but generally a constant number of adults caught throughout the period. Fishing mortality followed a similar trend to overall landings, with an increase through to 1998, but a steady decline since then. Similar to the Western GOM stock, the initial abundance of adults has declined to a constant average of around 5 million adults at the start of the spawning season. Recruits have similarly remained relatively constant throughout the period, marked with approximately five-year periods of higher than average or lower than average abundances.

Similar to the Western GOM stock, the lack of increase in abundances of juveniles and adults as fishing pressures and landings have decreased suggests forces other than fishing pressure may be currently limiting population growth. Additional drivers (e.g., habitat degradation, drought) could be driving this lack population growth during the last decade as fishing rates have decreased. An alternative hypothesis to fishery-driven abundances is that the yearly fishing effort is governed by environmentally-driven abundances, and therefore blue crabs would not be expected to increase with decreasing landings or effort. Instead, effort may track abundance as fishermen respond to environmentally-driven populations, where the declining nature of effort and landings is in response to large scale environmental degradation. Some of these issues are partly addressed in the Sensitivity Analyses using environmental forcing discussed below.

The base model fit the stock-recruitment relationship for the Eastern GOM stock with a higher steepness than the Western GOM stock, and subsequently less of a relationship between spawners and recruits, as can be seen in Figure 7.12. Overall, no large-scale patterns were evident in the residuals, although the residuals do exhibit some serial autocorrelation during certain periods (e.g., 1999-2002), that could correspond to periods of similar environmental conditions (e.g., multi-year drought periods).

7.1.3 Sensitivity Analyses

7.1.3.1 Western GOM stock

All sensitivity results and the corresponding reference points and stock status for each run are presented in Table 7.5. The sensitivity analyses show that the model was relatively insensitive to changes in the input data for the Western GOM stock (sensitivity runs bc-01-west through bc-13-

west). Each run had a relatively small effect on the overall log-likelihood and stock status relative to the estimated limits (F/F_{Limit}; N/N_{Limit}). Neither the juvenile vulnerability to the fishery (bc-01-west through bc-03-west) nor mortality inputs (bc-04-west through bc-09-west) had any appreciable change to the stock status or MSY. Similarly, inclusion of an environmental correlate with precipitation or stream flow (bc-10-west through bc-13-west), on both the recruitment and mortality process, had little effect on the model results. The model fit using the streamflow influence on natural mortality, along with the year-specific estimates of M, are presented in Figure 7.13.

Lack of any appreciable influence by precipitation or stream flow for the Western GOM stock was not expected given the literature showing strong links between blue crabs and freshwater input. However, the spatial coverage of the Western GOM stock spans multiple climatic zones that differ in their freshwater flows. Attempts to distill a single precipitation or stream flow index across these climatic zones may obfuscate any real linkages that exist. This issue is partly addressed below in sensitivities bc-23-west and bc-24-west.

Changes to the model configuration related to the stock recruitment process (bc-14-west, bc-15-west) had little improvement to the model fit (log-likelihood), and for the case where a Beverton-Holt relationship was used, no appreciable effect was found on the stock status. Note that using a steepness value of 0.99 (no stock-recruitment relationship) eliminates the ability to estimate MSY-based reference points.

The final set of sensitivity runs (bc-17-west through bc-24-west) looked at different stock structures within the Western GOM stock to obtain reference point estimates for each stock individually. Separating out the states individually found that both Texas and Mississippi are currently overfished and undergoing overfishing, while Louisiana and Alabama are not[2]. Following the subregion zones presented by Twilley et al. (2001), the central subregion (Louisiana, Mississippi, and Alabama) was found to not be overfished or undergoing overfishing. This central subregion is primarily driven by Louisiana, which makes up the vast majority of the catch. The western subregion (Texas) was found to be overfished and undergoing overfishing[2] Looking at the influence of freshwater input at this finer subregional scale (bc-23-west, bc-24-west), inclusion of a freshwater effect on natural mortality was found to significantly affect the western subregion model fit (Figure 7.14), but not the central subregion (Figure 7.15), when comparing the changes to the log-likelihoods.

7.1.3.1 Eastern GOM Stock

All sensitivity results are presented in Table 7.6. Overall, the Eastern GOM stock was more sensitive to the inputs and model configuration than the Western GOM stock when comparing

[2] Using only data from each individual state separately in the Western GOM stock model **does not** signify that Texas and Mississippi are currently overfished or undergoing overfishing because the parameter suite for the base Western GOM stock model remained the same for these runs, and only the landings and survey data were changed. To ascertain the stock status of individual states, which may not be appropriate given the stock structure, the models would have to be configured for each state independently and run with a full uncertainty analysis. Most importantly these runs use a combined four states Western-GOM stock parameterization of juvenile vulnerability, M, and Z, which could be different for each individual state.

the model fit values (log-likelihoods). However, despite the sensitivity in the model fit, the estimates of MSY and stock status were relatively stable across all sensitivities, with the exception of the streamflow influence on natural mortality (bc-11-east), which substantially increased the MSY estimate.

For the Eastern GOM stock, increasing the juvenile vulnerability to the fishery (bc-01-east through bc-03-east) improved the model fit (log-likelihood), suggesting that more juveniles may be susceptible to the fishery than modeled in the base model. As the proportion of the year that juveniles were susceptible increased, the corresponding estimates of F_{MSY} and N_{MSY} decreased. This suggests that as juveniles become more susceptible, F_{MSY} decreases to allow enough individuals to reach the adult stage and spawn. Although s=0.6 had the lowest negative log-likelihood (best fit), this value is biologically unlikely, as it would correspond to juveniles reaching legal size within approximately 5 months after spawning. However, a similar result could be obtained if fishing effort is concentrated during the time of the year that juveniles are of legal size (i.e., late spring, early summer). This appears to be the case in Florida (see section 4.2.2.3 Age and Size Composition), suggesting the possibility that more juveniles are susceptible than modeled in the base run. Future work to independently estimate juvenile vulnerability to the fishery would assist in selecting a more appropriate base run value.

Changes to the mortality rates (bc-04-east through bc-09-east) did influence the model fit for most of the runs, but had no substantial change to MSY or the stock status. Unlike the full Western GOM stock and the central subregion of the Western GOM stock, inclusion of environmental forcing, particularly when looking at streamflow on natural mortality, had a substantial impact on the Eastern GOM stock model results relative to the base run (bc-11; Figure 7.16). This effect was similarly shown for the western subregion component of the Western GOM stock (Texas), improving the models fits substantially for both (Figures 7.14 and 7.15). In both the Eastern GOM stock and the western subregion, the adult mortality increased markedly in years with low freshwater input. In the case of the Eastern GOM stock, a similar effect was shown on juveniles, but relatively absent for the western subregion juveniles. This freshwater effect was not evident on the recruitment process (bc-12, bc-13). For the Eastern GOM stock, this is not surprising, given the simultaneous peaks in both juvenile and adult abundances in years following a peak in freshwater input (Figure 5.8). As freshwater input increased, mortality decreased during that year, leading to peaks in the following year for both juveniles (a function of higher adult survival in the preceding low mortality year) and adults (a function of higher juvenile survival in the preceding year). The substantial improvement in the model fit when using the USGS streamflow data versus the precipitation data suggests that the higher resolution streamflow data captures more of the variability in freshwater input, as would be expected.

Similar to the Western GOM stock, changes to the stock-recruitment relationship had little influence on the model results (bc-14, bc-15). This would be expected for the Eastern GOM stock, where the estimated high steepness was not suggestive of a Ricker function, and fixing the steepness at 0.99 with a Beverton-Holt relationship (i.e., no relationship) was not substantially different from the steepness estimate using a Ricker model in the base run.

An effort time series was input as the final sensitivity (bc-16-east), using the estimated number of traps pulled per trip from the Florida Trip Ticket program. This sensitivity had a minor influence on the results relative to the base model, and in general the estimated effort series in them base model matched well to the input effort data. The input effort data did dramatically decrease the initial abundance of adults estimate, leading to a higher F estimate in the initial year relative to the base mode. However, due to the short life span of crabs, this change was not propagated through to multiple years of the model time series, thereby having a minor influence on the results.

7.1.4 Retrospective Analyses

No major patterns or biases were evident in the retrospective analysis for either abundances or fishing rates in either stock (Figures 7.17 and 7.18), nor in the reference points or stock status in either stock (Tables 7.7 and 7.8).

7.1.5 Uncertainty Analysis

Uncertainty was examined in our results through both the sensitivity runs and through the MCMC analyses. The MCMC analyses were run using the built-in ADMB features, for a total of 2,000,000 iterations with a thinning rate of every 1,000 iterations. Over this iteration time, the parameter estimates and subsequent reference points were relatively stable for both stocks (Figures 7.19-7.22). The exception was with the Western GOM stock, where the stock recruitment parameters (S_0 and steepness) experienced a primary and secondary stable region, which were evident in multiple exploratory chains. Since MSY based reference points are governed by the stock recruitment parameters, these stable regions were subsequently manifested in the trace plots of the reference point estimates (Figure 7.20). The amount of time the chain spent in the secondary stable region was minimal compared to the primary stable region, and had a limited impact on the posterior distribution, where a strong bi-modal peak was not evident in any of the density distributions.

7.1.6 Reference Point Results – Parameter Estimates and Sensitivity

The reference points are presented in Tables 7.7 and 7.8 for the Western and Eastern GOM stock, respectively. For this report, we present estimates of F_{MSY}, N_{MSY} and limits of fishing (F_{Limit}, N_{Limit}) derived using a default control rule (see section 9). Calculations of current numbers and rates (F, N, SPR) were done using the geometric mean of the last three years of the model run. For F, where the terminal year (2011) was not estimated, the geometric mean was taken of the last two years when estimates were available.

The estimated MSY was 164 million individual for the Western GOM stock, and 23 million individuals for the Eastern GOM stock. The uncertainty analyses from the MCMC analysis found that these estimates were relatively stable, particularly for the Eastern GOM stock where the median MCMC estimate was also 23 million crabs. The Western GOM stock MCMC analysis found a slightly higher median value for MSY at 168 million crabs, but 164 million was still within the interquartile range. Looking at the landings time series, fisheries of both stocks have landed less than the MSY for the majority of the time series.

For both stocks, the current F/F_{MSY} and F/F_{Limit} were <1.0 in both the base model fits and the MCMC analyses, suggesting that the stocks are currently not undergoing overfishing. In the Eastern GOM stock, the current N/N_{MSY} and N/N_{Limit} were > 1.0, suggesting that the stock is currently not overfished. However, in the Western GOM stock, the N/N_{MSY} is <1.0, suggesting a depressed state, although still within the overfished limit threshold where N/N_{Limit} is > 1.0. Phase plots are presented in section 9.0 showing the year-specific estimates of F and N (not geometric means) relative to F_{MSY} and N_{MSY}, respectively, along with the estimate of F and N (geometric means) (Figures 8.2 and 8.4).

7.2 Results of Surplus Production Model (ASPIC)

7.2.1 Goodness of Fit

7.2.1.1 Western Stock

The base run model for the Western GOM stock included the combined index of abundance derived from multiple states (Figures 7.23 and 7.24). A pattern in the residual plot for the Western GOM stock is apparent (Figure 7.25). The temporal distribution of residual error is characterized by runs of over and underestimates of the relative abundance of blue crabs relative to that derived in the model. This is especially apparent in the early (1986 to 1993) and middle portions of the time-series (1994 to 2005). Such patterning in the residuals indicates that latent factors, not reflected in the abundance index, are influencing population trajectory.

7.2.1.2 Eastern Stock

The base run model configuration for the Eastern GOM stock included the index from Florida only (Figure 7.26). In contrast to the residual pattern of the Western GOM stock base run, the temporal distribution of residual errors is much less pronounced for the Eastern GOM stock (Figure 7.27). However there is a pattern of under-estimation of the model to data.

7.2.2 Parameter Estimates

7.2.2.1 Western Stock

A variety of model parameters are estimated by the ASPIC formulation including K, B_1/K (starting biomass relative to K), MSY (maximum sustainable yield), and catchability coefficients qi, i = 1…m (where m is the number of abundance indices used). Estimated mean model parameters and confidence intervals of the base model were derived from non-parametric bootstrap in the ASPIC program (Prager 2004) and are presented in Table 7.9 for the Western GOM stock. The estimated maximum sustainable yield is approximately 61 million pounds of blue crab, but the bootstrapped 90% confidence interval indicates that there is much variance around this point estimates (90% CI: 14.5 to 64.7 million lbs). The mean biomass of crabs, at MSY, is equivalent to approximately 149 million adult blue crabs.

The temporal pattern of the combined state index for the Western GOM stock indicates that the relative biomass had a period of marked decrease from the mid-1980's to the mid-1990's (Figure 7.24). Around the year 2000 the relative biomass was stable with the exception of 2006 which had a relatively large relative abundance.

The estimated abundance of individuals in the Western GOM stock indicates a fairly consistent decrease in biomass beginning around 1960 (Figure 7.28). This corresponds with an increasing estimate of fishing mortality (Figure 7.28) at this time. From approximately 1985 to the present the fishing morality rate has ranged from 0.15 y^{-1} to 0.32 y^{-1}.

The relative biomass of crabs (relative to MSY) in the Western GOM stock is 0.95 (90% CI: 0.21 to 1.29, Table 7.9). In the time series this relationship has been variable (Figure 7.29) and it was only in the early 1990's that the mean estimate of relative biomass indicated that the stock was overfished. The fishery status for the stock during this period (Figure 7.29) indicates that overfishing has occurred but was punctuated with years where fishing mortality was less than F_{MSY}.

7.2.2.2 Eastern Stock

Table 7.10 summarizes the mean and bootstrapped model estimates from the Eastern GOM stock. The estimated maximum sustainable yield (biomass in lbs) is approximately 6.4 million (90% CI: 1 to 7.9 million lbs). The mean biomass of crabs at MSY equivalent to approximately 15.5 million adult blue crabs.

The temporal pattern of the Florida state index for the Eastern GOM stock indicates that the relative biomass is highly variable with no apparent long-term trend (Figure 7.26). The relative abundance in 2006 also exhibited a large relative spike in biomass, similar to that observed in the Western GOM stock combined abundance index.

Similar to the Western GOM stock, the estimated biomass of individuals in the Eastern GOM stock indicates a fairly consistent decrease over the time period for which landings are available (Figure 7.30).

The estimated biomass of individuals in the Eastern GOM stock indicates a fairly consistent decrease over the time period for which landings are available (Figure 7.30). This corresponds with a generally increasing trend in fishing mortality (Figure 7.30) over the time-series. From approximately 1995 to the present the fishing morality rate has reached 0.12 y^{-1}.

The relative abundance of crabs (relative to MSY) in the Eastern GOM stock in the terminal year is 3.13 (90% CI: 1.41 to 19.45; Table 7.10). In the time series this relationship has been variable (Figure 7.31), with large swings in the estimated F/F_{MSY} ratio. The estimated fishery status for the stock is that the stock has been overfished since the late 1970's (Figure 7.31).

7.2.3 Sensitivity Analyses

7.2.3.1 Western GOM Stock

The tabulated results of the sensitivity runs for the Western GOM stock indicate that the choice of index can have a large effect on the estimates of MSY and other reference points of management interest (Table 7.11). The pairwise differences in the Western GOM stock individual indices indicate that there are differences in the relative trajectories of each state's stock. The Western GOM combined index used in the base model configuration (sp-01-west) is positively correlated to the Alabama, Louisiana, and Texas state indices but negatively correlated to the Mississippi index, indicating that the temporal pattern of abundance in this state is fundamentally different from that of the neighboring northern Gulf States (Figure 7.32). This pattern is evident with the Central state index as well; Mississippi is negatively correlated to this index[3].

Although the index of abundance for Mississippi is negatively correlated to the other states' indices in the northern Gulf of Mexico, an examination of the estimated fishery reference points (Table 7.11) indicates that the model based on the Texas index (sp-03-west) is anomalously low[3]. The model configurations using Alabama, Louisiana, and Mississippi data each predict MSY values similar to those of the base run, with biomass estimates ranging from 60.9 to 69.3 million lbs. Only model run sp-06-west (Louisiana) indicates that the stock is not overfished or that overfishing is not occurring.

The analysis of the Western GOM stock with the alternative model shape, Fox, (sp-09-west) predicts an MSY, similar to that of the base model run and that the stock is not overfished and that overfishing is not occurring. The model runs with different initial values of B_0 (sp-west-08, sp-west-09) predicted nearly identical magnitudes of MSY, fishery and the stock status to that of the base model run.

The analysis of the stock status and fishery status of the Western GOM stock model runs indicate similar temporal trajectories in some model runs to the base model trajectory (Figure 7.33 and 7.34) with the exception of some model runs. sp-06-west is the model run using only Mississippi data and sp-04-west is the model using only Alabama data, both predict that the stock has been overfished and that overfishing occurred during most of the time-series[3]. sp-09-west and sp-03-west have are similar in that both indicate a decline in B/B_{MSY} over the time series.

7.2.3.2 Eastern GOM Stock

The tabulated results of the sensitivity runs for the Western GOM stock indicate that the choice of index affects the estimates of MSY and other reference points of management interest (Table 7.12). The pairwise differences in the two Eastern GOM stock indices (fishery-independent and

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[3] Using only data from each individual state separately in the Western GOM stock model **does not** signify that Texas and Mississippi are currently overfished or undergoing overfishing because the parameter suite for the base Western GOM stock model remained the same for these runs, and only the landings and survey data were changed. To ascertain the stock status of individual states, which may not be appropriate given the stock structure, the models would have to be configured for each state independently and run with a full uncertainty analysis. Most importantly these runs use a combined four states Western-GOM stock parameterization of juvenile vulnerability, M, and Z, which could be different for each individual state.

fishery-dependent data sources) indicate correspondence; they are positively correlated to each other (Figure 7.35).

The inclusion of the commercial CPUE data series results in and increase in the estimated value of MSY to 7.65 million lbs. This model with both relative abundance indices results in similar estimates of the stock and fishery status for the terminal year, 2012, that the stock is overfished and that overfishing is occurring.

The analysis of the Western GOM stock with the alternative Fox model shape (sp-05-east) indicates that the magnitude of MSY, the fishery and the stock status are similar to that of the base model run. The model runs with different initial values of B_0 (sp-east-03, sp-east-04) predicted similar magnitudes of MSY, fishery and the stock status to that of the base model run.

The analysis the stock status and fishery status of the Eastern GOM stock model runs indicate similar temporal trajectories (Figure 7.36 and 7.37); in 1988 to 1990 the biomass was reduced relative to BMSY and has continued to decline. Similarly, in many runs, but not all, overfishing is occurring (Figure 7.36).

7.2.4 Retrospective Analyses

Some bias was detected in the retrospective pattern for the Western GOM stock (sp-06- to sp-10-west, Figure 7.38). The base model estimate predicts the greatest biomass and lowest *F* rate.

Pronounced biases were evident in the retrospective analysis for abundances and fishing rates (Figure 7.39) in the Eastern GOM stock. Although model fit to each of the indices is satisfactory the retrospective pattern is troubling, indicating that the fishery reference points and stock and fishery status estimates may be questionable.

7.2.5 Uncertainty Analysis

Bootstrapped estimates of uncertainty were determined for the base model runs in both stocks (Table 7.9 and 7.10) and are discussed above.

7.2.6 Reference Point Results – Parameter Estimates and Sensitivity

The reference points are presented in Table 7.9 and 7.10 for the Western and Eastern GOM stocks, respectively and the results are discussed above.

Table 7.1 Western GOM stock parameter estimates from the base run. Abundance estimates are in millions of individuals. The first two columns are from the ADMB base model fit and delta-method calculation of error, while the last two columns are from the MCMC runs. Note: because effort was fixed at 1.0 for the base model run, the initial q estimate is equivalent to the initial F estimate.

Parameter	Base Estimate	SD	MCMC Median	MCMC 95% CI
InitialN	165.52	18.59	172.50	139.72-213.85
InitialR	644.19	49.81	659.64	571.14-764.24
InitialF	0.55	0.06	0.53	0.43-0.65
S0	111.92	29.14	120.13	85.95-203.85
h	0.72	0.16	0.69	0.52-1

Table 7.2 Western GOM stock estimated abundances (millions of individuals) at the start of the model year for juveniles and adults, and the estimate full F for the base model run, along with the MCMC median and 95% confidence intervals.

Year	Juvenile Abundance			Adult Abundance			Fishing Rate (F)		
	Base Estimate	MCMC Median	MCMC 95% CI	Best Estimate	MCMC Median	MCMC 95% CI	Best Estimate	MCMC Median	MCMC 95% CI
1985	644.19	659.64	571-764	165.52	172.50	140-214	0.55	0.53	0.43-0.65
1986	529.34	540.25	472-619	170.90	177.59	148-213	0.77	0.74	0.61-0.9
1987	617.05	631.22	560-722	134.36	140.14	116-169	1.26	1.21	0.99-1.49
1988	548.69	559.23	490-638	115.95	121.49	98-150	1.25	1.20	0.98-1.47
1989	675.01	693.01	602-799	103.13	107.57	87-133	0.82	0.79	0.65-0.96
1990	682.42	698.49	608-805	143.34	149.43	124-181	0.87	0.84	0.69-1.03
1991	516.44	527.13	460-607	149.58	155.84	128-190	1.05	1.00	0.81-1.24
1992	610.27	621.83	551-709	111.99	116.75	94-145	1.11	1.07	0.88-1.29
1993	472.41	483.65	426-554	118.78	123.60	102-149	1.06	1.01	0.83-1.24
1994	346.39	354.76	312-407	98.96	103.45	85-127	1.62	1.55	1.22-1.92
1995	400.26	408.15	359-467	58.61	61.98	48-81	1.54	1.48	1.19-1.82
1996	436.91	447.10	391-507	64.34	67.37	54-85	1.46	1.40	1.15-1.69
1997	578.67	592.41	522-680	72.44	75.85	61-93	1.24	1.19	0.98-1.44
1998	366.81	372.93	331-423	102.53	107.14	87-131	1.66	1.60	1.32-1.93
1999	493.33	504.68	446-571	60.73	63.52	51-79	2.06	1.98	1.63-2.37
2000	375.48	382.48	334-437	65.43	68.74	55-86	1.64	1.57	1.28-1.91
2001	422.89	431.53	383-489	59.28	62.05	50-77	1.61	1.56	1.3-1.86
2002	400.80	408.41	361-463	66.11	68.87	57-84	1.82	1.76	1.47-2.09
2003	438.49	448.24	396-510	58.89	61.34	50-76	1.61	1.56	1.29-1.86
2004	416.88	426.65	372-491	68.19	71.36	58-87	1.41	1.35	1.12-1.64
2005	607.89	623.09	543-715	71.25	74.55	60-92	0.98	0.94	0.79-1.14
2006	400.07	406.57	358-468	117.66	122.50	101-147	1.18	1.14	0.94-1.37
2007	367.74	375.77	330-429	81.92	85.29	70-104	1.40	1.35	1.12-1.62
2008	480.01	492.30	432-561	65.45	68.45	55-84	1.39	1.33	1.11-1.61
2009	318.47	324.25	281-373	81.15	84.96	69-103	1.36	1.30	1.09-1.58
2010	382.10	390.84	338-452	58.89	61.37	49-75	1.12	1.08	0.89-1.3
2011	403.67	412.00	348-501	72.38	75.04	61-92	1.12	1.08	0.89-1.3

Table 7.3 Eastern GOM stock parameter estimates from the base run. Abundance estimates are in millions of individuals. The first two columns are from the ADMB base model fit and delta-method calculation of error, while the last two columns are from the MCMC runs. Note: because effort was fixed at 1.0 for the base model run, the initial q estimate is equivalent to the initial F estimate.

Parameter	Base Estimate	SD	MCMC Median	MCMC 95% CI
InitialN	27.21	9.85	22.86	13.3-32.63
InitialR	31.72	13.87	31.43	15.6-59.86
InitialF	0.89	0.34	1.03	0.81-1.63
S0	7.55	1.21	8.13	6.34-11.85
h	1.26	0.28	1.18	0.85-1.73

Table 7.4 Eastern GOM stock estimated abundances (millions of individuals) at the start of the model year for juveniles and adults, and the estimate full F for the base model run, along with the MCMC median and 95% confidence intervals.

Year	Juvenile Abundance			Adult Abundance			Fishing Rate (F)		
	Base Estimate	MCMC Median	MCMC 95% CI	Best Estimate	MCMC Median	MCMC 95% CI	Best Estimate	MCMC Median	MCMC 95% CI
1989	31.72	31.43	16-60	27.21	22.86	13-33	0.89	1.03	0.81-1.63
1990	23.17	25.84	15-39	11.45	9.93	6-16	2.18	2.21	1.54-3.14
1991	60.67	61.76	46-82	3.90	4.09	2-7	1.83	1.77	1.26-2.48
1992	34.93	35.67	25-51	10.00	10.36	6-16	2.69	2.52	1.73-3.56
1993	45.35	47.17	37-64	4.63	5.01	3-9	3.42	3.17	2.13-4.08
1994	40.74	41.29	32-53	4.58	5.13	3-9	3.31	3.10	2.23-3.99
1995	65.93	66.57	57-78	4.27	4.63	3-8	2.40	2.34	1.93-2.81
1996	44.83	44.98	39-51	9.08	9.35	7-12	4.13	4.08	3.57-4.41
1997	66.24	67.36	59-77	3.67	3.75	3-5	1.94	1.90	1.59-2.23
1998	69.91	70.68	64-79	10.52	10.82	9-13	3.95	3.84	3.27-4.24
1999	36.35	36.70	32-42	6.03	6.34	5-8	3.32	3.21	2.56-3.89
2000	29.31	29.80	26-35	3.82	4.01	3-5	3.01	2.92	2.25-3.68
2001	28.92	29.39	26-34	3.38	3.54	3-5	2.85	2.76	2.22-3.41
2002	34.16	34.67	31-40	3.51	3.66	3-5	2.60	2.54	2.09-3.04
2003	65.09	66.19	58-75	4.46	4.61	4-6	2.07	2.02	1.67-2.43
2004	49.52	50.13	44-57	9.96	10.29	8-13	1.85	1.80	1.47-2.2
2005	58.74	59.49	53-67	8.55	8.81	7-11	1.54	1.51	1.28-1.79
2006	44.52	44.99	40-51	11.05	11.34	9-14	2.34	2.29	1.87-2.79
2007	22.08	22.53	19-27	6.58	6.78	5-9	1.77	1.70	1.3-2.33
2008	18.92	19.30	16-23	4.08	4.29	3-6	2.05	1.97	1.5-2.62
2009	39.31	39.91	35-46	3.07	3.22	2-4	1.55	1.51	1.25-1.82
2010	50.85	51.62	45-59	7.14	7.36	6-9	2.03	1.97	1.6-2.42
2011	29.54	29.72	26-35	8.09	8.34	6-11	2.03	1.97	1.6-2.42

Table 7.5 Western GOM stock sensitivity runs and retrospective analyses. F/F_{Limit} and N/N_{Limit} refer to the current status of the stock for each run, where red values for F/F_{Limit} (>1) represent current overfishing and red values for N/N_{Limit} (<1) represent overfished. **NA** indicates measure was not able to be determined.

Run #	Run	negLL	MSY	FMSY	NMSY	F/F_{Limit}	N/N_{Limit}
bc-00-west	**Base Model**	179.33	164.35	1.70	78.54	0.72	1.79
bc-01-west	s=0.2	179.18	167.65	1.92	98.72	0.64	1.86
bc-02-west	s=0.4	179.61	162.35	1.57	64.23	0.78	1.73
bc-03-west	s=0.6	180.86	160.11	1.40	46.08	0.84	1.64
bc-04-west	M={1.95, 1.05}	172.73	174.42	1.55	73.65	0.68	1.86
bc-05-west	M={1, 1}	178.19	167.95	1.42	120.38	0.68	1.80
bc-06-west	Average Z*0.7	179.32	172.74	1.04	144.00	0.63	1.94
bc-07-west	Average Z*1.3	179.73	161.58	2.26	54.44	0.78	1.69
bc-08-west	Max F/M=3	179.33	164.35	1.70	78.54	0.72	1.79
bc-09-west	Max F/M=5	179.33	164.35	1.70	78.54	0.72	1.79
bc-10-west	Precipitation on M	178.48	170.30	1.74	79.18	0.65	1.90
bc-11-west	Streamflow on M	176.37	170.61	1.58	88.85	0.65	1.90
bc-12-west	Precipitation on R	178.90	164.13	1.75	75.79	0.70	1.85
bc-13-west	Streamflow on R	179.06	162.07	1.69	78.00	0.73	1.80
bc-14-west	Beverton-Holt	179.20	165.99	2.24	56.57	0.55	2.48
bc-15-west	h=0.99	179.64	**NA**	**NA**	**NA**	**NA**	**NA**
bc-16-west	Effort Time Series	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
bc-17-west	TX	124.23	35.84	0.90	34.96	6.10	0.25
bc-18-west	LA	110.81	150.79	2.19	52.88	0.53	2.63
bc-19-west	AL	26.29	8.86	1.92	3.66	0.38	1.67
bc-20-west	MS	-6.73	2.05	1.50	1.14	1.30	0.83
bc-21-west	West Subregion (TX)	124.23	35.84	0.90	34.96	6.10	0.25
bc-22-west	Central Subregion	127.79	158.68	2.10	58.67	0.54	2.48
bc-23-west	West Sub. Stream. M	108.37	30.03	0.65	41.40	4.44	0.33
bc-24-west	Cent. Sub. Stream. M	127.74	157.87	2.10	58.37	0.54	2.50
bc-25-west	Retro 2010	176.35	163.48	1.66	80.36	0.82	1.70
bc-26-west	Retro 2009	165.46	162.86	1.61	82.97	0.90	1.85
bc-27-west	Retro 2008	152.65	169.67	1.80	75.75	0.77	2.15
bc-28-west	Retro 2007	152.13	169.31	1.79	76.10	0.65	2.19
bc-29-west	Retro 2006	148.68	172.66	1.83	75.57	0.70	2.09

Table 7.6 Eastern GOM stock sensitivity runs and retrospective analyses. F/F_{Limit} and N/N_{Limit} refer to the current status of the stock for each run, where red values for F/F_{Limit} (>1) represent current overfishing and red values for N/N_{Limit} (<1) represent overfished. **NA** indicates measure was not able to be determined.

Run #	Run	negLL	MSY	FMSY	NMSY	Fcurr/ FLimit	Ncur/ NLimit
bc-00-east	**Base Model**	140.21	23.16	3.48	4.75	0.51	2.37
bc-01-east	s=0.2	152.19	24.90	4.35	6.42	0.38	2.83
bc-02-east	s=0.4	129.20	22.32	3.00	3.76	0.64	1.85
bc-03-east	s=0.6	110.31	22.95	2.76	2.18	0.77	1.40
bc-04-east	M={1.78, 1.22}	136.88	24.83	3.29	4.15	0.46	2.55
bc-05-east	M={1, 1}	142.97	23.06	3.42	5.68	0.50	2.41
bc-06-east	Average Z*0.7	153.38	26.42	3.02	6.66	0.36	3.08
bc-07-east	Average Z*1.3	139.19	22.25	3.66	4.22	0.61	1.95
bc-08-east	Max F/M=3	149.26	23.64	3.25	5.36	0.47	2.53
bc-09-east	Max F/M=5	138.58	23.13	3.62	4.47	0.52	2.31
bc-10-east	Precipitation on M	119.46	25.30	2.05	10.54	0.66	1.25
bc-11-east	Streamflow on M	52.09	36.75	3.26	8.30	0.36	1.72
bc-12-east	Precipitation on R	136.80	22.64	3.37	4.87	0.53	2.29
bc-13-east	Streamflow on R	135.30	28.81	4.78	3.49	0.37	3.22
bc-14-east	Beverton -Holt	139.95	26.15	6.00	2.01	0.29	5.61
bc-15-east	h=0.99	139.95	**NA**	**NA**	**NA**	**NA**	**NA**
bc-16-east	Effort Time Series	142.49	21.95	2.91	5.83	0.58	2.19
bc-25-east	Retro 2010	133.65	23.83	3.41	5.04	0.50	1.84
bc-26-east	Retro 2009	129.37	22.91	3.30	5.08	0.57	1.76
bc-27-east	Retro 2008	124.00	24.68	3.54	4.93	0.47	3.27
bc-28-east	Retro 2007	121.70	26.46	3.86	4.62	0.41	4.15
bc-29-east	Retro 2006	84.26	27.48	3.46	5.68	0.43	3.96

Table 7.7 Western GOM stock reference points estimates for the base model and MCMC runs. Numbers (e.g., MSY, N_{MSY}) are in millions of individuals.

Reference Point	Base Model Estimate	MCMC Quantiles 2.50%	25%	50%	75%	97.50%
MSY	164.35	158.81	163.78	168.16	176.64	199.24
F_{MSY}	1.70	1.01	1.33	1.58	1.90	2.59
N_{MSY}	78.54	55.67	71.76	85.37	103.50	157.93
U_{MSY}	0.50	0.39	0.45	0.48	0.52	0.57
F_{Limit}	1.70	0.95	1.33	1.58	1.90	2.59
N_{Limit}	39.27	27.83	35.88	42.69	51.75	78.97
F/F_{MSY}	0.72	0.46	0.62	0.75	0.90	1.18
N/N_{MSY}	0.89	0.46	0.71	0.86	1.02	1.28
U/U_{MSY}	0.85	0.72	0.80	0.87	0.94	1.07
F/F_{Limit}	0.72	0.46	0.62	0.75	0.90	1.27
N/N_{Limit}	1.79	0.92	1.41	1.72	2.04	2.57
$SPR_{Current}$	0.43	0.40	0.42	0.44	0.45	0.48

Table 7.8 Eastern GOM stock reference points estimates for the base model and MCMC runs. Numbers (e.g., MSY, N_{MSY}) are in millions of individuals.

Reference Point	Base Model Estimate	MCMC Quantiles 2.50%	25%	50%	75%	97.50%
MSY	23.16	21.40	22.32	23.17	24.59	28.72
F_{MSY}	3.48	2.27	2.87	3.28	3.73	4.58
N_{MSY}	4.75	3.70	4.51	5.19	6.02	8.22
U_{MSY}	0.63	0.57	0.61	0.62	0.64	0.65
F_{Limit}	3.48	2.27	2.87	3.28	3.73	4.58
N_{Limit}	2.37	1.85	2.26	2.60	3.01	4.11
F/F_{MSY}	0.51	0.36	0.46	0.53	0.61	0.77
N/N_{MSY}	1.18	0.70	0.96	1.13	1.29	1.60
U/U_{MSY}	0.85	0.78	0.82	0.85	0.88	0.93
F/F_{Limit}	0.51	0.36	0.46	0.53	0.61	0.77
N/N_{Limit}	2.37	1.40	1.91	2.26	2.58	3.21
$SPR_{Current}$	0.37	0.33	0.36	0.37	0.39	0.42

Table 7.9 Mean estimate and bootstrapped-derived confidence intervals from the ASPIC base run for the western stock. K, MSY, and B_{MSY} are biomass (lbs) of crabs.

Parameter Name	Mean Estimate	90% lower	90% upper
B_1/K	0.46	0.03	1.00
K	502,500,000	158,800,000	4,294,000,000
q_1	8.74E-09	9.20E-10	2.91E-08
MSY	61,120,000	14,520,000	64,670,000
B_{MSY}	251,200,000	79,410,000	2,147,000,000
F_{MSY}	0.24	0.03	0.82
$B./B_{MSY}$	0.95	0.21	1.29
$F./F_{MSY}$	1.01	0.70	2.50

Table 7.10 Mean estimate and bootstrapped-derived confidence intervals from the ASPIC base run for the Eastern GOM stock. K, MSY, and B_{MSY} are biomass (lbs) of crabs.

Parameter Name	Mean Estimate	90% lower	90% upper
B_1/K	1.02	1.01	1.36
K	397,700,000	164,200,000	1,965,000,000
q_1	1.93E-08	1.02E-09	3.74E-08
MSY	6,371,000	1,055,000	7,911,000
B_{MSY}	198,900,000	82,120,000	982,700,000
F_{MSY}	0.03	0.00	0.05
$B./B_{MSY}$	0.35	0.04	1.77
$F./F_{MSY}$	3.13	1.41	19.45

Table 7.11 Mean estimates of base and sensitivity surplus production model runs from Western GOM stock.

Model Name	Fmsy	MSY (lbs)	MSY (# of crabs)	F/F_{MSY}	B/B_{MSY}	K (lbs)	Data Range (Landings)		B_0	B_1/K Initial	Model Shape	Indices	Notes
sp-01-west	0.24	60,943,214	148,641,985	1.05	0.92	500,637,260	1950	2011	Estimated	0.75	LOGISTIC	Western Combined INDEX	
sp-02-west	0.50	64,994,901	158,524,149	0.70	1.28	257,588,120	1950	2011	Estimated	0.75	LOGISTIC	Central INDEX	
sp-03-west	0.01	5,806,046	14,161,088	9.10	1.07	1,617,872,800	1950	2011	Estimated	0.75	LOGISTIC	Texas INDEX	
sp-04-west	0.00	4,645,082	11,329,468	38.63	0.32	7,689,461,200	1950	2011	Estimated	0.75	LOGISTIC	Alabama INDEX	
sp-05-west	1.61	69,274,543	168,962,300	0.57	1.44	86,251,718	1950	2011	Estimated	0.75	LOGISTIC	Louisiana INDEX	
sp-06-west	0.10	65,475,386	159,696,063	1.73	0.51	1,251,585,400	1950	2011	Estimated	0.75	LOGISTIC	Mississippi INDEX	
sp-07-west	0.24	60,944,296	148,644,624	1.05	0.92	500,614,870	1950	2011	Estimated	0.25	LOGISTIC	Western Combined INDEX	
sp-08-west	0.24	60,970,087	148,707,529	1.05	0.92	498,363,960	1950	2011	Estimated	0.50	LOGISTIC	Western Combined INDEX	
sp-09-west	0.36	61,895,179	150,963,851	0.87	1.10	471,087,450	1950	2011	Estimated	0.75	FOX	Western Combined INDEX	
sp-10-west	0.27	61,525,634	150,062,522	0.78	0.94	461,344,180	1950	2010	Estimated	0.75	LOGISTIC	Western Combined INDEX	Retrospective analysis
sp-11-west	0.29	62,035,721	151,306,637	1.17	0.88	428,183,350	1950	2009	Estimated	0.75	LOGISTIC	Western Combined INDEX	Retrospective analysis
sp-12-west	0.27	61,527,902	150,068,054	0.98	0.87	458,482,080	1950	2008	Estimated	0.75	LOGISTIC	Western Combined INDEX	Retrospective analysis
sp-13-west	0.30	62,285,056	151,914,771	1.13	0.86	415,601,460	1950	2007	Estimated	0.75	LOGISTIC	Western Combined INDEX	Retrospective analysis
sp-14-west	0.25	60,914,352	148,571,590	1.40	0.81	483,555,730	1950	2006	Estimated	0.75	LOGISTIC	Western Combined INDEX	Retrospective analysis

Table 7.12 Mean estimates of base and sensitivity surplus production model runs from Eastern GOM stock.

Model Name	Fmsy	MSY (lbs)	MSY (# of crabs)	F/F_{MSY}	B/B_{MSY}	K (lbs)	Data Range (Landings)		B_0	B_1/K Initial	Model Shape	Indices	Notes
sp-01-east	0.03	6,374,231	15,546,905	3.13	0.35	397,530,950	1950	2011	Estimated	0.75	LOGISTIC	Florida Index	
sp-02-east	0.04	7,650,538	18,659,849	1.88	0.49	341,850,610	1950	2011	Estimated	0.75	LOGISTIC	Florida Index, Florida Commercial CPUE Index	
sp-03-east	0.03	6,355,281	15,500,685	3.14	0.35	398,546,780	1950	2011	Estimated	0.25	LOGISTIC	Florida Index	
sp-04-east	0.03	6,371,258	15,539,654	3.13	0.35	397,680,990	1950	2011	Estimated	0.50	LOGISTIC	Florida Index	
sp-05-east	0.06	7,203,695	17,569,988	2.54	0.39	327,037,200	1950	2011	Estimated	0.75	FOX	Florida Index	
sp-06-east	0.00	1,004,209	2,449,290	17.55	0.34	710,068,680	1950	2010	Estimated	0.75	LOGISTIC	Florida Index	Retrospective analysis
sp-07-east	0.00	1,004,204	2,449,278	31.55	0.11	1,546,458,100	1950	2009	Estimated	0.75	LOGISTIC	Florida Index	Retrospective analysis
sp-08-east	0.00	1,004,201	2,449,271	21.47	0.13	2,000,524,400	1950	2008	Estimated	0.75	LOGISTIC	Florida Index	Retrospective analysis
sp-09-east	0.26	12,525,876	30,550,917	0.98	0.56	95,053,893	1950	2007	Estimated	0.75	LOGISTIC	Florida Index	Retrospective analysis
sp-10-east	0.37	13,278,658	32,386,971	1.13	0.63	71,517,172	1950	2006	Estimated	0.75	LOGISTIC	Florida Index	Retrospective analysis

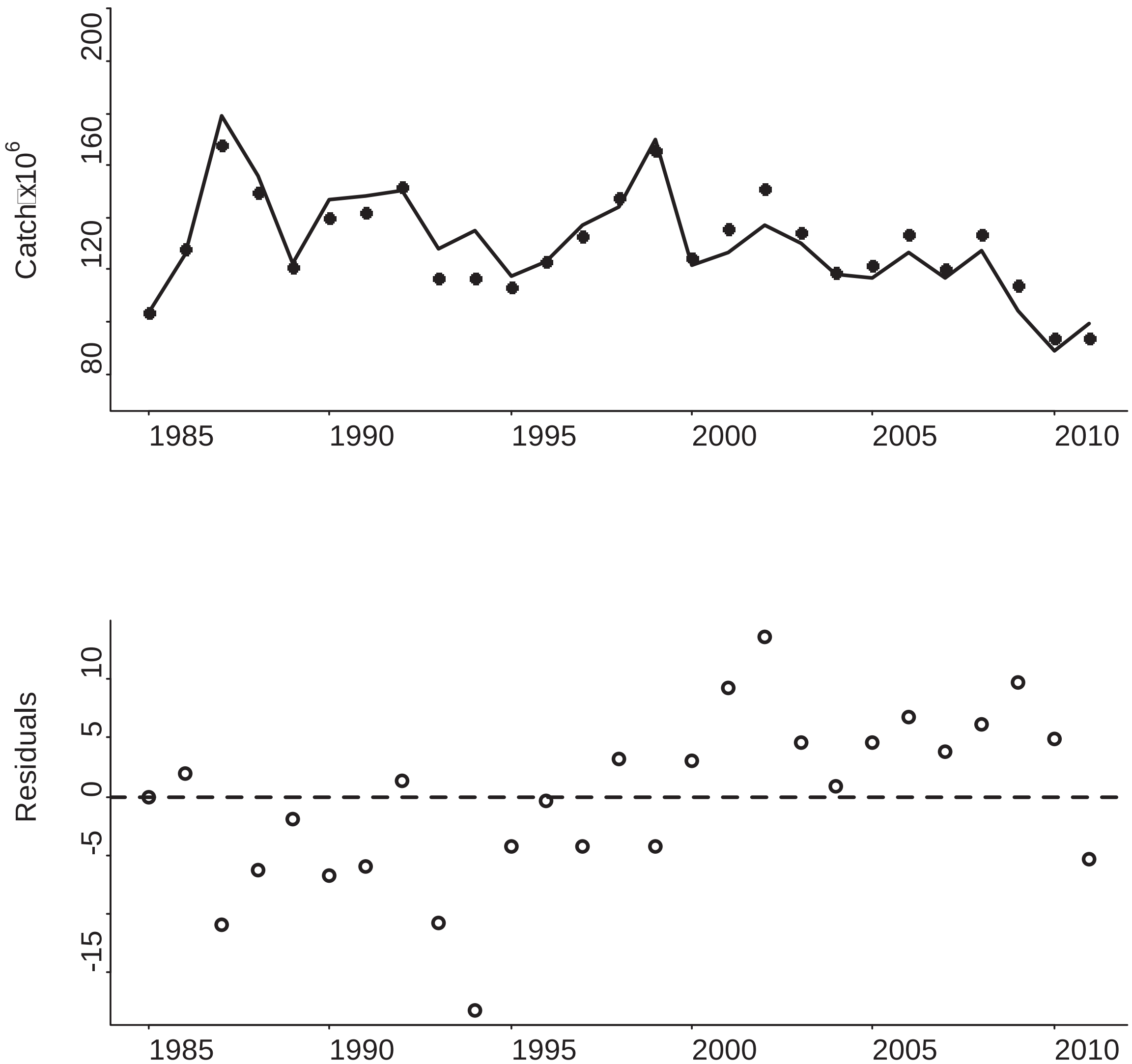


Figure 7.1 Western GOM stock observed (points) and estimated (line) landings for the base run (top pane), with model residuals (bottom pane).

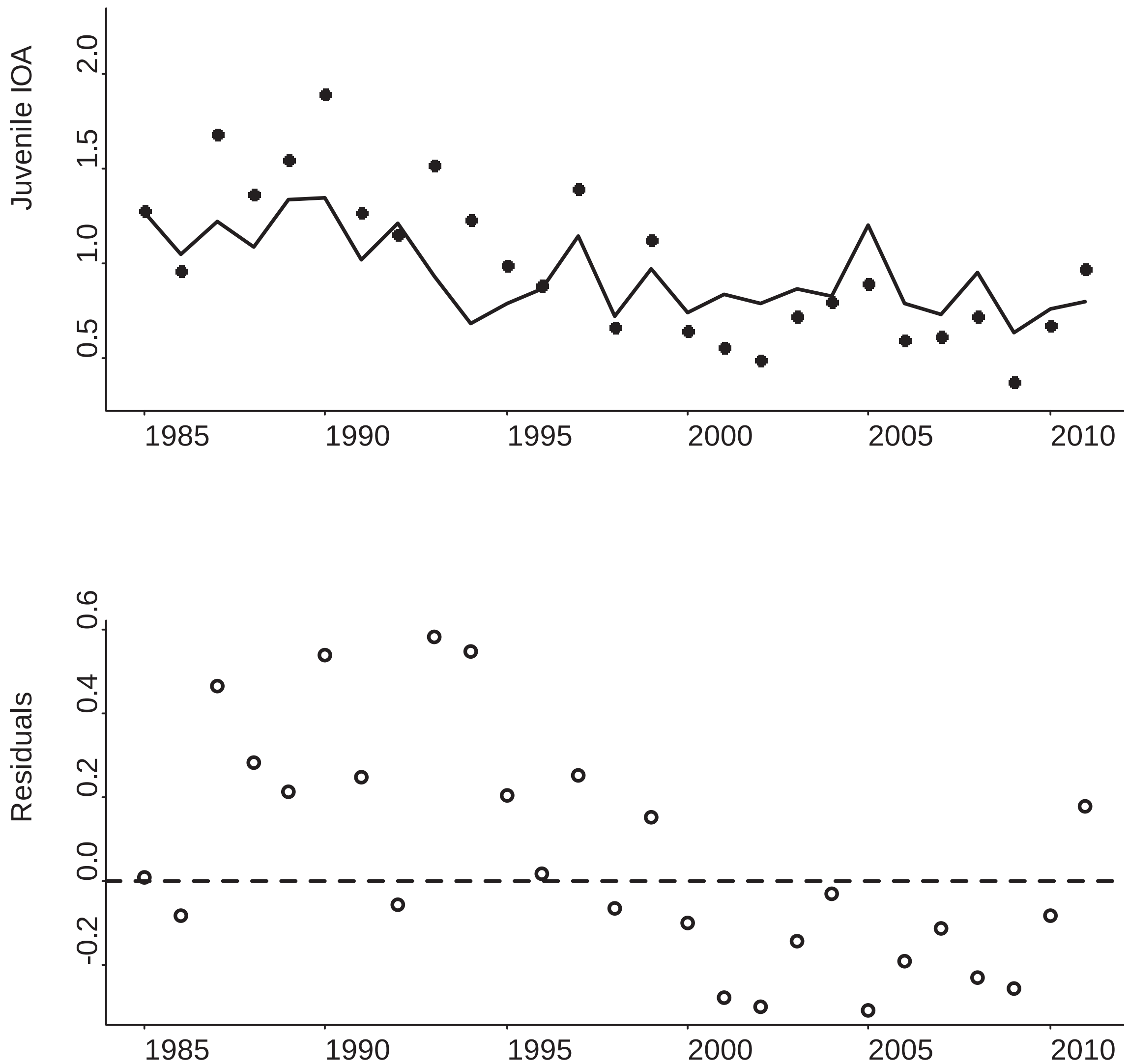


Figure 7.2 Western GOM stock observed (points) and estimated (line) index of abundance of juveniles for the base run (top pane), with model residuals (bottom pane).

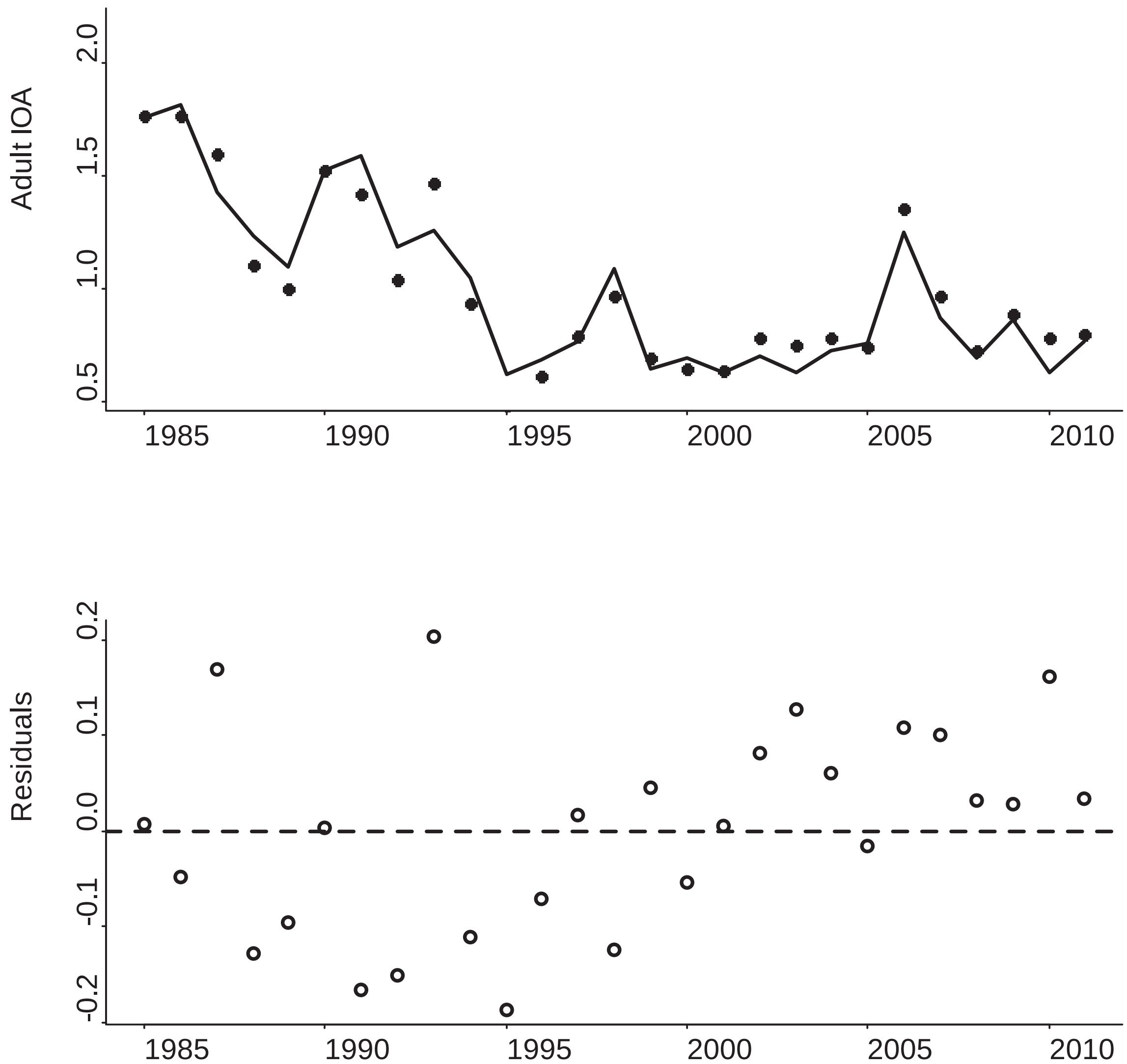


Figure 7.3 Western GOM stock observed (points) and estimated (line) index of abundance of adults for the base run (top pane), with model residuals (bottom pane).

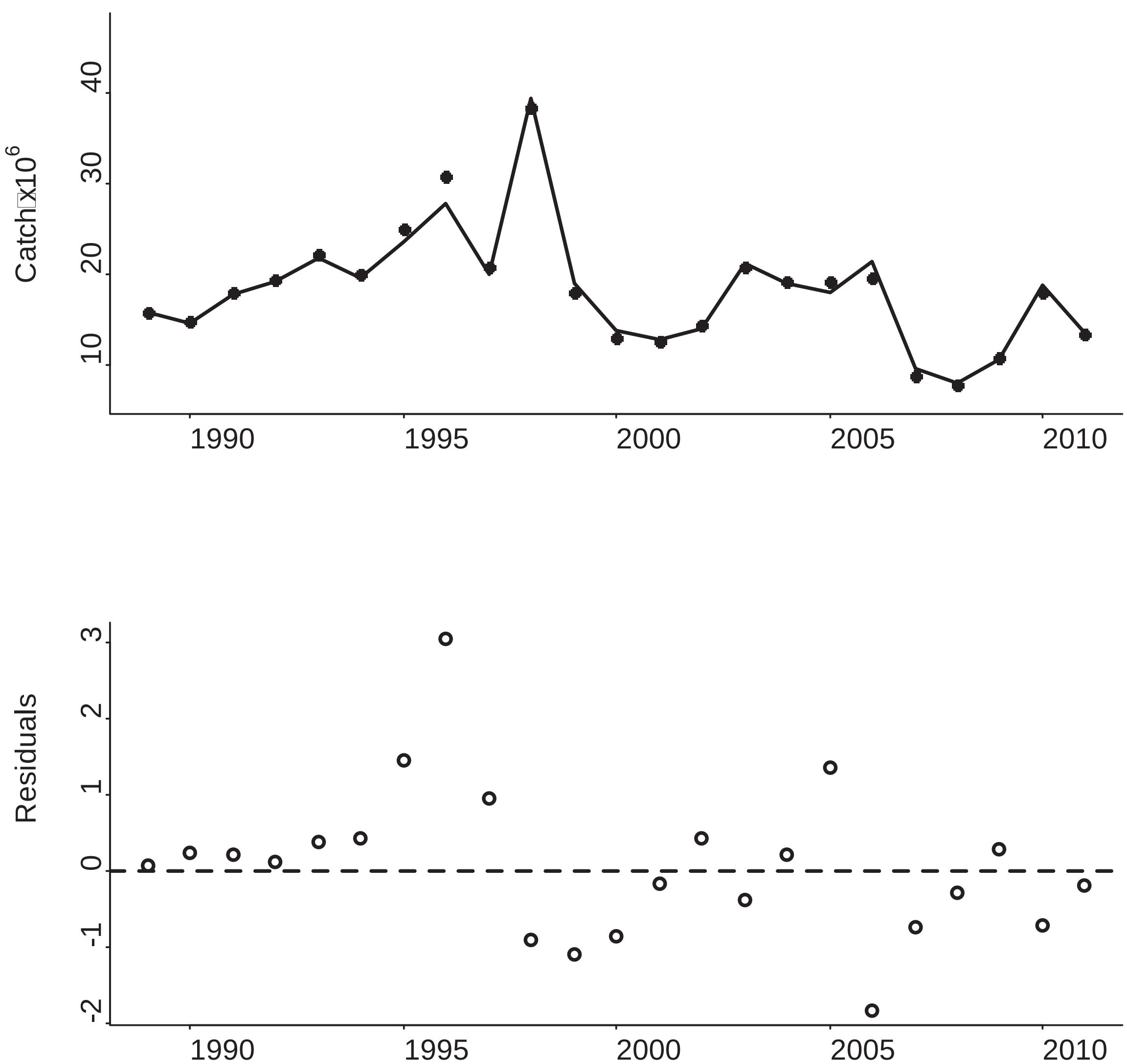


Figure 7.4 Eastern GOM stock observed (points) and estimated (line) landings for the base run (top pane), with model residuals (bottom pane).

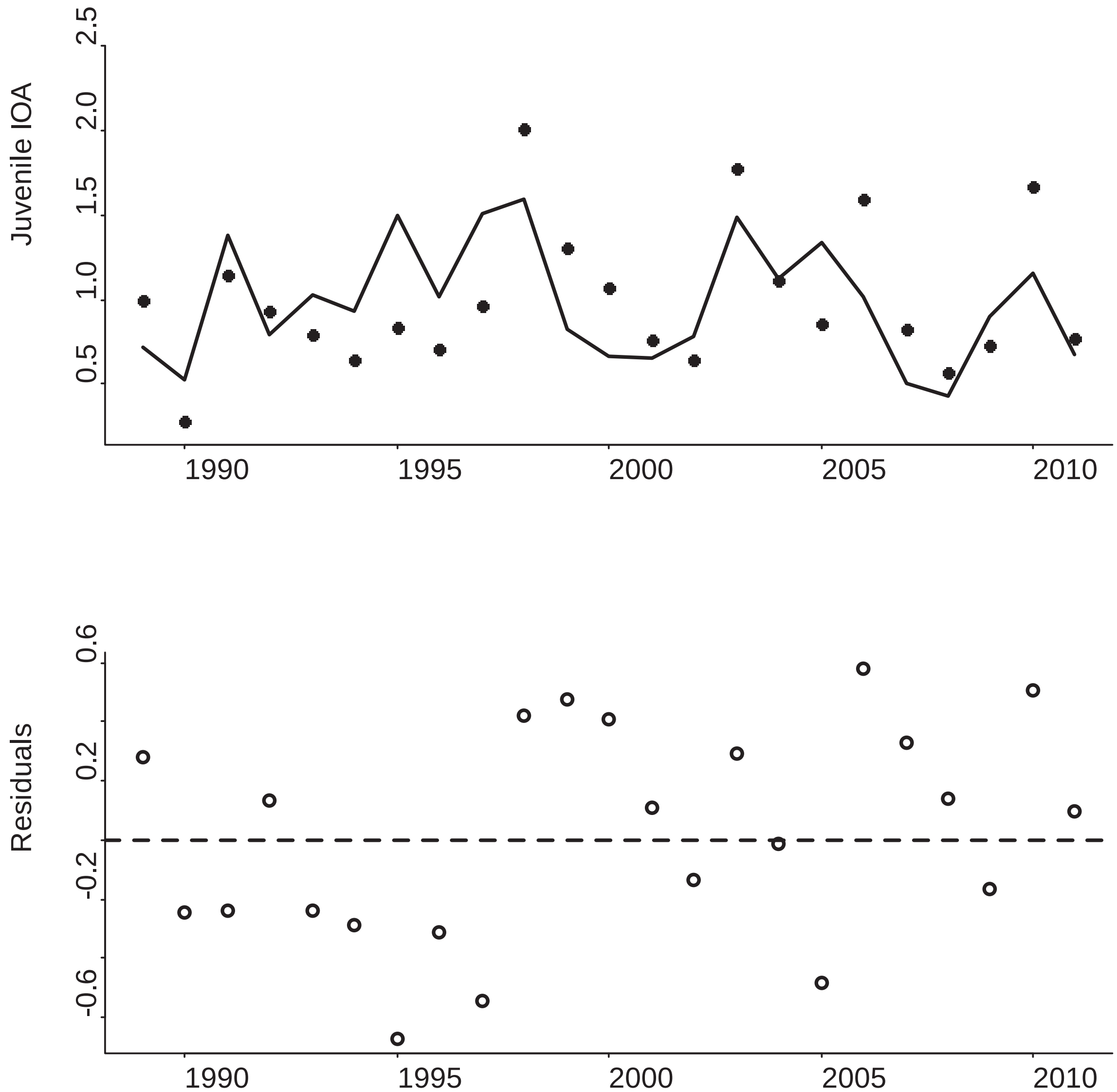


Figure 7.5 Eastern GOM stock observed (points) and estimated (line) index of abundance of juveniles for the base run (top pane), with model residuals (bottom pane).

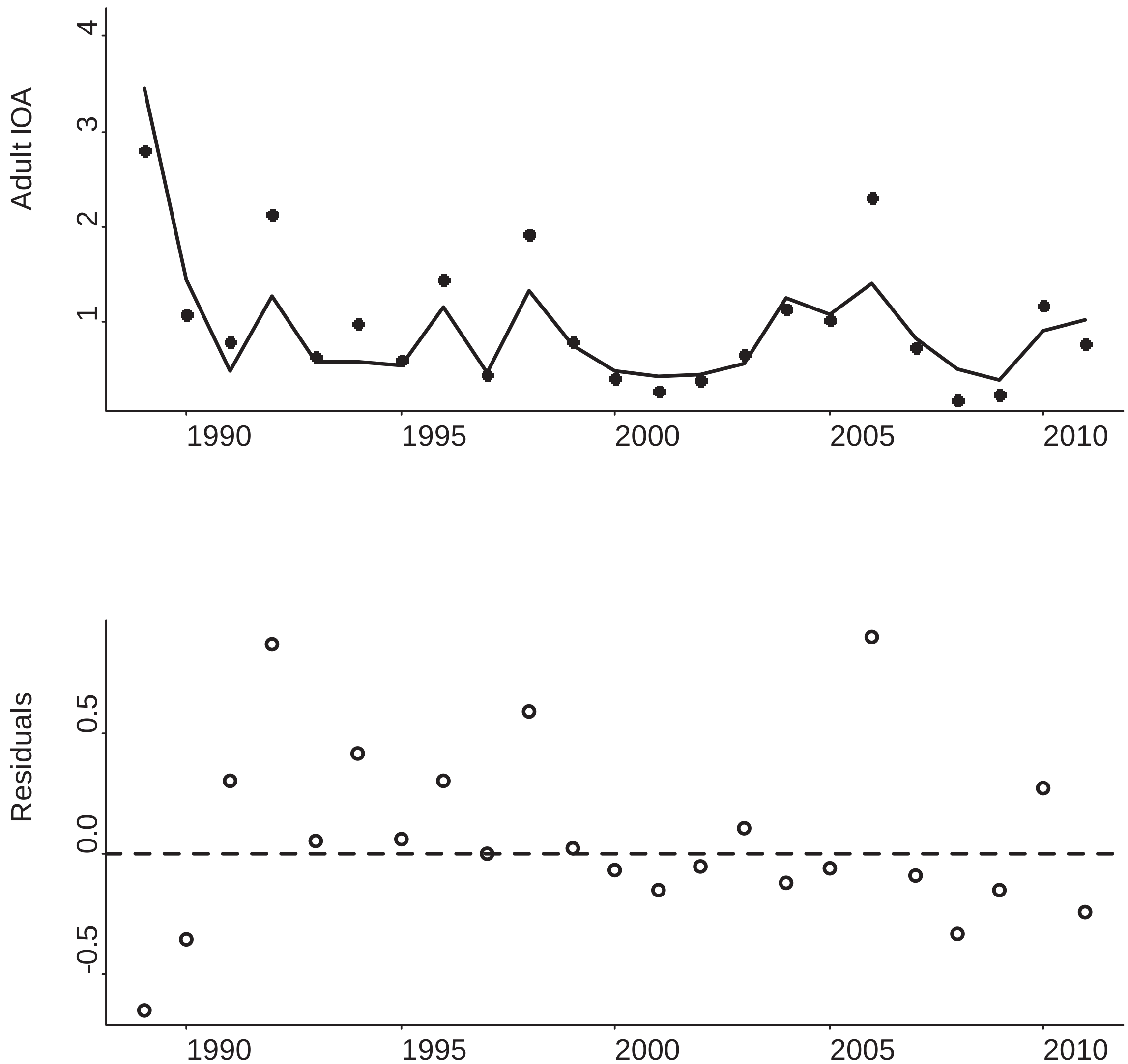


Figure 7.6 Eastern GOM stock observed (points) and estimated (line) index of abundance of adults for the base run (top pane), with model residuals (bottom pane).

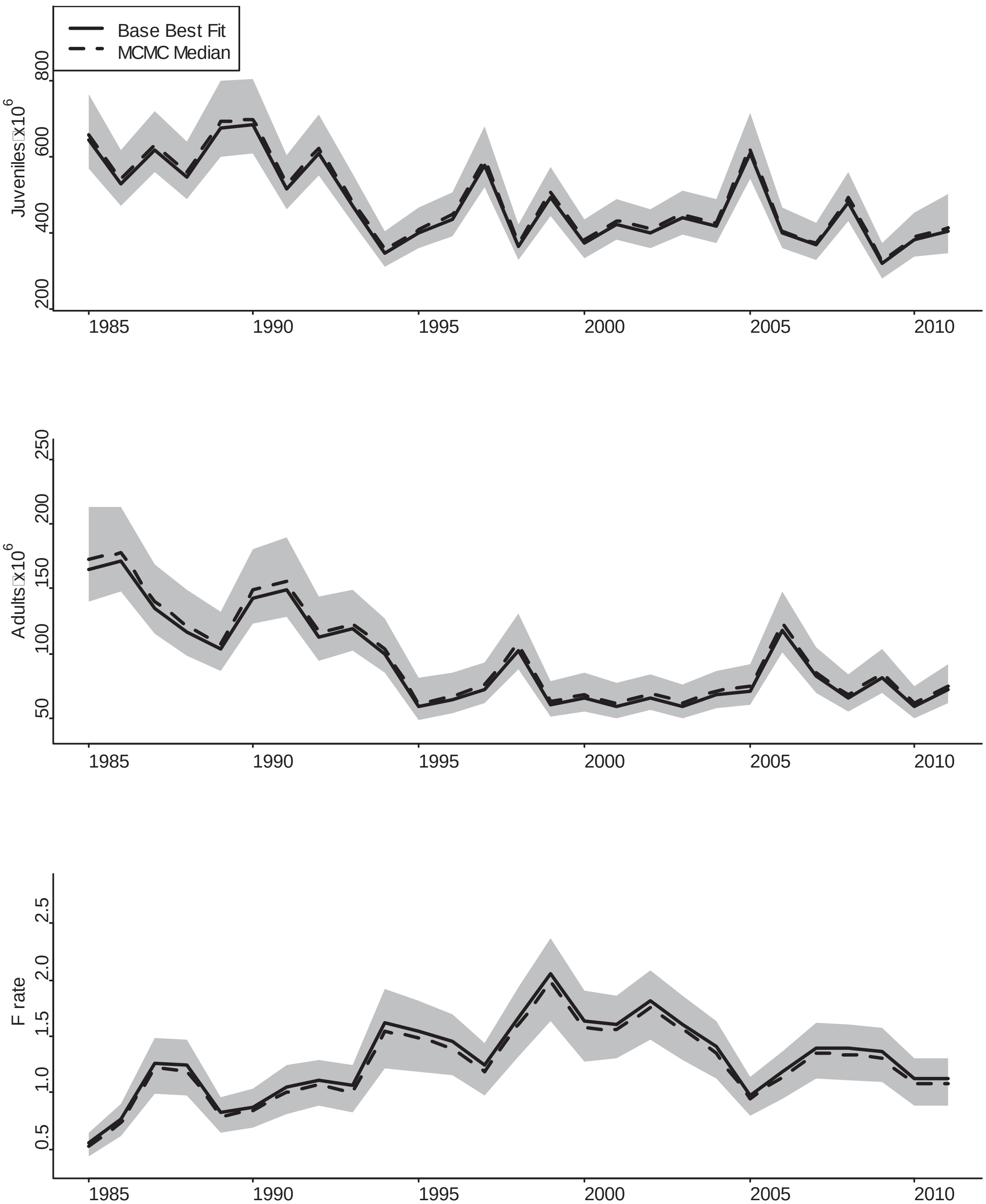


Figure 7.7 Western GOM stock predicted abundance of juveniles and adults at the start of the year (top two panes) and the F rate (bottom pane) from the base model run best fit (solid line) and the MCMC median estimate (dotted line). 95% confidence intervals are presented from the MCMC runs.

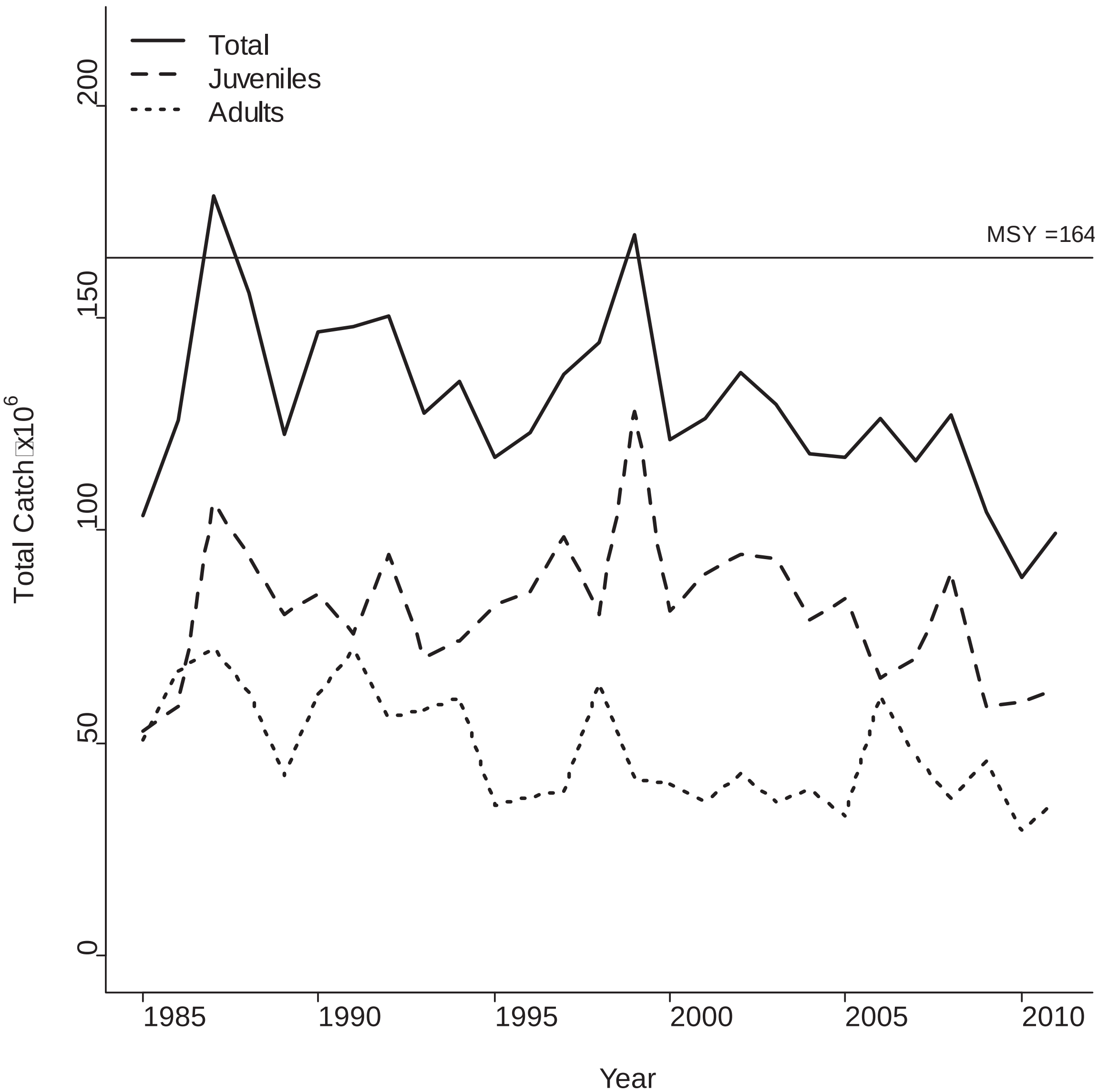
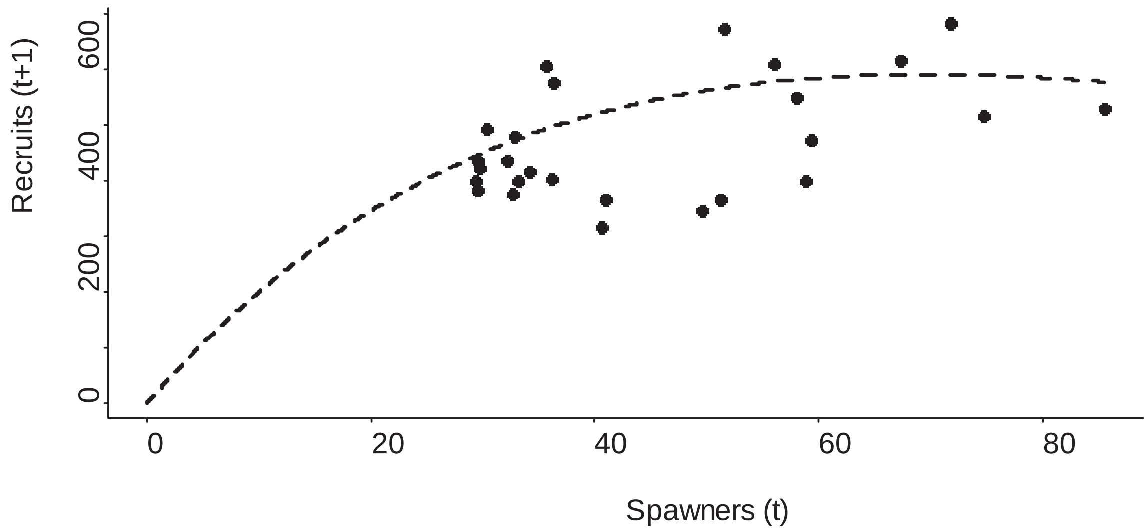


Figure 7.8 Western GOM stock total landings per stage relative to MSY.



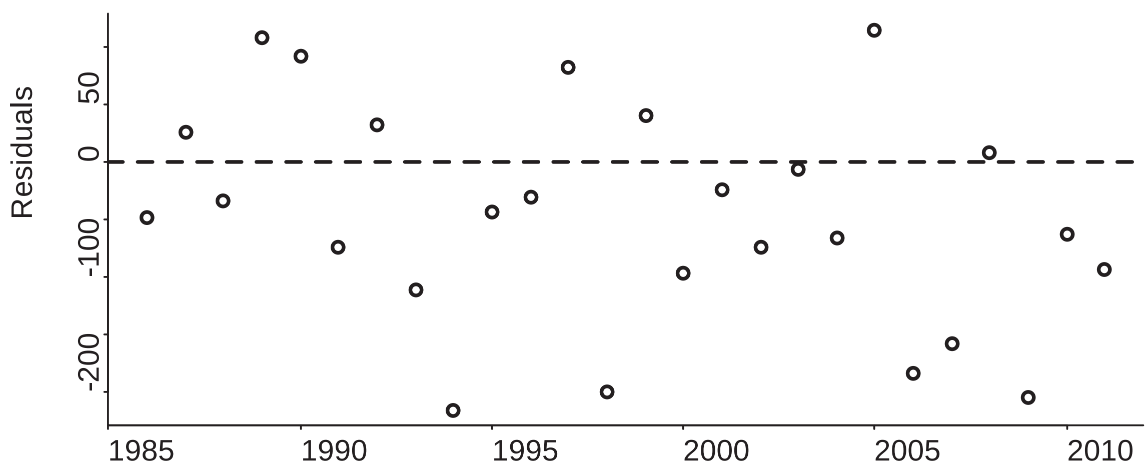


Figure 7.9 Western GOM stock estimated stock recruitment relationship (top pane) with year-specific residuals (bottom pane).

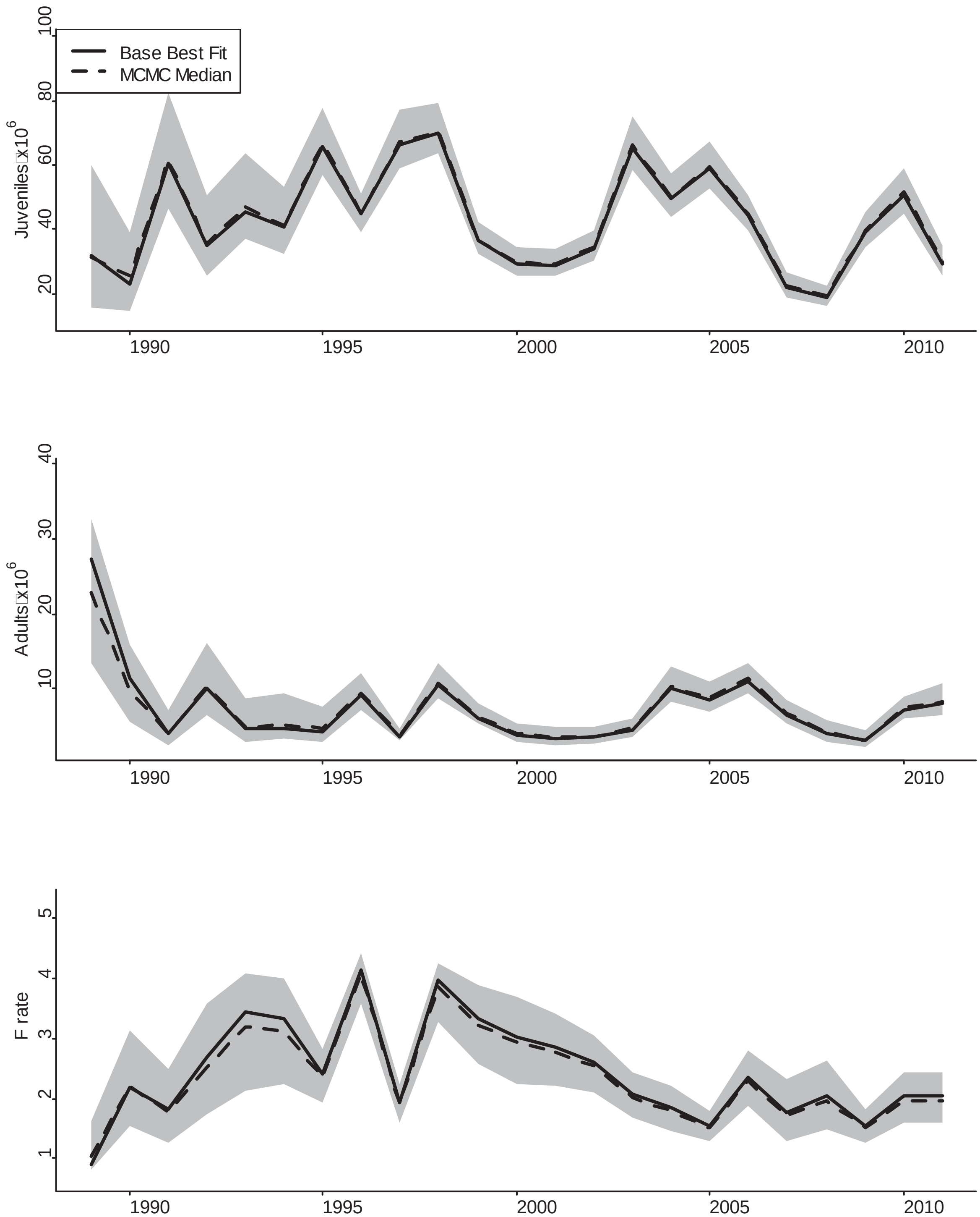


Figure 7.10 Eastern GOM stock predicted abundance of juveniles and adults at the start of the year (top two panes) and the F rate (bottom pane) from the base model run best fit (solid line) and the MCMC median estimate (dotted line). 95% confidence intervals are presented from the MCMC runs.

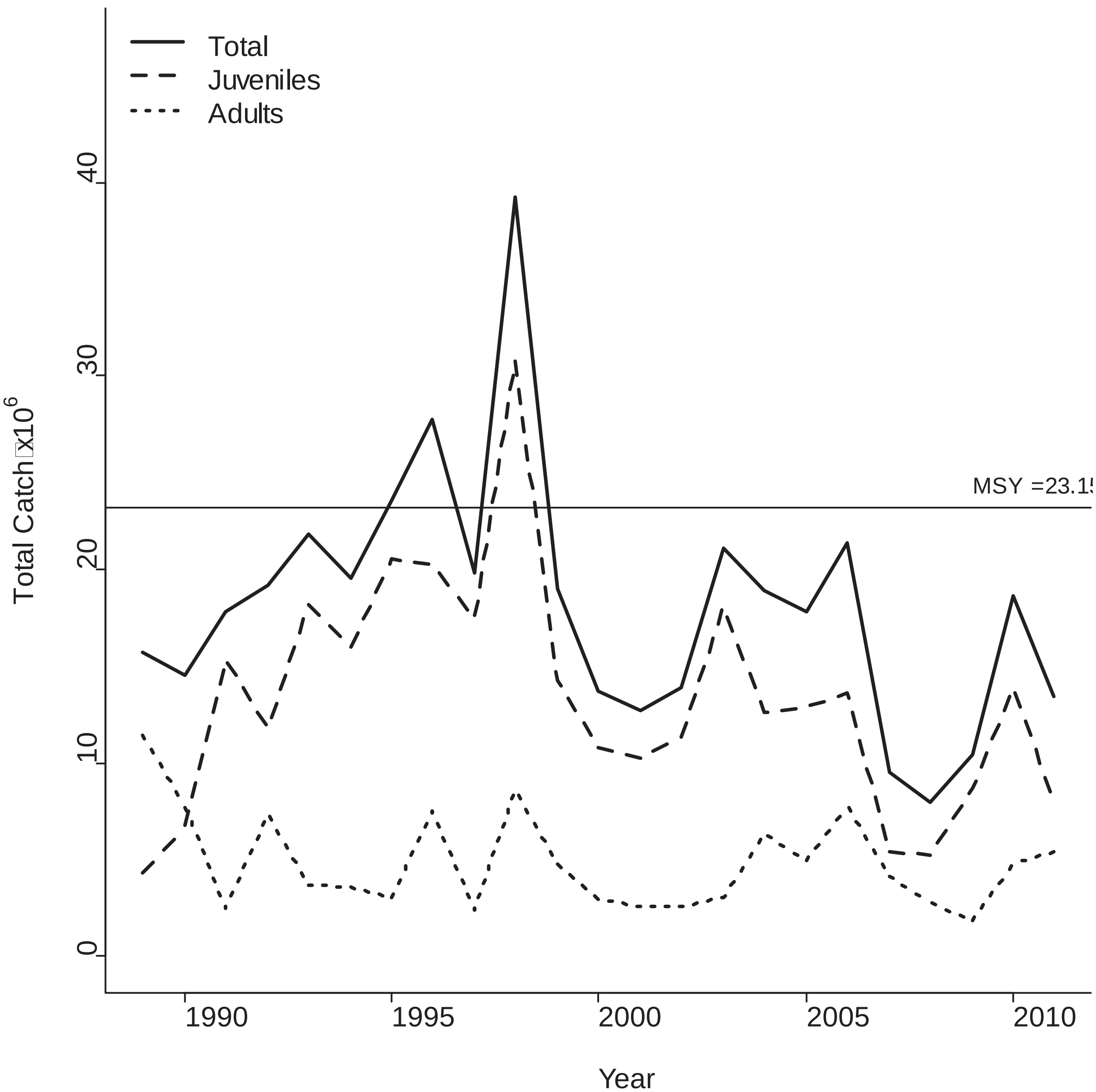


Figure 7.11 Eastern GOM stock total landings per stage relative to MSY.

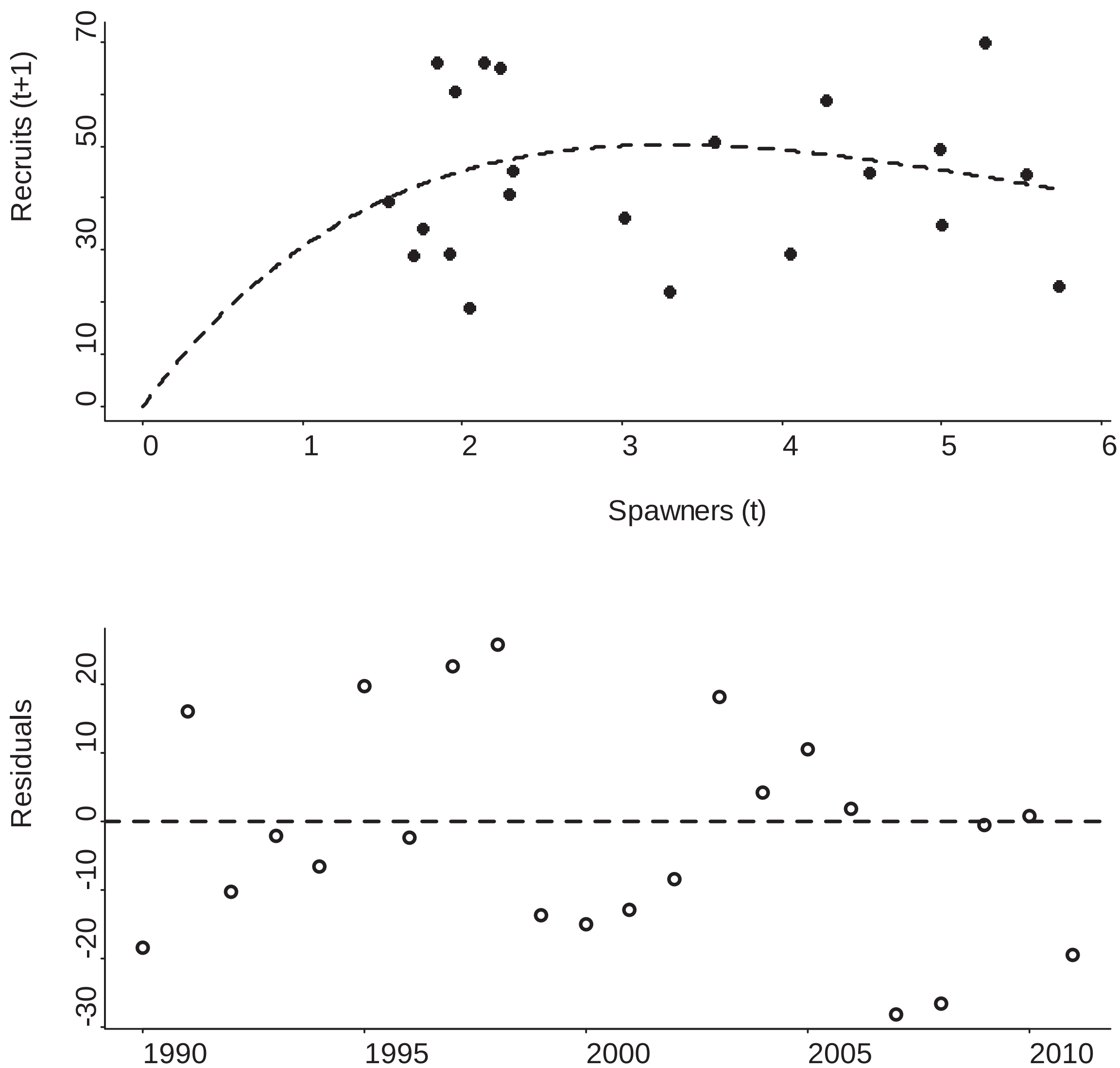


Figure 7.12 Eastern GOM stock estimated stock recruitment relationship (top pane) with year-specific residuals (bottom pane).

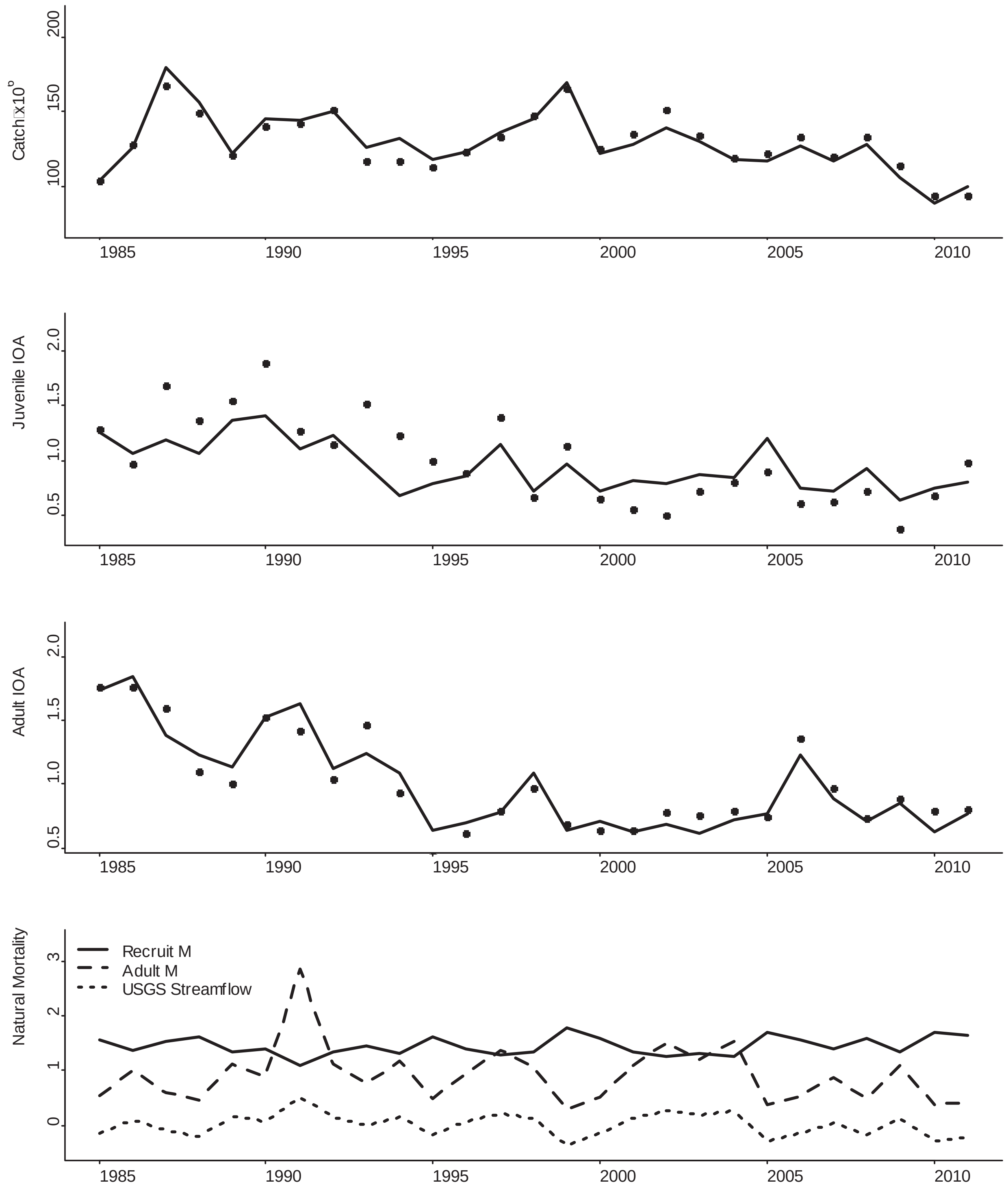


Figure 7.13 Western GOM stock model fit and natural mortality (M) time series from sensitivity run bc-11-west (streamflow influence on year-specific estimates of mortality).

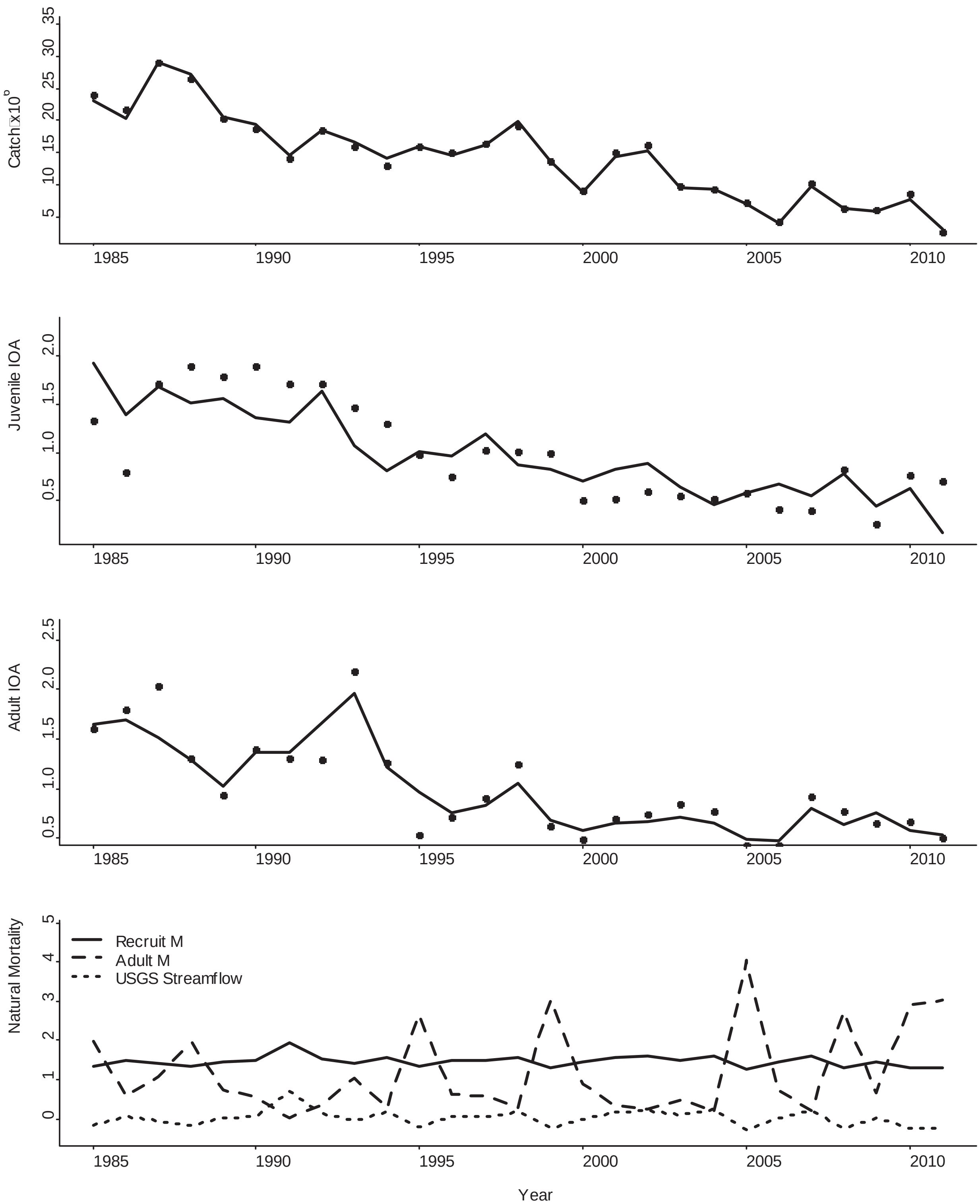


Figure 7.14 Western subregion stock (Texas) model fit and natural mortality (M) time series from sensitivity run bc-22-west (streamflow influence on year-specific estimates of mortality).

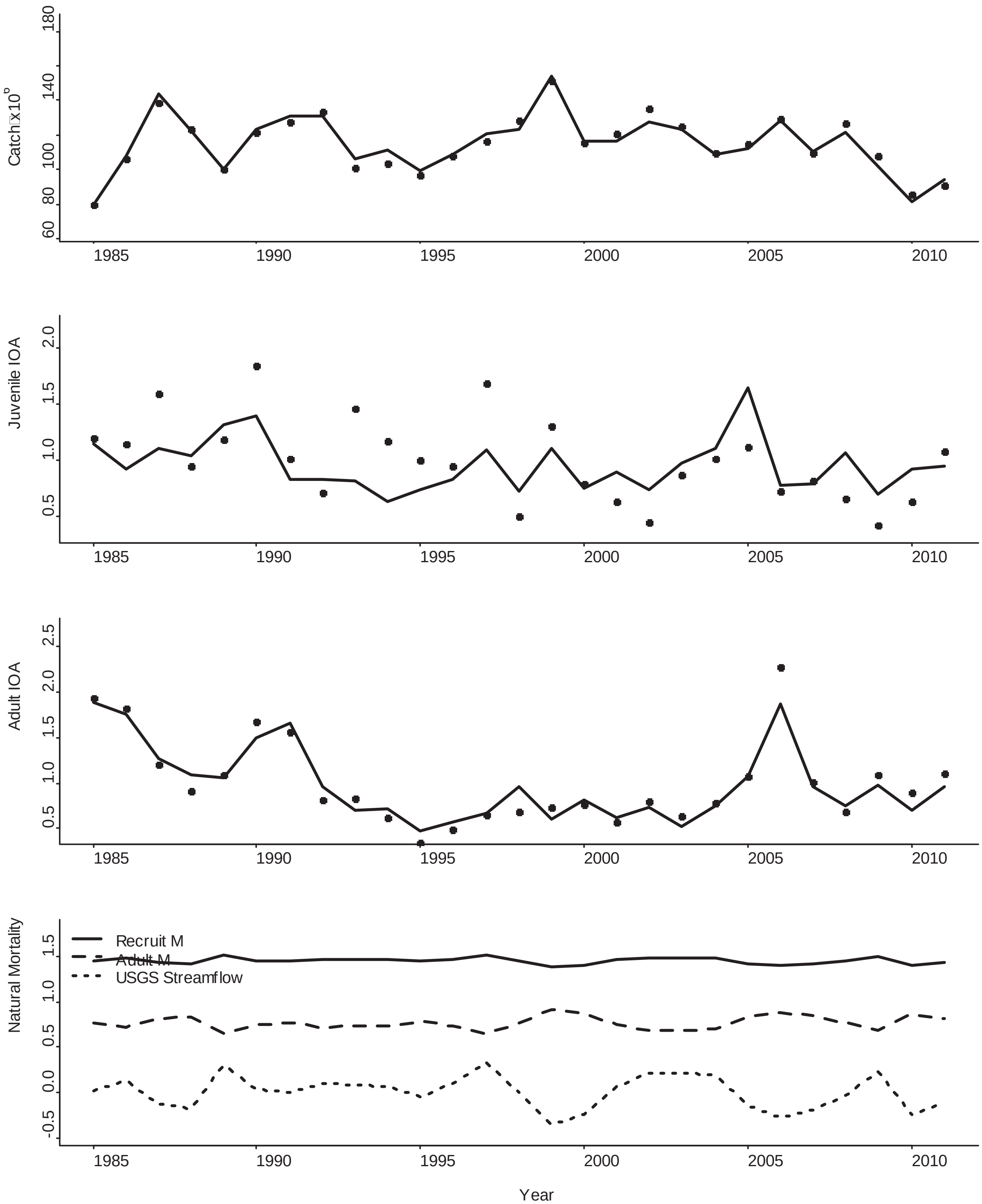


Figure 7.15 Central subregion stock (Louisiana, Mississippi, Alabama) model fit and natural mortality (M) time series from sensitivity run bc-23-west (streamflow influence on year-specific estimates of mortality).

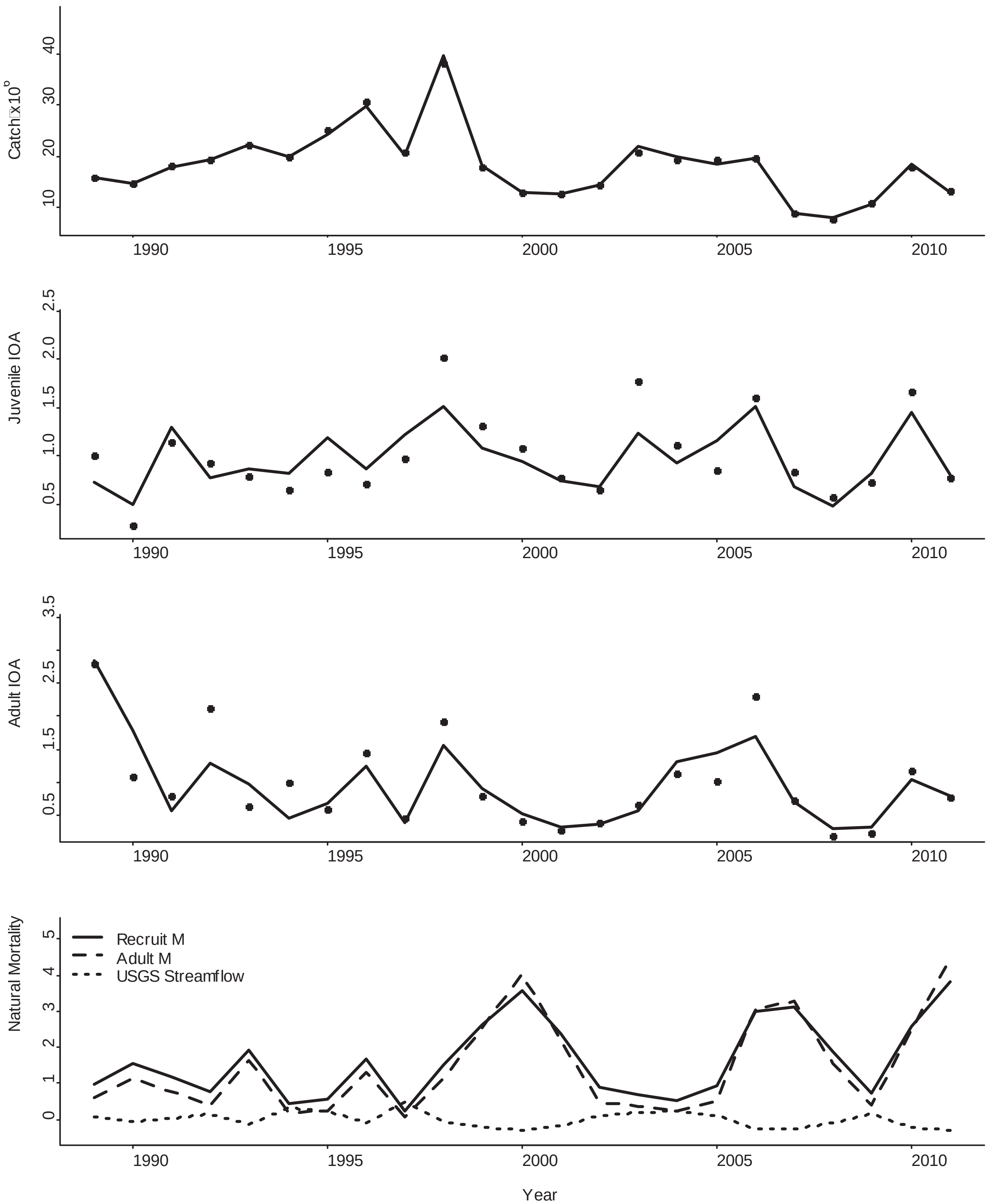


Figure 7.16 Eastern GOM stock model fit and natural mortality (M) time series from sensitivity run bc-11-east (streamflow influence on year-specific estimates of mortality).

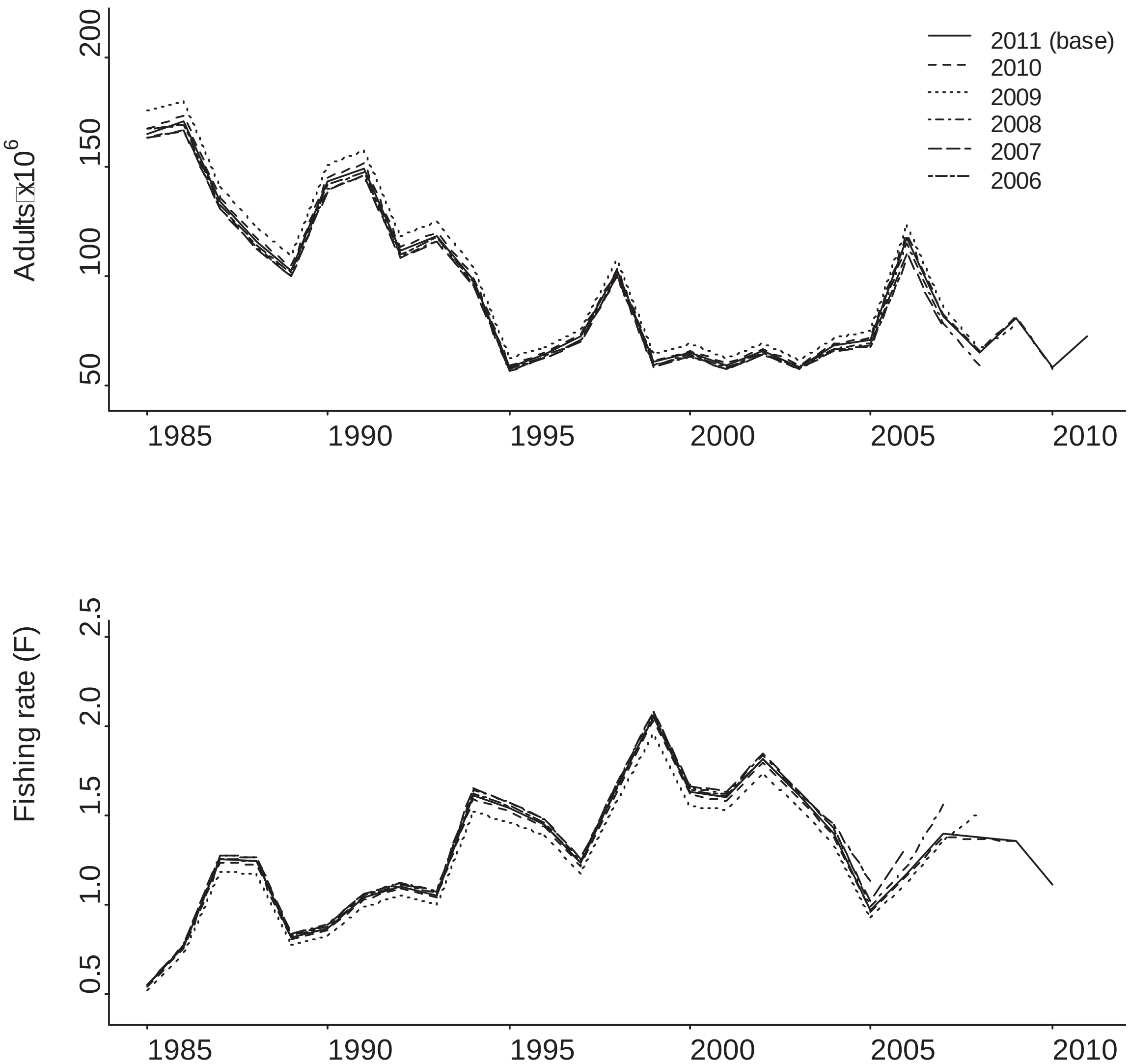


Figure 7.17 Western GOM stock retrospective bias for adult abundances (top pane) and fishing rate (bottom pane). *Note:* the terminal year F was not estimated with this model.

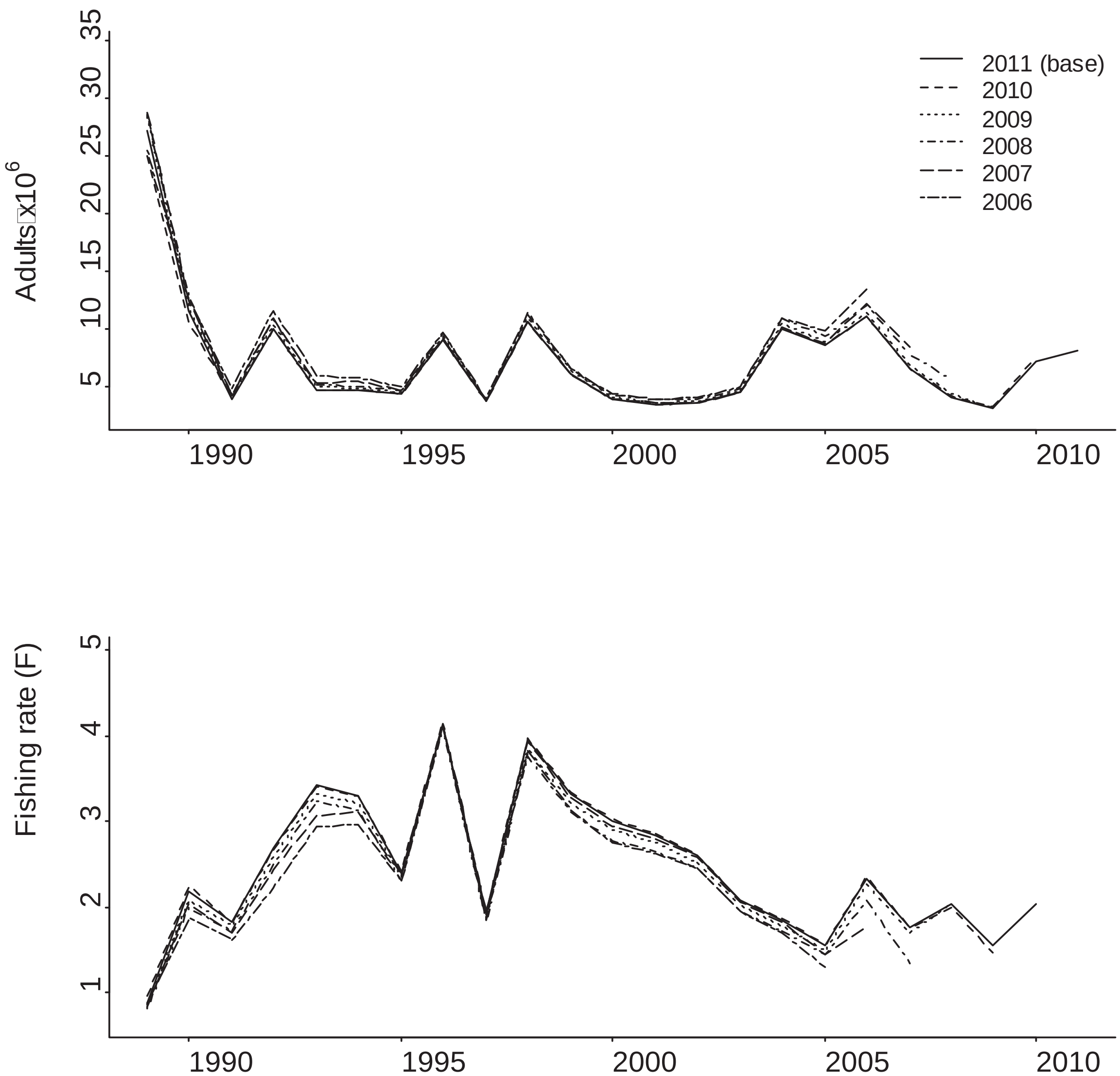


Figure 7.18 Eastern GOM stock retrospective bias for adult abundances (top pane) and fishing rate (bottom pane). *Note*: the terminal year F was not estimated with this model.

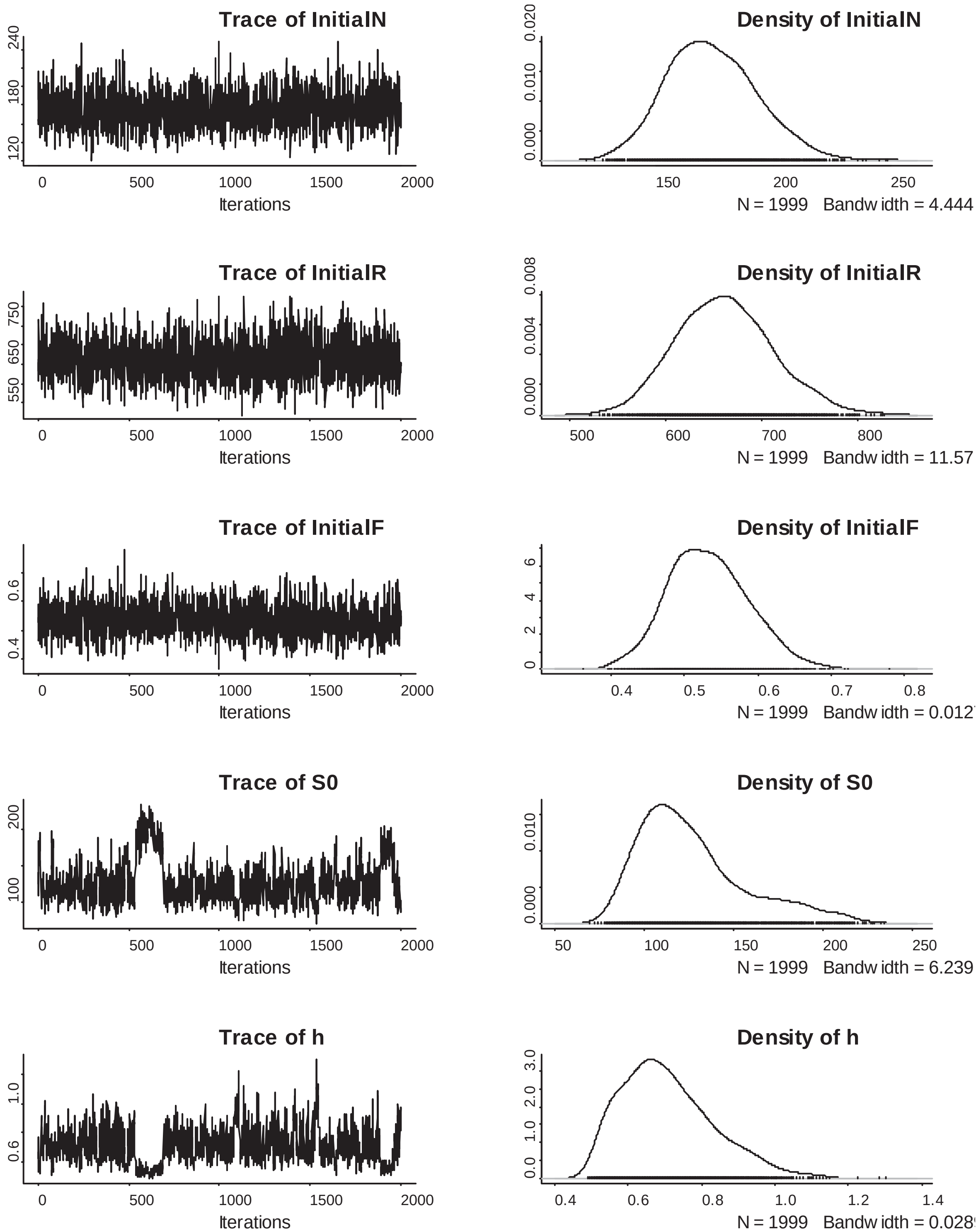


Figure 7.19 Western GOM stock MCMC posterior distributions of the base model parameter estimates (not including year-specific F deviations and recruitment deviations). Note the presence of two relatively stable regions in the trace plots for the stock-recruitment parameters, which were evident in multiple independent MCMC chains. Initial F is equivalent to the initial q estimate since effort is set to 1.0 for all years.

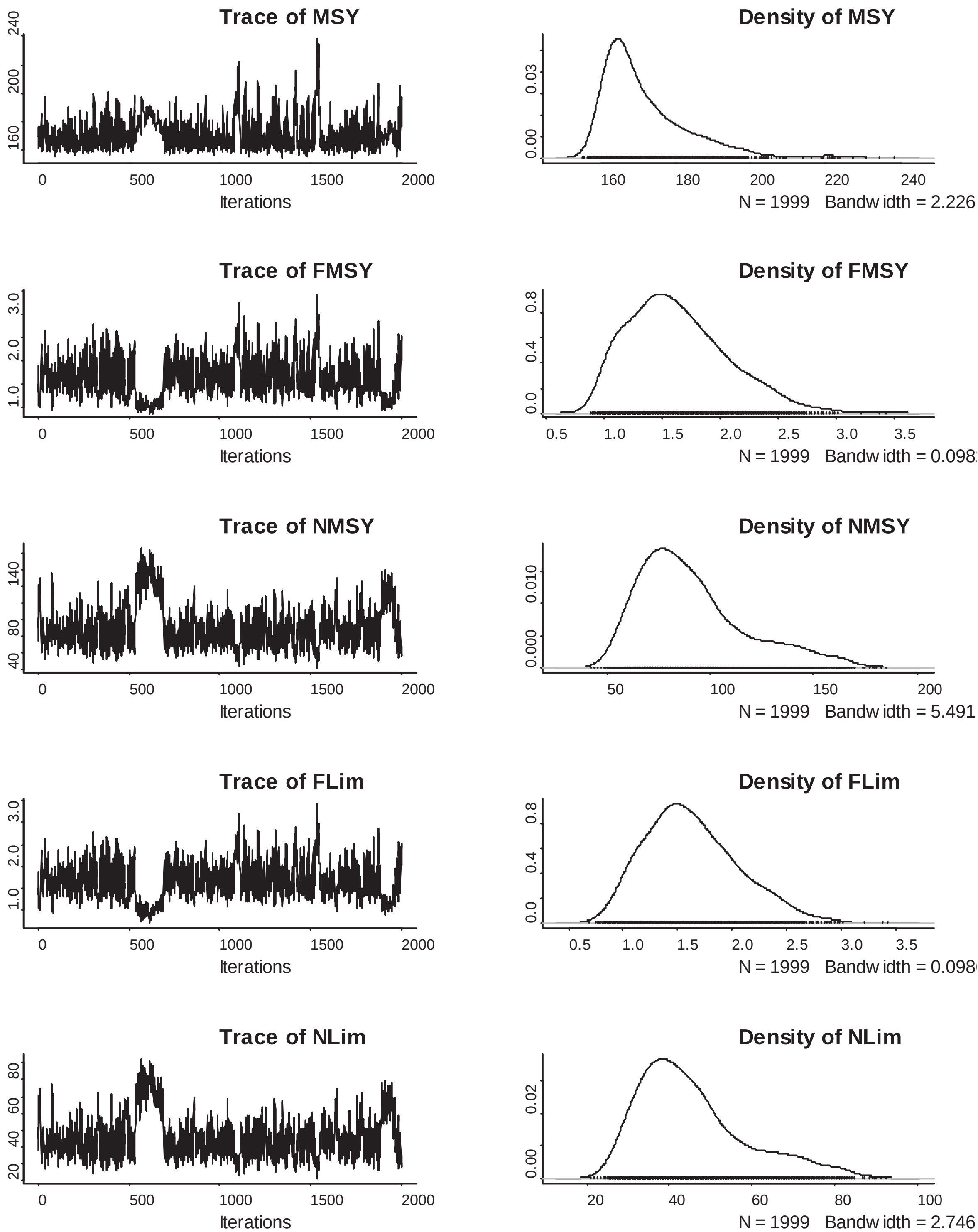


Figure 7.20 Western GOM stock MCMC posterior distributions of the reference points. Note the presence of two relatively stable regions in the trace plots corresponding to the regions in the stock-recruitment parameters.

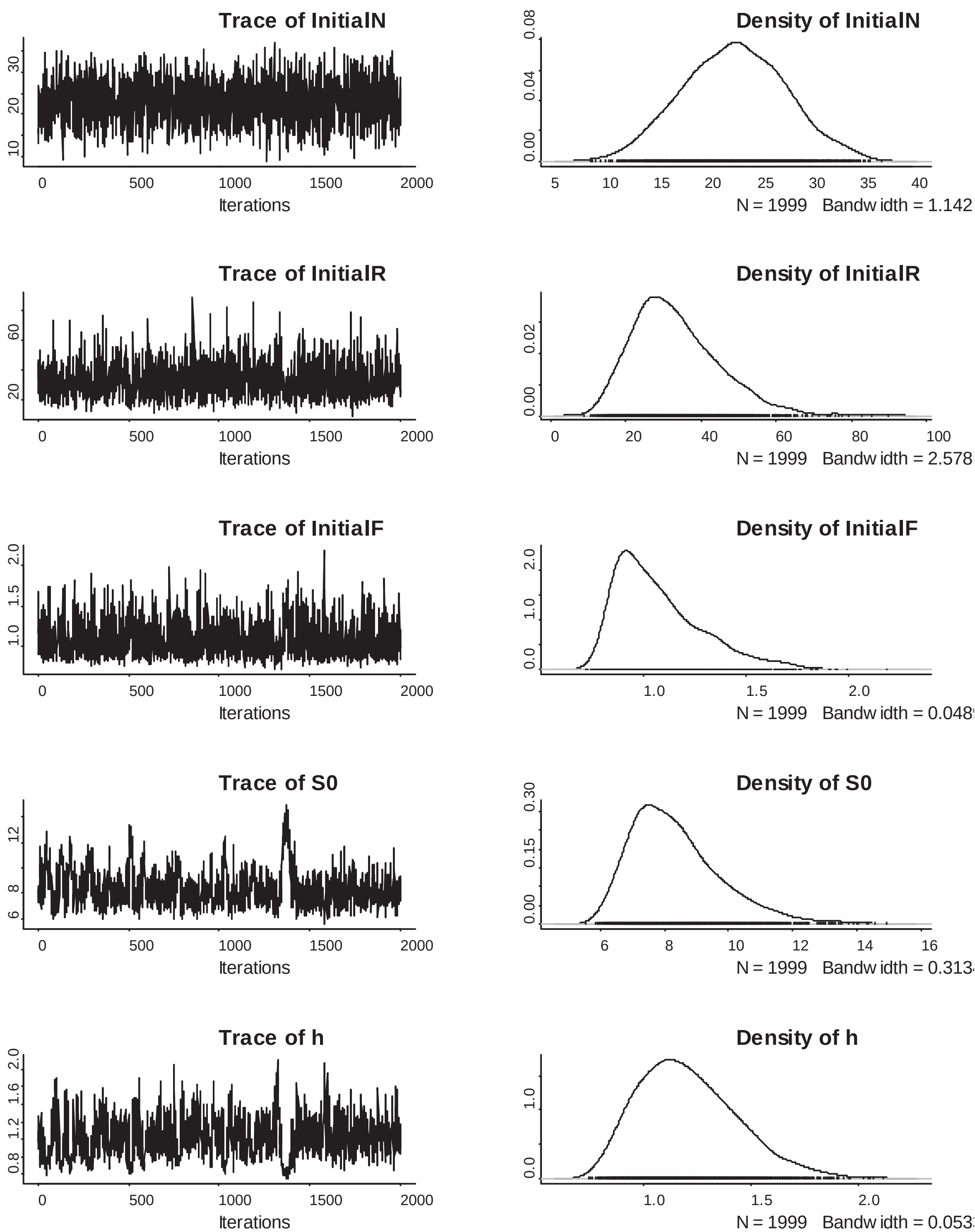


Figure 7.21 Eastern GOM stock MCMC posterior distributions of the base model parameter estimates (not including year-specific F deviations and recruitment deviations). Initial F is equivalent to the initial q estimate since effort is set to 1.0 for all years.

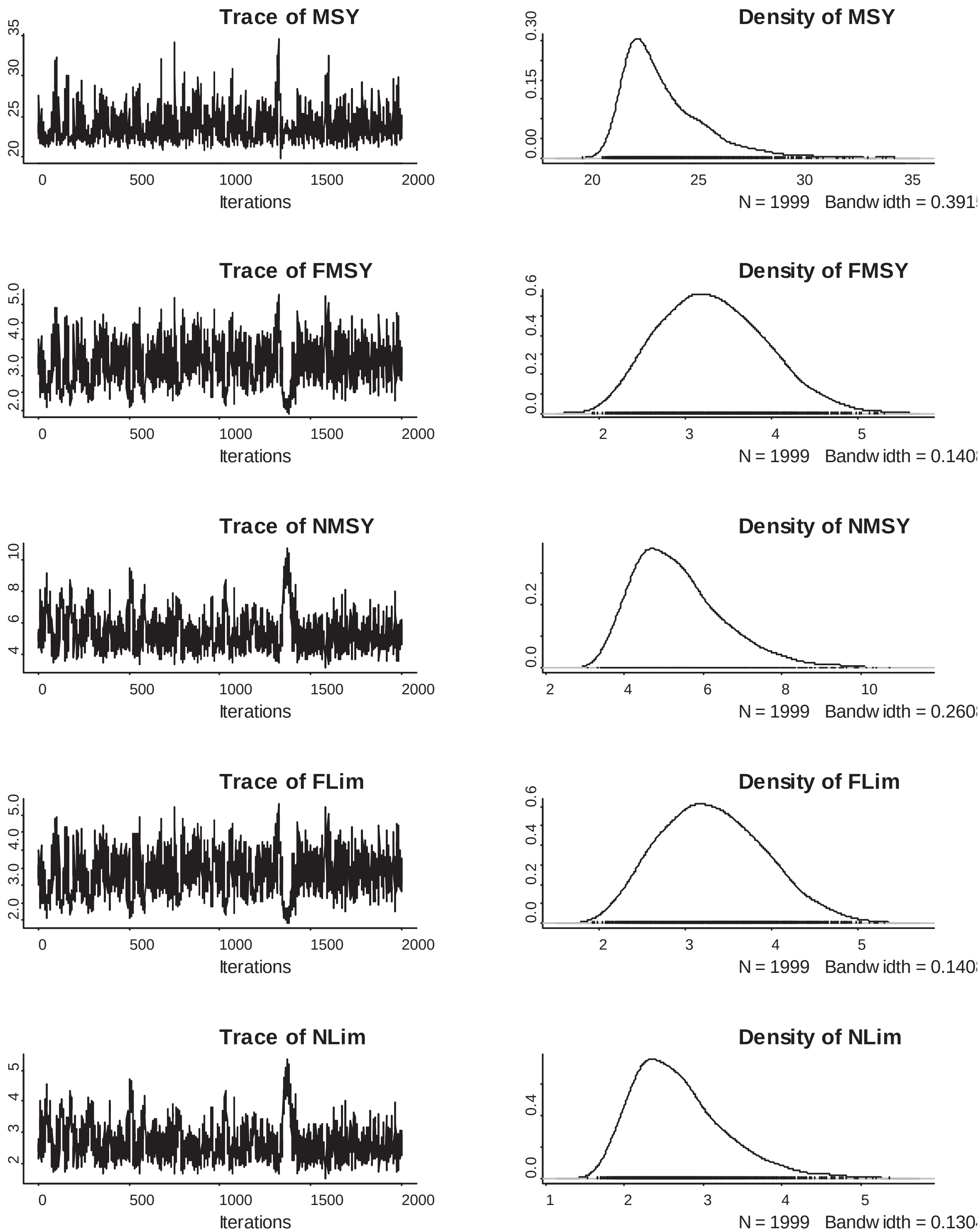


Figure 7.22 Eastern GOM stock MCMC posterior distributions of the reference points for the Eastern GOM stock.

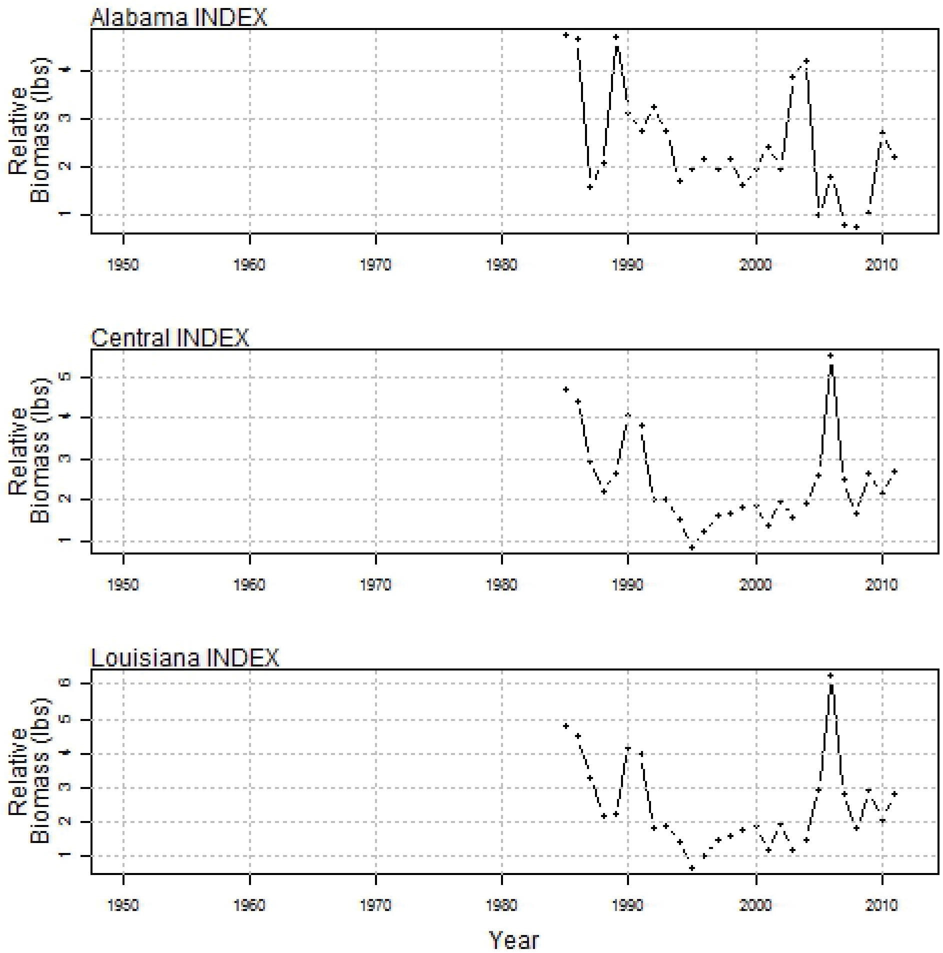


Figure 7.23 Western GOM stock individual state and combined indices used in the ASPIC base model and sensitivity analysis. The "Central index" is the composite index derived from Louisiana, Mississippi, and Alabama only.

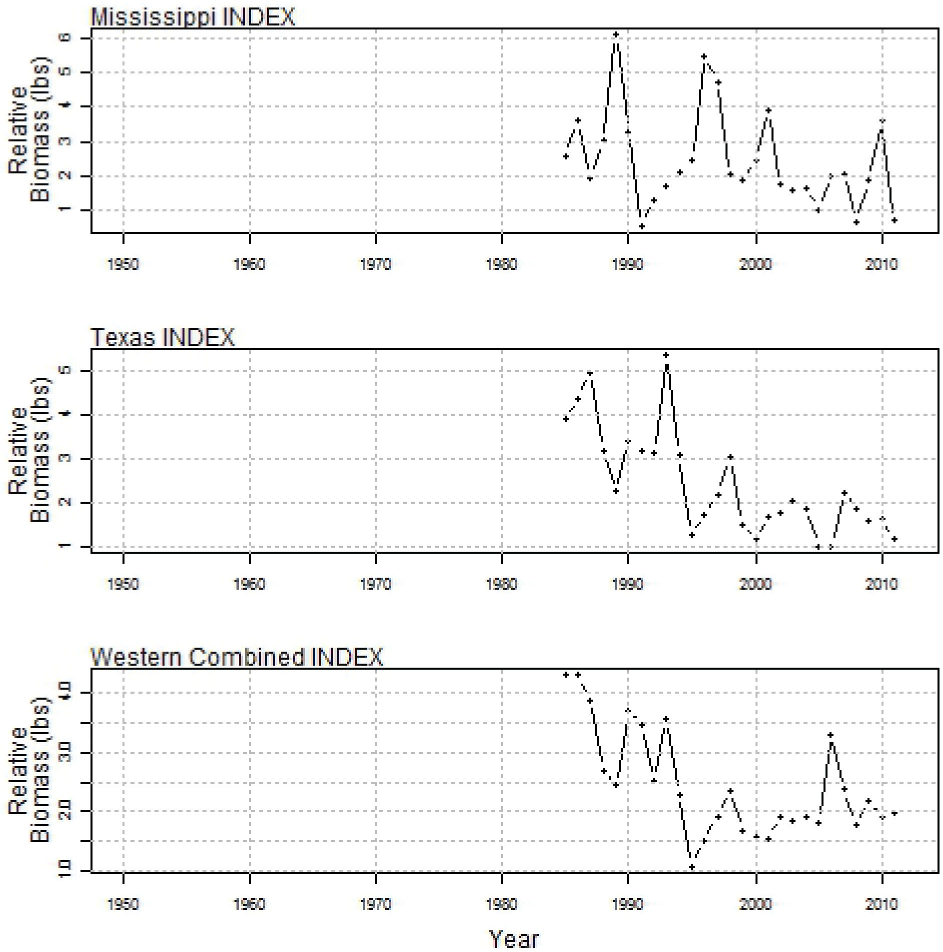


Figure 7.24 Western GOM stock individual state and combined indices used in the ASPIC base model and sensitivity analysis. The "Western Combined" index is the composite index derived from Texas, Louisiana, Mississippi, and Alabama.

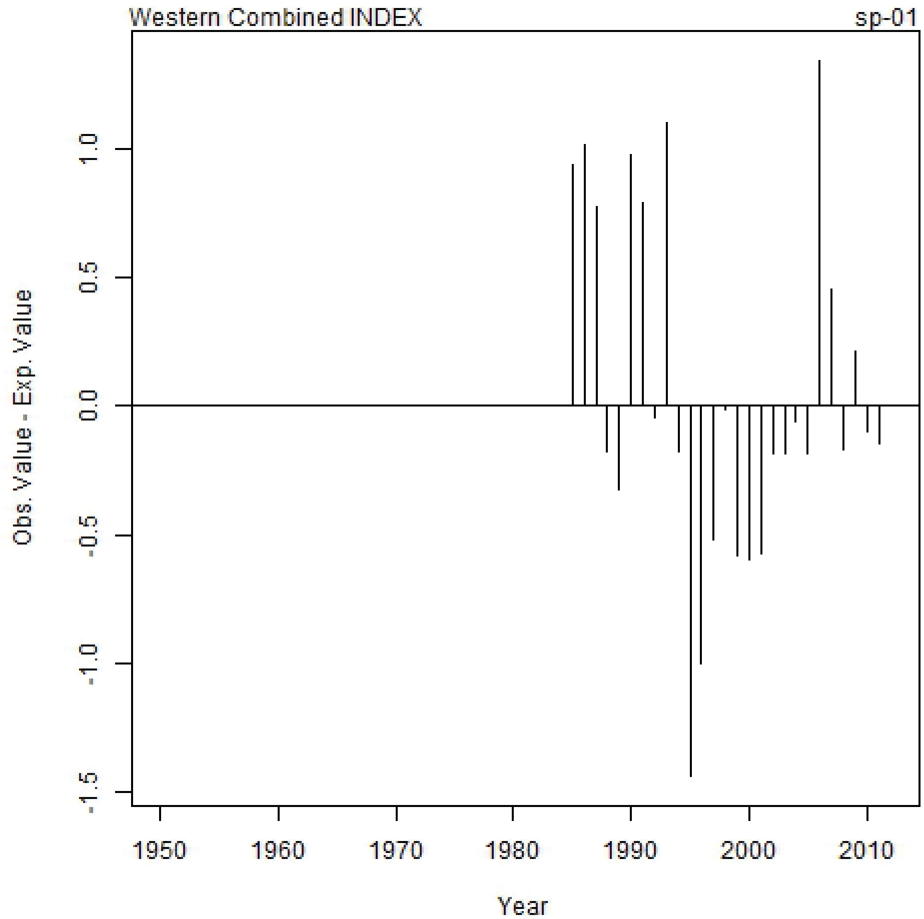


Figure 7.25 Residual pattern of adult abundance (observed – model estimated) for the Western GOM stock ASPIC base model run (sp-01-west).

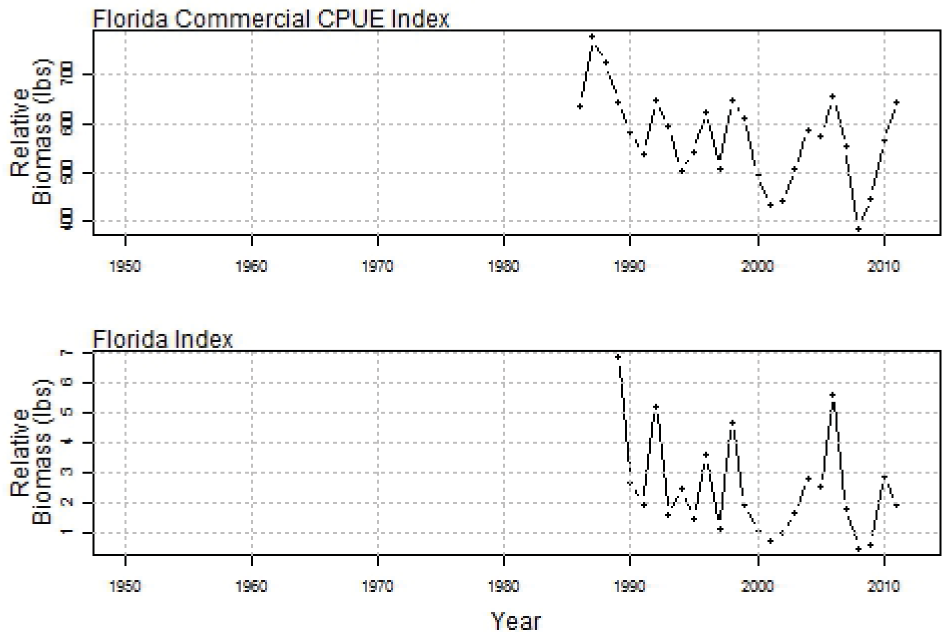


Figure 7.26 Eastern GOM stock indices used in the ASPIC base model and sensitivity analysis. The "Florida index" is used in the base run and both the Florida index and Florida Commercial CPUE indices are used in a sensitivity run.

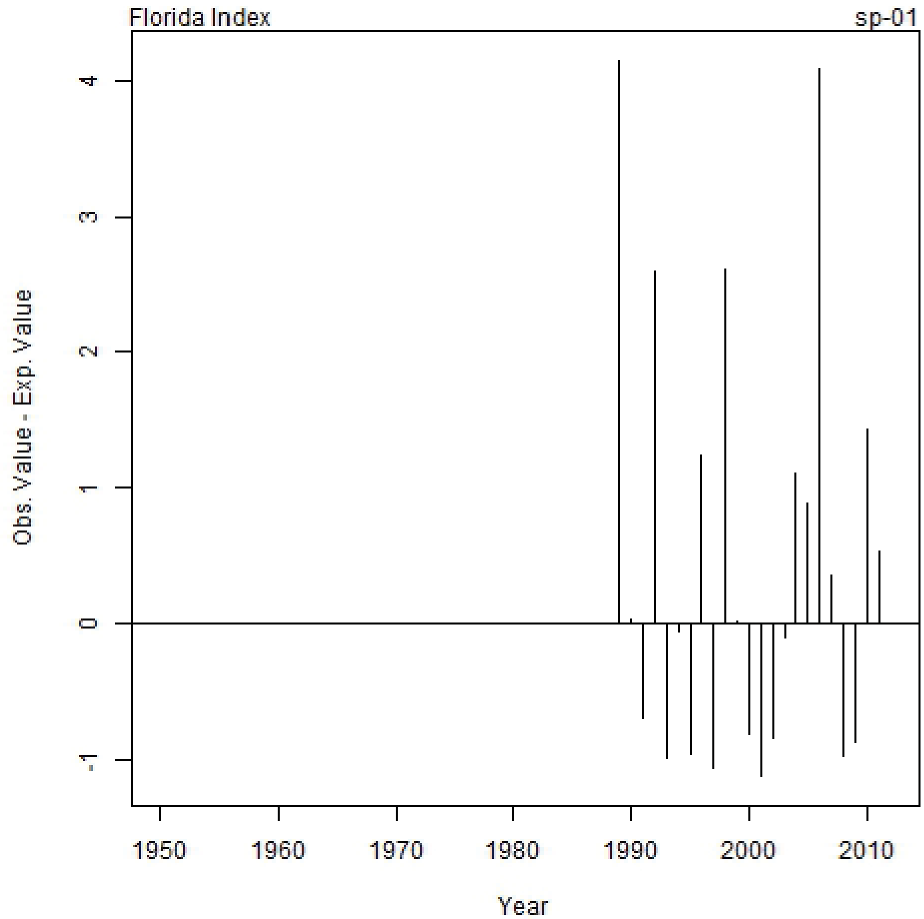


Figure 7.27 Residual pattern of adult abundance (observed – model estimated) for the Eastern GOM stock base model run (sp-01-east).

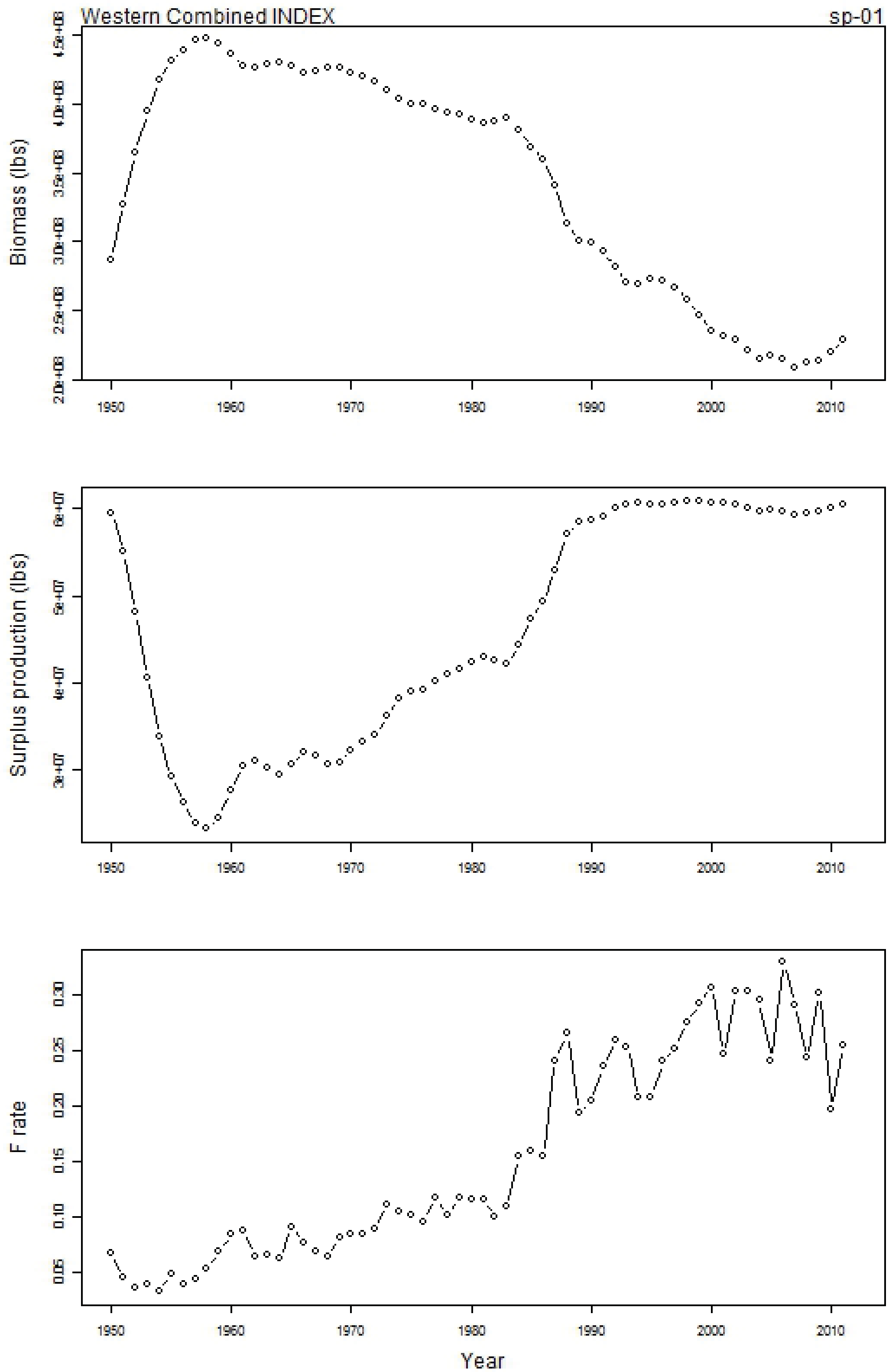


Figure 7.28 Western GOM stock predicted mean annual biomass, surplus production, and fishing mortality from the ASPIC base model run.

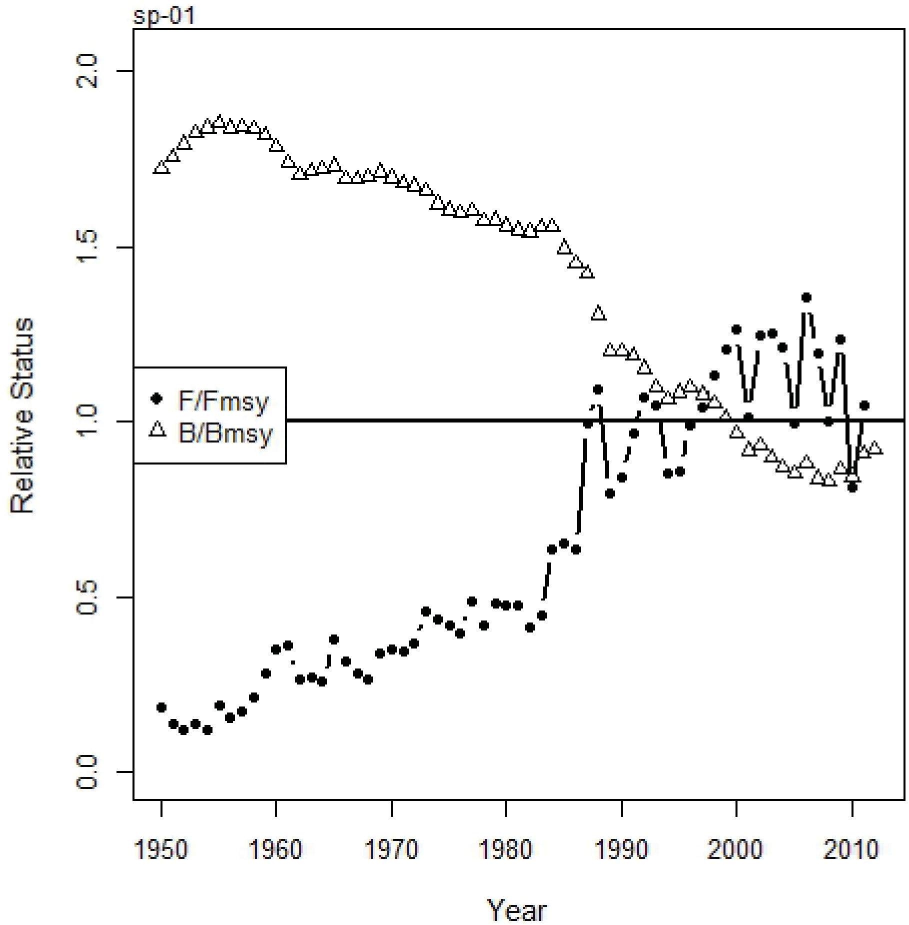


Figure 7.29 Western GOM stock fishery and stock status for the ASPIC base model run.

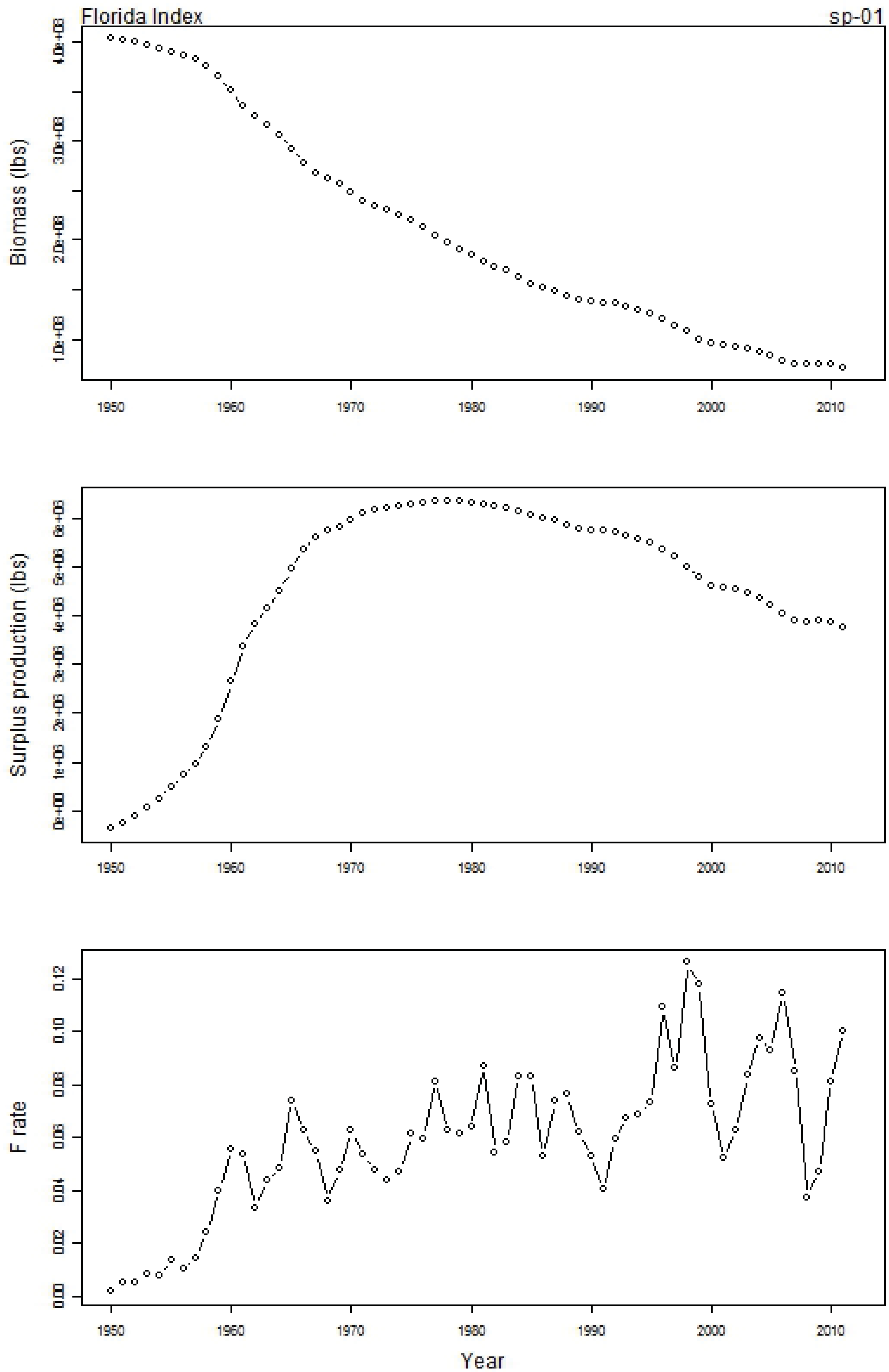


Figure 7.30 Eastern GOM stock predicted mean annual biomass, surplus production, and fishing mortality from the ASPIC base model run.

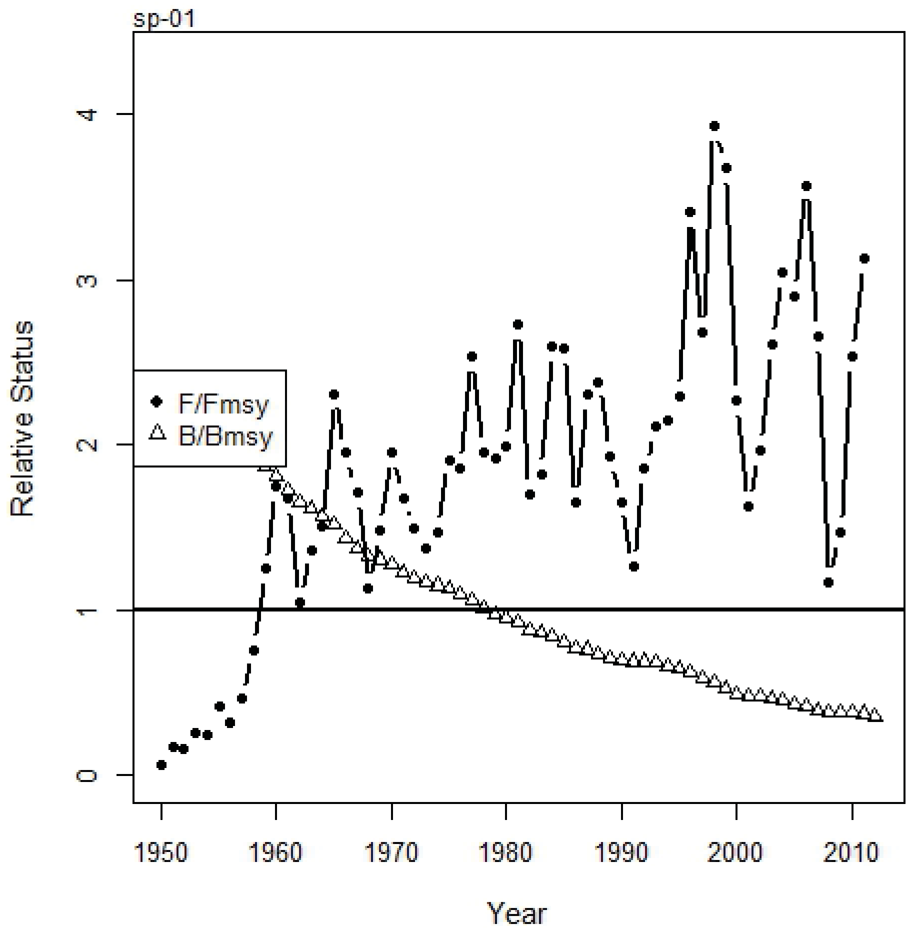


Figure 7.31 Eastern GOM stock fishery and stock status for the ASPIC base model run.

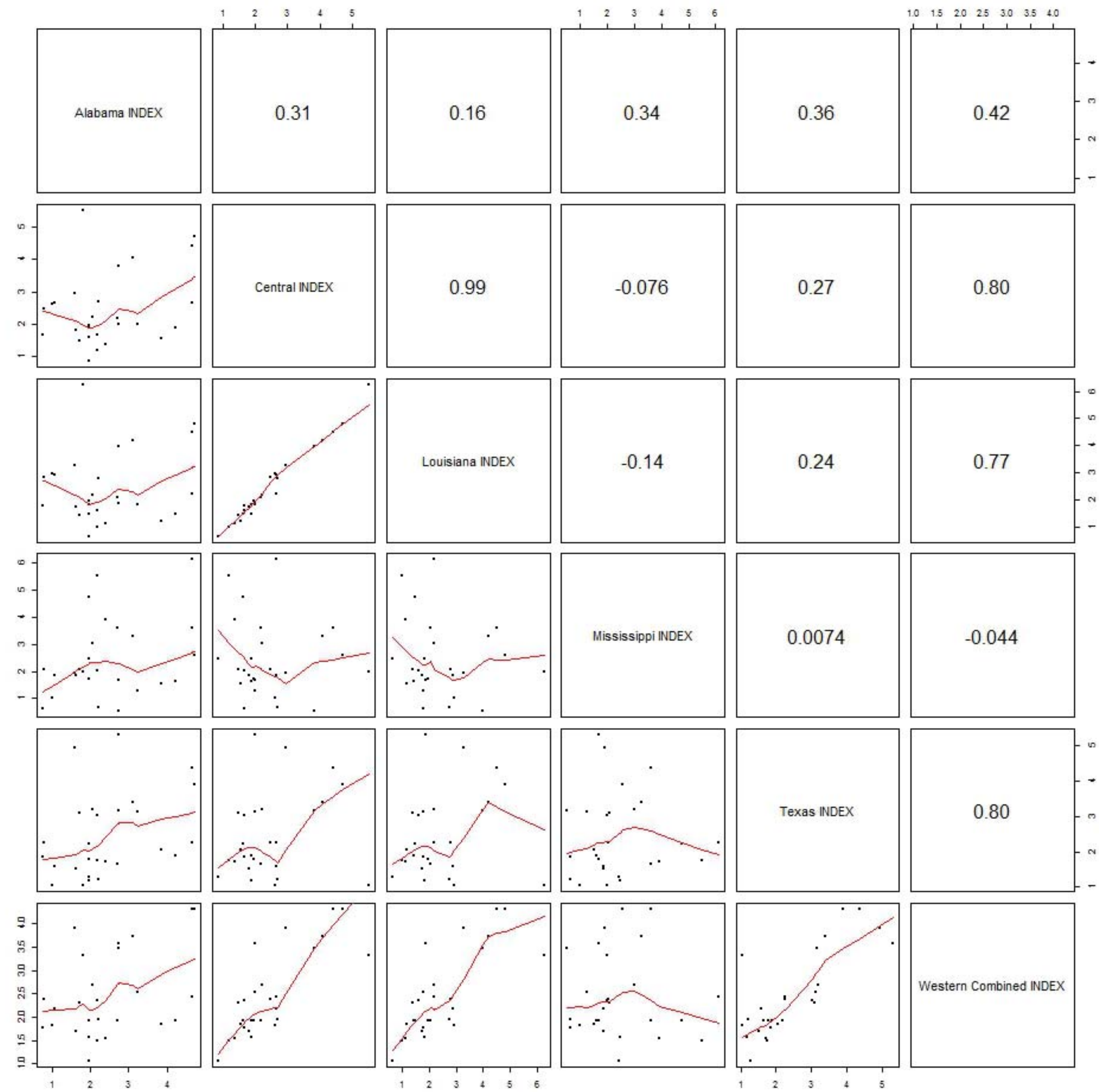


Figure 7.32 Pairwise comparison of abundance indices used in base (western combined index) and sensitivity model runs. The red line in the lower panel is the loess smoothed estimate and is included for enhanced visualization. The top right panel displays the value of the Pearson product-moment correlation.

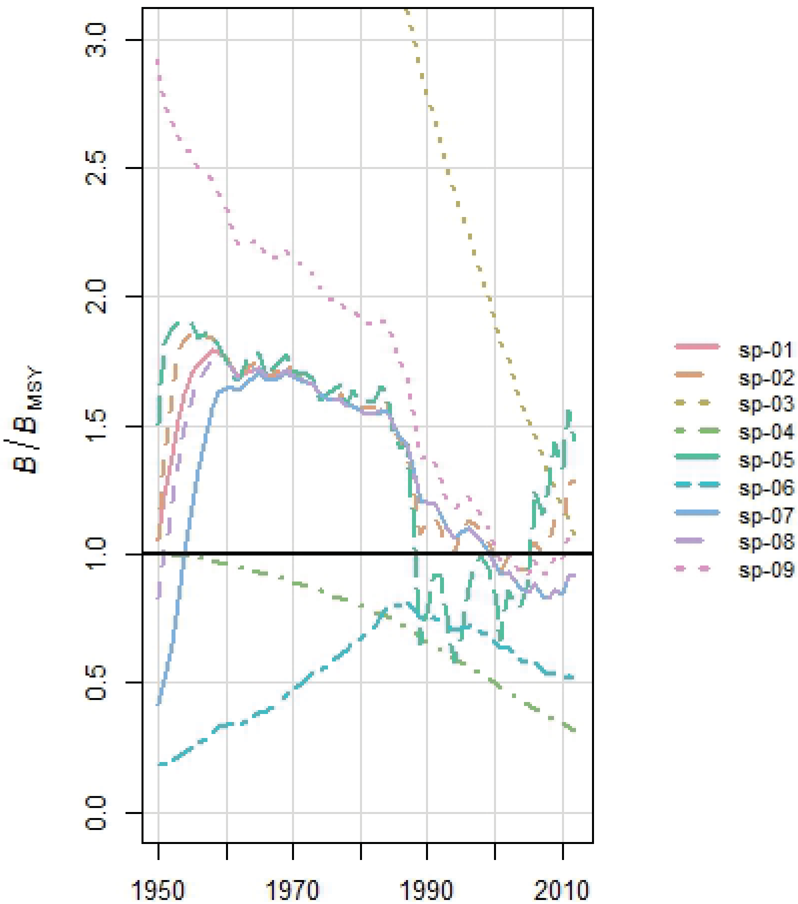


Figure 7.33 Relative abundance (B/B_{MSY}) for the Western GOM stock from each sensitivity model run (sp-01-west to sp-09-west).

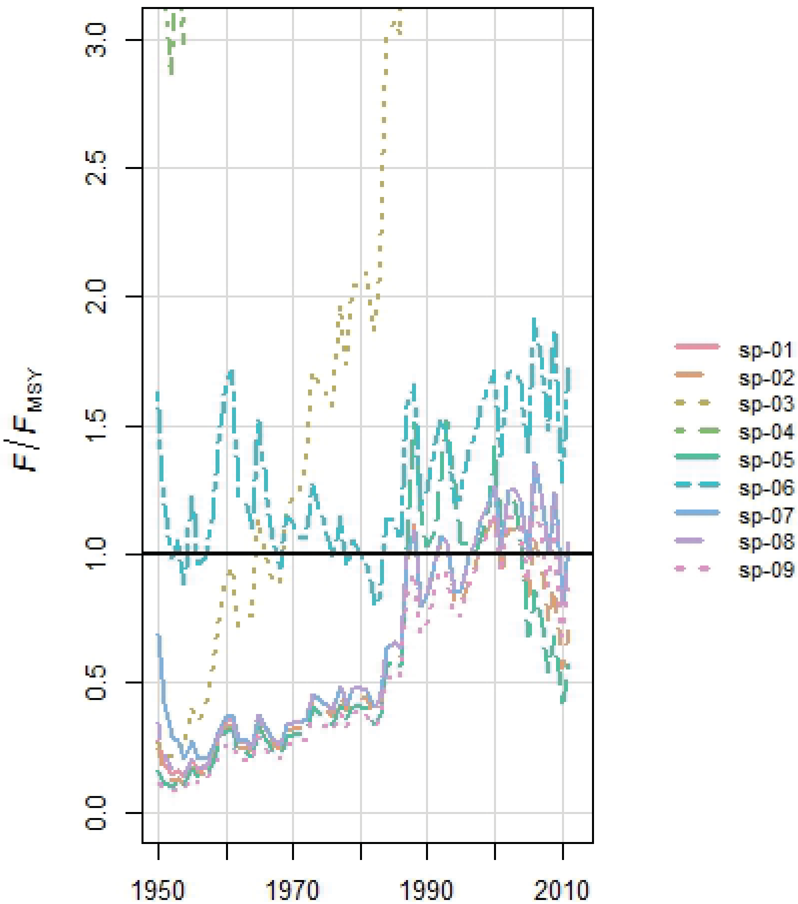


Figure 7.34 Relative fishing mortality rate (F/F_{MSY}) for the Western GOM stock from each sensitivity model run (sp-01-west to sp-09-west).

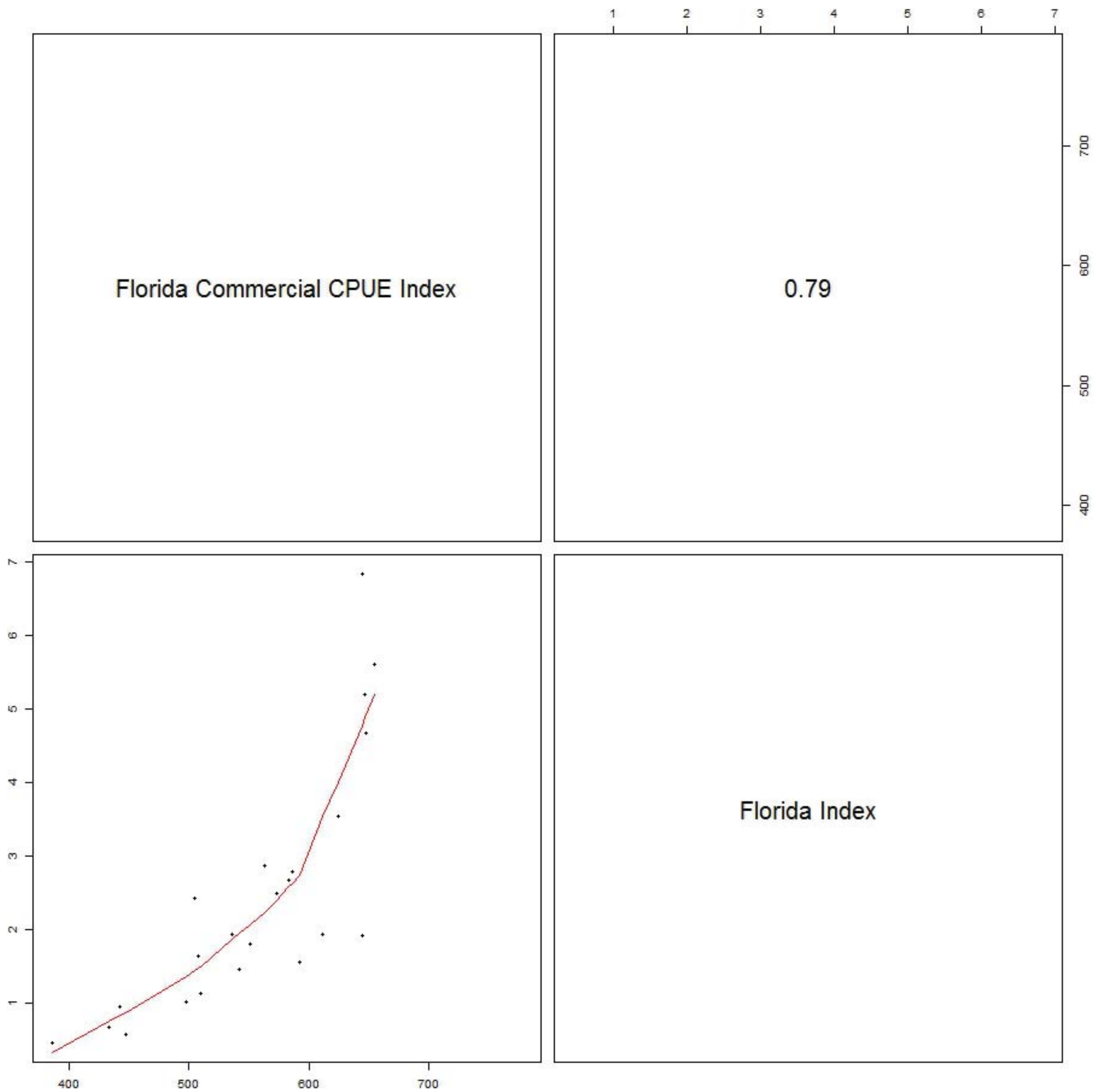


Figure 7.35 Pairwise comparison of abundance indices used in Eastern GOM stock sensitivity model runs. The red line in the lower panel is the loess smoothed estimate and is included for enhanced visualization. The top right panel displays the value of the Pearson product-moment correlation.

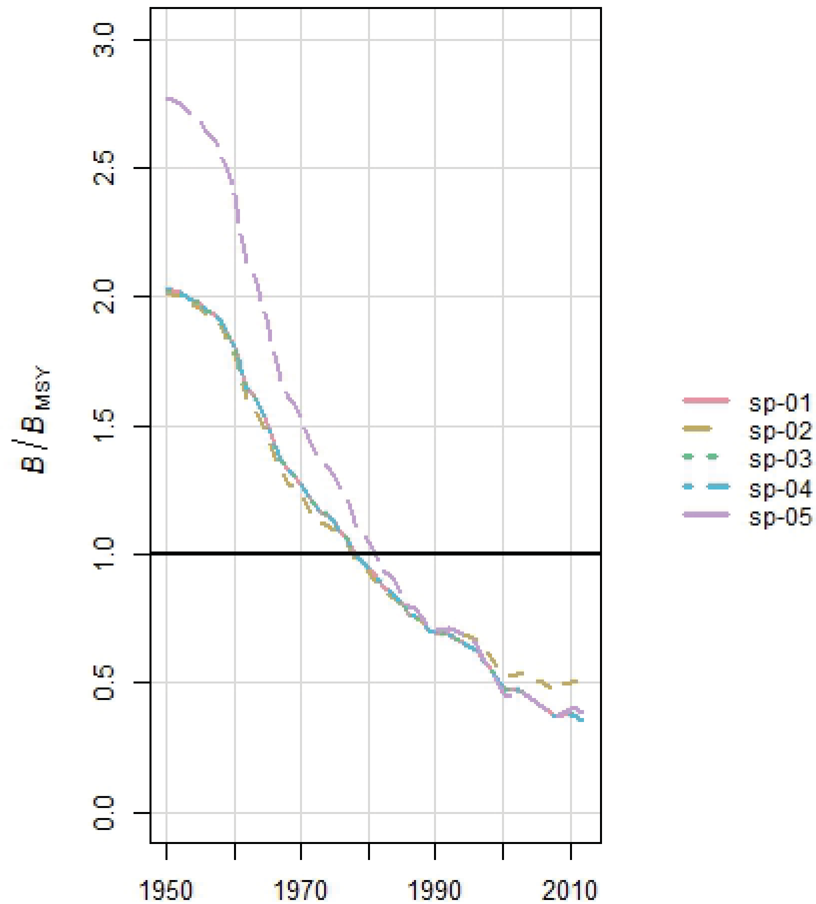


Figure 7.36 Relative abundance (B/B_{MSY}) for the Eastern GOM stock from each sensitivity model run (sp-01-east to sp-05-east).

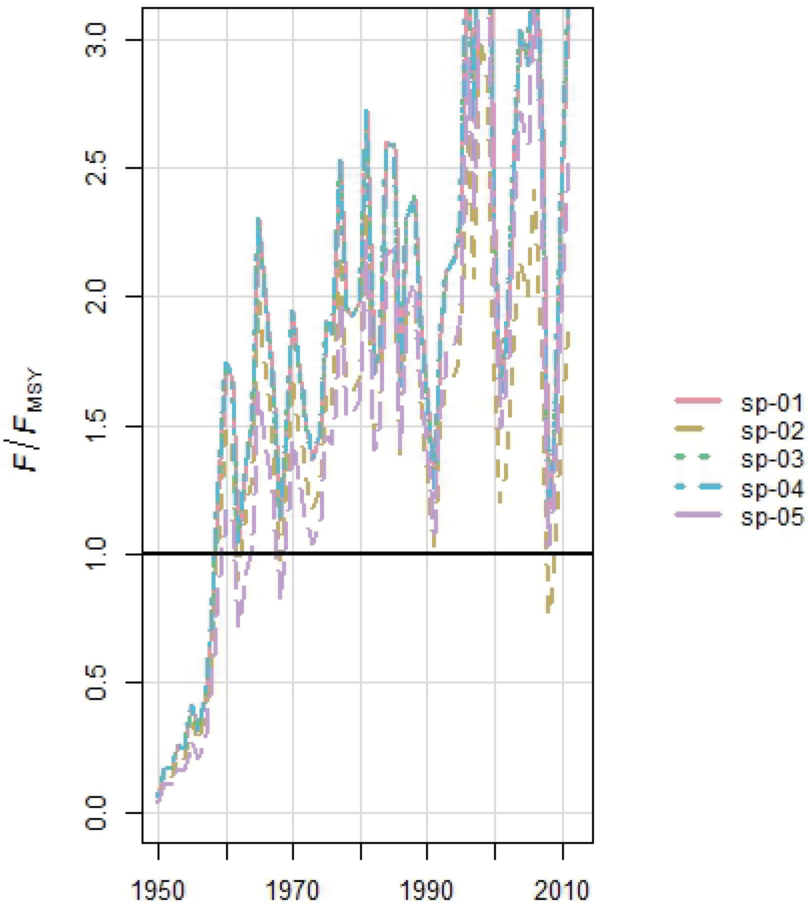
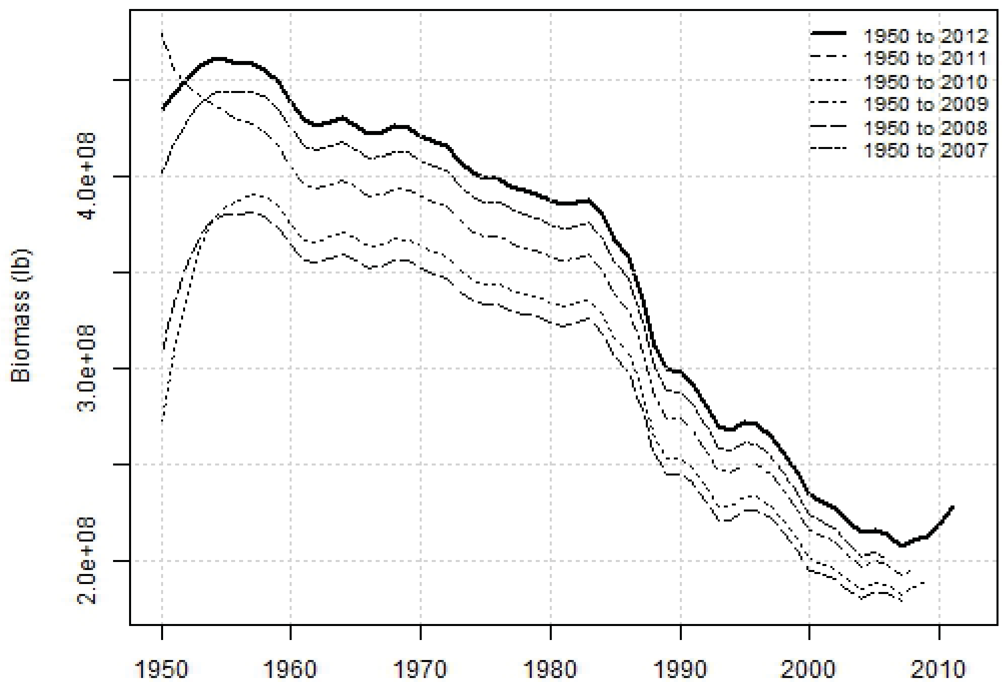


Figure 7.37 Relative fishing mortality rate (F/F_{MSY}) for the Eastern GOM stock from each sensitivity model run (sp-01-east to sp-05-east).



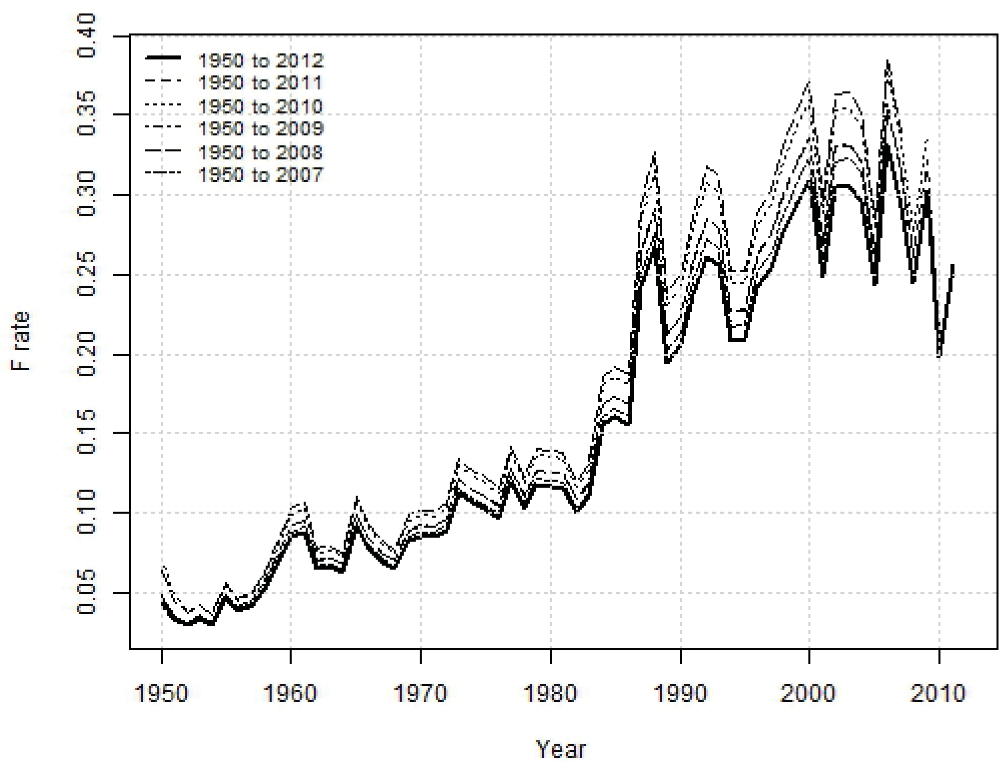
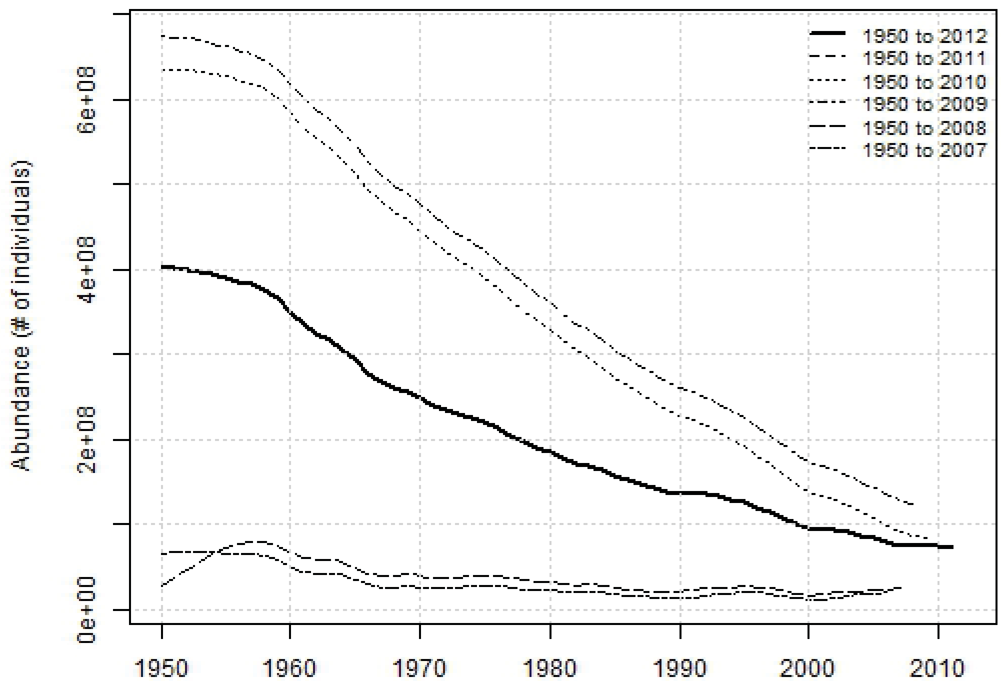


Figure 7.38 Western GOM stock retrospective bias for adult biomass (top pane) and fishing rate (bottom pane). *Note:* the terminal year F was not estimated with this model.



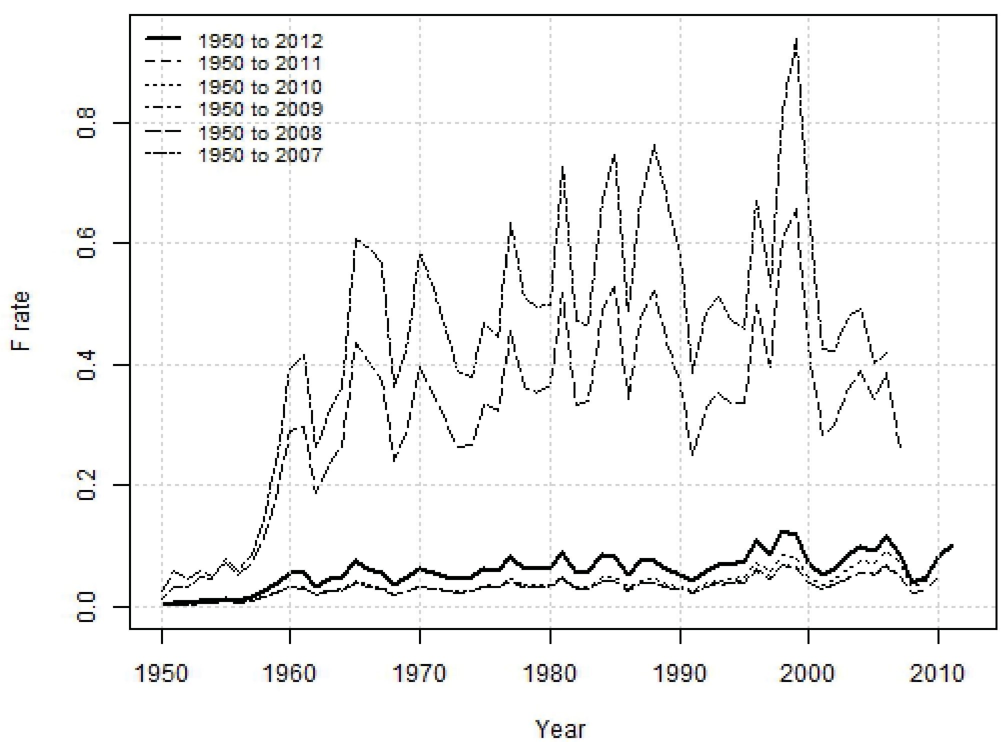


Figure 7.39 Eastern GOM stock retrospective bias for adult biomass (top pane) and fishing rate (bottom pane). *Note:* the terminal year F was not estimated with this model.

8.0 Stock Status

8.1 Current Overfishing, Overfished/Depleted Definitions

For this report, we present proposed limits (F_{Limit}, N_{Limit}) of fishing using the default limit control rule outlined in the Technical Guidance on the Use of Precautionary Approaches to Implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act (Restrepo et al. 1998) to establish limits to fishing mortality as a function of adult abundance. Control rules are needed to define the management actions needed if the limit is approached or exceeded, as well as the management goals when the stock status is not overfished or undergoing overfishing. The rule is based on three parameters: F_{MSY}, N_{MSY}, and c. The parameter c describes the rate of responsiveness that management desires to recover a stock fished to levels below N_{MSY}. The rule is as follows:

$$\mathrm{F(N)} = \mathrm{F_{MSY}N/cN_{MSY}} \text{ for all } \mathrm{N} \leq \mathrm{cN_{MSY}} \quad [17]$$

$$\mathrm{F(N)} = \mathrm{F_{MSY}} \text{ for all } \mathrm{N} > c\mathrm{N_{MSY}}$$

where c is defined as the larger of ($1 - M$ or 0.5). Thus, regardless of stock size, the fishing mortality rate cannot be allowed to increase over F_{MSY} and must be reduced below F_{MSY} to zero as abundance declines below cN_{MSY} to zero.

It is important to note that the proposed control rule alone cannot prevent unsustainable harvest from occurring. Pre-specified decision rules need to be in place detailing the management response to be taken when the limits are approached or exceeded. Once these rules are specified and agreed upon, an updated fishery management plan is needed specifically detailing them.

8.2 Stock Status Determination

It is important to note that because blue crabs are potentially influenced by the environment, as suggested for the Eastern GOM stock and western subregion (Texas) within the Western GOM stock, calculation of overfished and overfishing status in particular years can be biased, if the system is not at equilibrium or average conditions. Therefore, judging the status of the stock with reference only to fishing may not be appropriate for this species. For example, an extended drought or high predation period during the end of the time series would bias estimates of MSY and subsequent reference points, since the system during the terminal years would not be at "average" conditions. Taking the current estimates as geometric mean of the last few years attempts to account for this issue, but only works if the variability among years are not serially autocorrelated during these latter years (i.e., a span of years where environmental influences are similar).

8.2.1 Western GOM Stock

The history of the Western GOM blue crab stock relative to F/F_{MSY}, N/N_{MSY} and the proposed default control rule is illustrated in Figures 8.1 and 8.2. Calculations of current numbers and rates (F, N, SPR) were done using the geometric mean of the last three years of the model run.

For F, where the terminal year (2011) was not estimated, the geometric mean was taken of the last two years when estimates were available.

8.2.1.1 Overfishing Status

For the Western GOM stock, the current F/F_{MSY} and F/F_{Limit} were <1.0 in both the base model fits and the MCMC analyses, suggesting that the stock is currently not undergoing overfishing. However, the stock did experience overfishing in 1999 and 2002.

8.2.1.2 Overfished Status

In the Western GOM stock, the current N/N_{MSY} is <1.0, suggesting a depressed state, although still within the overfished limit threshold where N/N_{Limit} is > 1.0. However, the stock has been <1.0 N/N_{MSY} the majority of the last decade with the exceptions of the years 2006, 2007 and 2009.

8.2.1.3 Control Rules

The control rule phase plot shows the recent history of status variables relative to their proposed limits (Figure 8.2) and provides the year-specific estimates of F and N (not geometric means) relative to F_{MSY} and N_{MSY}, respectively, along with the current estimate of F and N (geometric means).

8.2.1.4 Uncertainty

The Western GOM stock MCMC analysis found a slightly higher median value for MSY at 168 million crabs, but 164 million was still within the interquartile range (see section 7.1.5; Figures 7.19 and 7.20).

8.2.2 Eastern GOM Stock

The history of the Eastern GOM blue crab stock relative to F/F_{MSY}, N/N_{MSY}, and the proposed default control rule is illustrated in Figures 8.3 and 8.4. Calculations of current numbers and rates (F, N, SPR) were done using the geometric mean of the last three years of the model run. For F, where the terminal year (2011) was not estimated, the geometric mean was taken of the last two years when estimates were available.

8.2.2.1 Overfishing Status

For the Eastern GOM stock, the current F/F_{MSY} and F/F_{Limit} were <1.0 in both the base model fits and the MCMC analyses, suggesting that the stocks are currently not undergoing overfishing. However, the stock did experience overfishing in 1996 and 1998.

8.2.2.2 Overfished Status

In the Eastern GOM stock, the N/N_{MSY} and N/N_{Limit} were > 1.0, suggesting that the stock is currently not overfished. However, in the most recent decade, the stock was <1.0 N/N_{MSY} in 2003, 2008, and 2009.

8.2.2.3 Control Rules

The control rule phase plot shows the recent history of status variables relative to their proposed limits (Figure 8.4) and provides the year-specific estimates of F and N (not geometric means) relative to F_{MSY} and N_{MSY}, respectively, along with the estimate of F and N (geometric means).

8.2.2.4 Uncertainty

The uncertainty analyses from the MCMC analysis found that these estimates were relatively stable, particularly for the Eastern GOM stock where the median MCMC estimate was also 23 million crabs (see section 7.1.5; Figures 7.21 and 7.22).

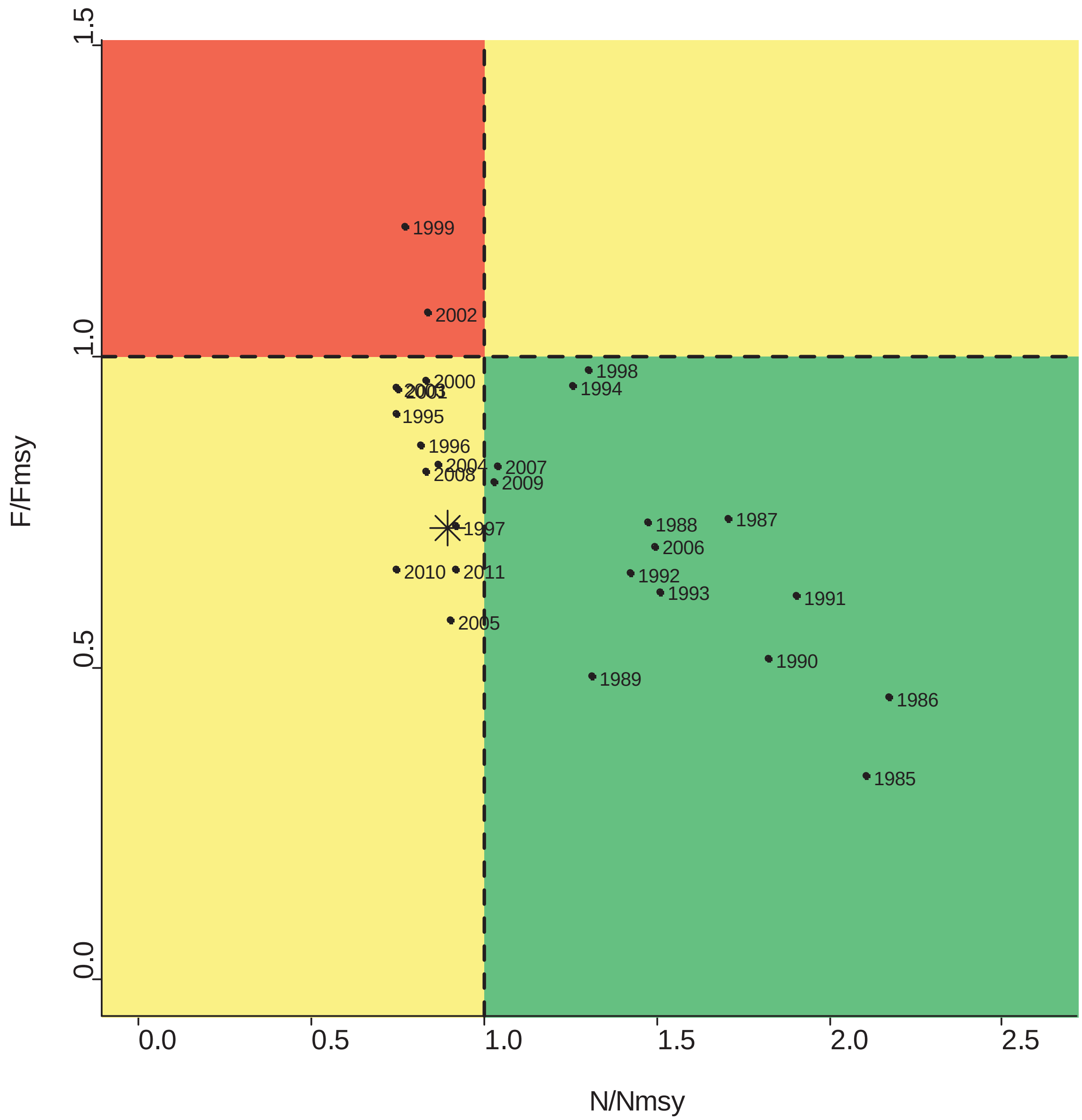


Figure 8.1 Western GOM stock status relative to F/F_{MSY} and N/N_{MSY}.

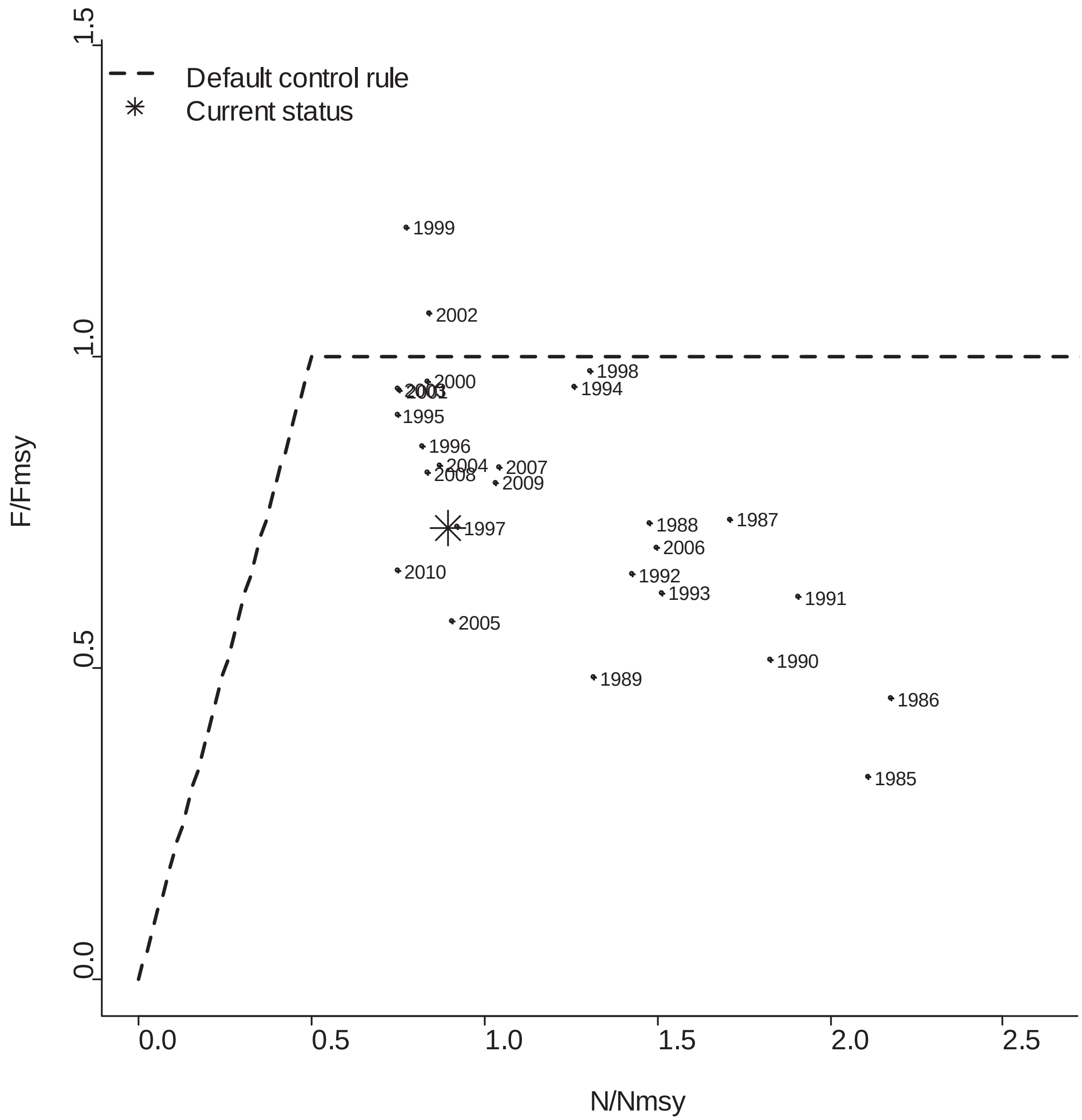


Figure 8.2 Western GOM stock status relative to proposed control rule. All points below the control rule line are not overfished or undergoing overfishing relative to the default limits proposed in this assessment.

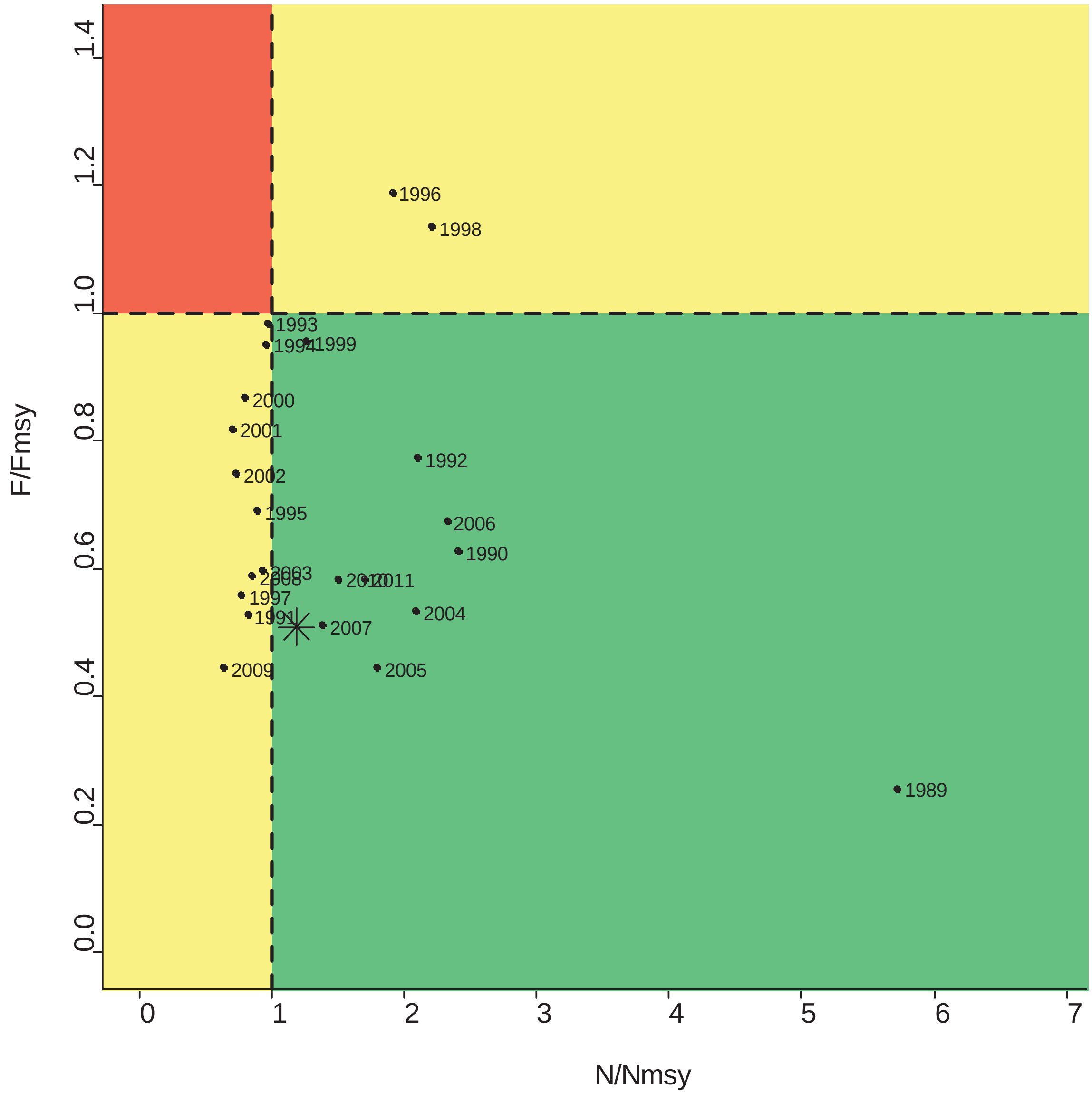


Figure 8.3 Eastern GOM stock status relative to F/F_{MSY} and N/N_{MSY}.

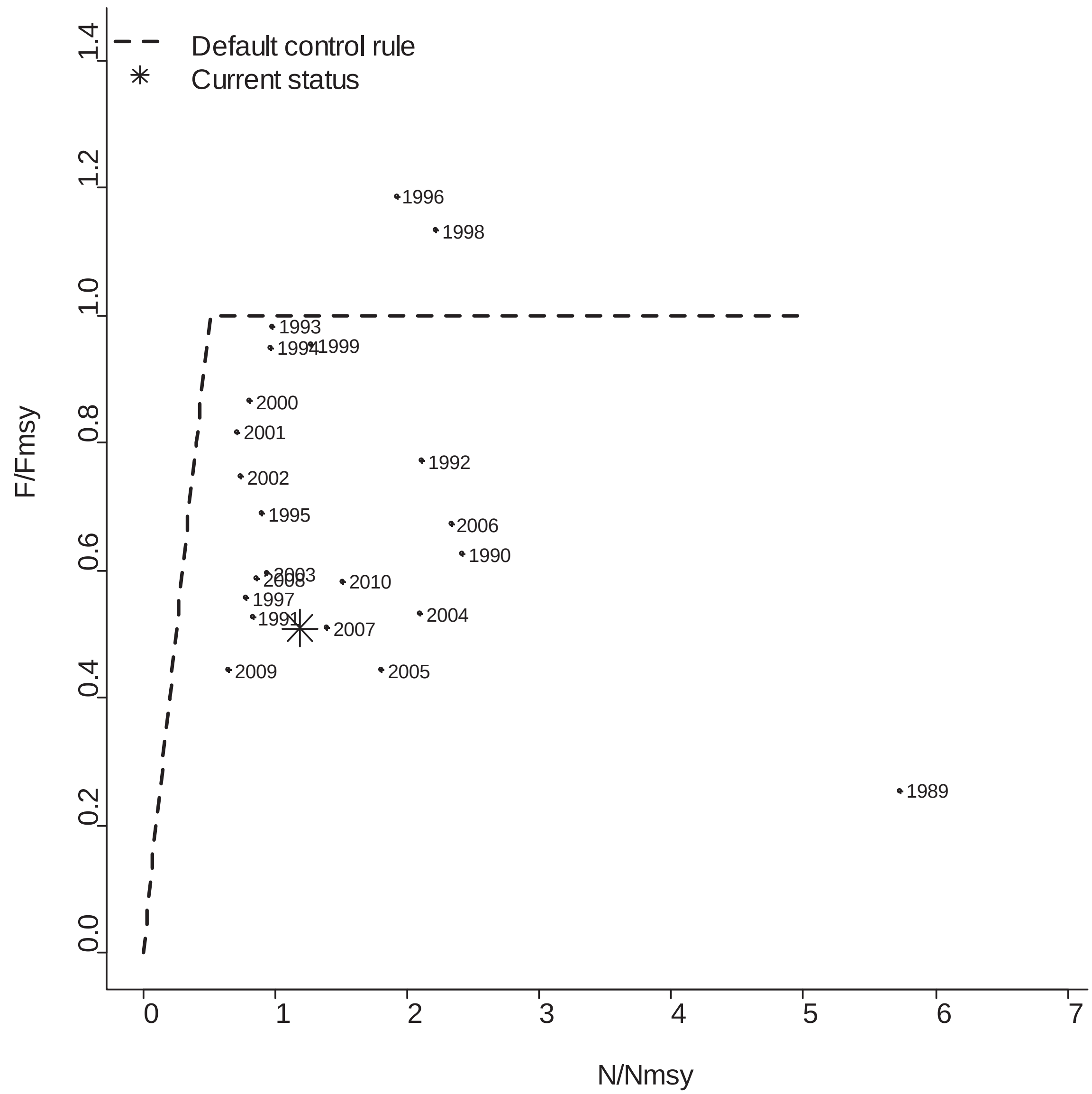


Figure 8.4 Eastern GOM stock status relative to proposed control rule. All points below the control rule line are not overfished or undergoing overfishing relative to the default limits proposed in this assessment.

9.0 Research Recommendations

9.1 Further Analyses

It is recommended that further analysis focus on detecting trends in environment conditions that influence blue crab population dynamics. This is partly due to feedback received from researchers in the field that are emphatic about the strong role environmental drivers play in determining blue crab productivity, but also observations made along the way. It was found during this analysis that the western and eastern divide used to partition stocks did not adequately account for differences between climatic sub regions along the GOM coastline.

Twilley et al. 2001 lists three distinct climatic eco-zones on the Gulf coastal plain, a western zone, a central zone and an eastern zone (Figure 9.1), which differ in relation to what occurs on the upland Gulf coastal plains and ocean currents moving up from the south. These zones influence regional trends in rainfall, water quality, drought conditions and habitat alteration, which are all likely strong drivers of blue crab abundance, but not captured in this assessment model as presently configured.

Disaggregation of blue crab stocks according to these zones should provide a more suitable breakdown of the GOM blue crab populations and enable a more thorough analysis of any environment effects. It should be noted that adapting this sort of approach does not discount the effects of commercial and recreation fishing, but rather recognizes the importance of analyzing environment influences in conjunction with these activities. In this, it is also recommended that such an analysis be structured around providing management options that can be applied within the framework of existing jurisdiction.

9.2 Modeling approach

A future modeling approach will elaborate on the basic two-stage model used for this assessment in order to include spatial segregation of the stocks. While a two-stage model is not spatially-explicit, and assumes a single population for the area of interest, it will be possible in a future model to combine the GOM (Eastern and Western) stocks if desired, thus allowing two modeling options.

Option1: Develop three separate two-stage based models for each aforementioned sub-climatic zone (i.e. Western (Texas), central (Louisiana to Alabama) and Eastern (Florida)).

Option 2: Develop one GOM blue crab model that includes multiple parameters for spatial differences, and single model parameters for those that are theoretically similar or shared among stocks (e.g., stock-recruitment parameters).

9.1 Data Needs

9.1.1 Commercial

Only commercial landings data by year and month are currently available. Having auxiliary data to accompany these would be a huge step forward in improving stock assessments. Foremost is the complete lack of commercial effort data with which to pair commercial landings. Having this additional data would allow a suite of alternate assessment approaches to be adopted and applied towards improving certain important model parameter estimates. In addition, having biostatistical sampling data on the sex and size of blue crabs caught would allow a more comprehensive sex based stock assessment similar to what was used in the Chesapeake model (Miller et al. 2011), and/or a length-based assessment as is commonly used for other crustaceans with molt-frequency style growth.

9.1.2 Recreational

Currently, there is no information or data on recreational blue crab catches. Quantifying the number, size and sex by region and season would fill a large void in this knowledge gap for the blue crab fishery.

9.1.3 Crab Bycatch in Shrimp Trawls

While NOAA collects data on shrimp effort in bays from across the GOM, the amount of crab caught is unknown as is the mortality induced after capture, sorting and release. For this assessment it was assumed that mortality on blue crabs after capture in shrimp trawls was negligible. However, any data on the effect shrimp trawls have on blue crab mortality would be useful to examine this effect more closely.

9.1.4 Diets and Predation

As we move towards more ecosystem based assessment models, we will need larger data sets which link environmental drivers to population dynamics. Paramount to this is predator prey relationships including data on the prime diet items of blue crabs by region and the availability of these items in response to environmental changes. Any trend data or information on micro benthic invertebrate’s abundance would be useful.

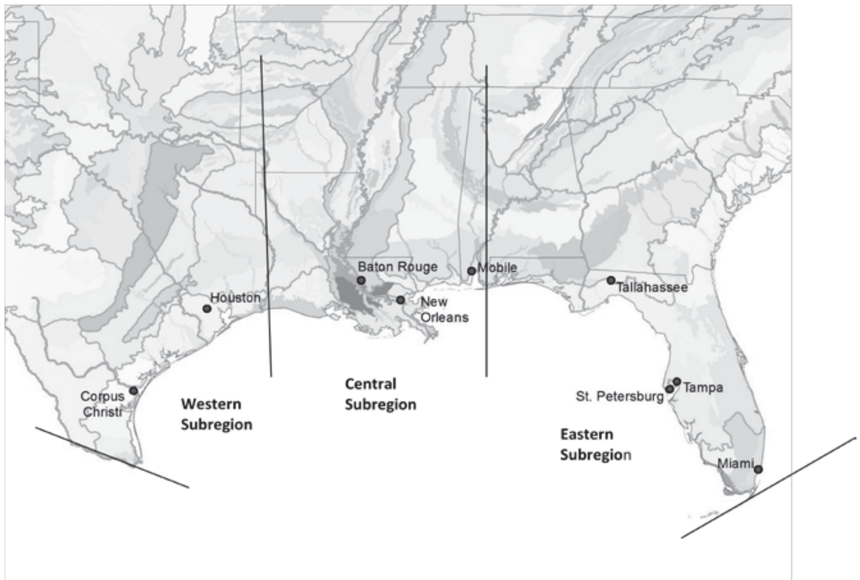


Figure 9.1 The Gulf Coastal Plain is divided into three subregions that differ in climate: Western (Texas), Central (Louisiana to Alabama) and Eastern (Florida) (*from* Twilley et al. 2001).

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Appendix A.1 ADMB Source Code for Two-stage Model (CMSA.tpl)

```
//#####################################################################
//#####################################################################

// Adapted from Chesapeake Bay 2010 blue crab assessment
//By: M. Wilberg 2/28/2011
//
//Adapted by W Cooper 2012
//Major changes:
//          1) Pulled out sex-specific due to limited biostatistical sampling of landings in Gulf
//          2) Added stage-specific mortality, including in ref points
//          3) Added environmental influences on S-R and stage-specific M
// 4) Added retrospective analyses and projections

//#####################################################################
//#####################################################################

TOP_OF_MAIN_SECTION
//increase number of estimated parameters
 gradient_structure::set_NUM_DEPENDENT_VARIABLES(2000);
 gradient_structure::set_GRADSTACK_BUFFER_SIZE(2000400);
 gradient_structure::set_CMPDIF_BUFFER_SIZE(10000000);
 arrmblsize = 10000000;


//#####################################################################
//#####################################################################
DATA_SECTION
 init_adstring DataFile;
 !! ad_comm::change_datafile_name(DataFile);

 init_int testing      //toggle to turn on/off console output for testing
 init_int fyear   //first year of the model run
 init_int lyear   //last year of the model run
 init_int retroYears
 init_int projYears

 int timeSteps  //number of time steps in a year
 int stages            //number of stages/ages to model
 !! timeSteps=1;
 !! stages=2;

 int retroSteps
 int projSteps
 !! retroSteps=retroYears*timeSteps;
 !! projSteps=projYears*timeSteps;

 //Because coded to be multiple time steps per year, need to define an indexing scheme that isn't year-based
 int mTimeSteps     // total model time steps for population dynamics
 int startIndex        //starting index for the model
 int endIndex                        //ending index for the model
 !!mTimeSteps = (lyear-fyear+1)*timeSteps; //calculate the time steps in the model
 !!startIndex=1000;                  //set a value, can be anything > the lag of environment time series

 //substract off the retrospective period
 !!endIndex=startIndex+mTimeSteps-1-retroSteps;  //substract 1 since startIndex is first step

 //#################################
```

```
//#Catch Data
//##################################
init_int ftcyear  //first year of total catch
init_int ltcyear  //last year of total catch
int cStartIndex
int cTimeSteps  //catch time steps based on catch years
!!cTimeSteps = (ltcyear-ftcyear+1)*timeSteps;
!!cStartIndex = (ftcyear-fyear)*timeSteps+startIndex;
init_vector com_TC_obs(cStartIndex,cStartIndex+cTimeSteps-1)  //total catch
init_number C_cv                                                //catch data standard deviation
init_int effFlag                    //flag to use effort time series
init_vector com_Eff_obs(cStartIndex,cStartIndex+cTimeSteps-1)  //total catch


//##################################
//#Survey data
//##################################
//Adults
init_int numAdSurv
init_int fsayear  //first year of adult surveys
init_int lsayear  //last year of adult surveys
int adTimeSteps
int adStartIndex
!!adTimeSteps=(lsayear-fsayear+1)*timeSteps;
!!adStartIndex = (fsayear-fyear)*timeSteps+startIndex;
init_matrix ad_survey_obs(1,numAdSurv,adStartIndex,adStartIndex+adTimeSteps-1)  //Adult survey CPUE
init_matrix ad_survey_cv(1,numAdSurv,adStartIndex,adStartIndex+adTimeSteps-1)          //Survey CVs for adults
init_vector sa_time(1,numAdSurv)                      //survey time

//Recruits
init_int numRecSurv
init_int fsryear
init_int lsryear
int recTimeSteps
int recStartIndex
!!recTimeSteps=(lsryear-fsryear+1)*timeSteps;
!!recStartIndex = (fsryear-fyear)*timeSteps+startIndex;
init_matrix re_survey_obs(1,numRecSurv,recStartIndex,recStartIndex+recTimeSteps-1)  //Recruit survey CPUE
init_matrix re_survey_cv(1,numRecSurv,recStartIndex,recStartIndex+recTimeSteps-1)         //survey SDs for recruits
init_vector sr_time(1,numRecSurv)

//##################################
//#Fishery params
//##################################
init_number p_rec  //Proportion of recreational harvest per region
init_number p_under  //Proportion of harvest underreporting per region
init_number maxF //Max F for F_pen calculation
init_number maxM             //Max M for F_pen calculation


//##################################
//#Adult Z estimates as prior
//##################################
init_number aveZ
init_number Z_cv


//##################################
//#Life History params
//##################################
```

```
 init_number sratio                                   //Sex ratio
 init_vector M(1,stages)                      //mortality at age for each stage (e.g., for CS: recruits, post-recruits)
 vector Myr(1,stages)                         //M rate on per year basis (for ref points)
 init_vector pSpawn(1,stages)          //proportion of females spawning in each season for differential spawning throughout the
year
 init_number sp_time  //proportion of the time step before spawning occurs
 init_int SRSwitch                            //switch for recruit function formulation; 1=bev holt, 2=ricker

 LOCAL_CALCS
//convert M to the appropriate time frame from per year basis
 Myr=M;
 M=M/timeSteps;
 END_CALCS


 //##################################
 //#Environmental time series params/data
 //##################################
 init_int numEnvTS
 init_int feyear   //first year of the model
 init_int leyear   //last year of the model
 int eTimeSteps
 int eStartIndex                //this should be less than the startIndex
 !!eTimeSteps = (leyear-feyear+1)*timeSteps;
 !!eStartIndex = (feyear-fyear)*timeSteps+startIndex;
 init_matrix envObs(1,numEnvTS,eStartIndex,eStartIndex+eTimeSteps-1)          //environmental time series (regions,
season,timesteps)
 init_vector env_cv(1,numEnvTS)          //environmental time series (regions, season,timesteps)
 init_int envRecTS                                    //time series # that influences recruitment
 init_int envRecLag                           //lag of recruitment influence
 init_vector envMTS(1,stages)                                 //time series # that influences mortality
 init_vector envMLag(1,stages)                                               //lag in mortality influence
 matrix env(1,numEnvTS,eStartIndex,endIndex+projSteps+1) //add on one for the forward stepping recruitment


 //##################################
 //#Projections
 //##################################
 init_matrix envProj(1,numEnvTS,endIndex+1,endIndex+projSteps+1)
 init_vector effProj(endIndex+1,endIndex+projSteps+1) //START with terminal year since non-estimable F


 //##################################
 //#Parameters (initial val, min, max, phase)
 //##################################

 init_number init_NIni
 init_vector init_NParams(1,3)
 init_number init_RIni
 init_vector init_RParams(1,3)

 //F params
 init_number F_qIni
 init_vector F_qParams(1,3)
 init_number F_devIni
 init_vector F_devParams(1,3)
 init_number eff_cvIni
 init_vector eff_cvParams(1,3)

 //recruitment  params
```

```
init_number rec_devIni
init_vector rec_devParams(1,3)
init_number rec_cvIni
init_vector rec_cvParams(1,3)

init_number S0Ini
init_vector S0Params(1,3)
init_number steepIni
init_vector steepParams(1,3)

init_number sr_beta_envIni
init_vector sr_beta_envParams(1,3)
init_vector M_beta_envIni(1,stages)
init_vector M_beta_envParams(1,3)
init_number M_cvIni
init_vector M_cvParams(1,3)
init_vector selIni(1,stages)
init_vector selParams(1,3)


//#################################
//#Likelihood Weights
//#################################

init_number com_lambda                //survey weight
init_vector sa_lambda(1,numAdSurv)              //survey weight
init_vector sr_lambda(1,numRecSurv)
init_number recDev_lambda             //survey weight
init_number effort_lambda             //survey weight
init_number aveZ_lambda               //survey weight


//#################################
//#Additional param control flags not addressed in data section
//#################################
init_number biasAdj                                         //Adjustment multiplier for bias correction factor


//#################################
//#Reference point calcs
//#################################
//number for reference point explorations
init_number Fval_init                                                    //lowest value of F used in SPR calcs
init_number Fval_max                                              //highest value of F used in SPR calcs
init_number Fval_inc                                                     //increment for F
int Fval_num
!!Fval_num=(Fval_max-Fval_init)/Fval_inc+1;
init_int nspr        //number of values F-%SPR will be calculated at
init_vector SPR_targ(1,nspr)  //Values of SPR for Fval reference point calculations


//#################################
//#EOF Test
//#################################
init_int test                         //check that data read in appropriately



//#################################
//#Additional Variables
```

```
//###############################

//Total harvest including recreational
vector TC_obs(cStartIndex,cStartIndex+cTimeSteps-1)  //total catch

//Variances for data sets
number C_var  //variance of catch
number Z_var  //variance of catch
matrix ad_survey_var(1,numAdSurv,adStartIndex,adStartIndex+adTimeSteps-1)  //variances for adult surveys
matrix re_survey_var(1,numRecSurv,recStartIndex,recStartIndex+recTimeSteps-1)  //variances for recruitment surveys


//Define index varaibles
int y  //index variable for time step
int s  //index variable for season
int r  //index variable for region
int i  //index variable
number year  //for report section
int ispr
int iter
int iterMCMC
!!iterMCMC=0;
int index

LOCAL_CALCS

 if (SRSwitch==2) steepParams(2)=5.0;   //make sure to bound steepness appropriately for Ricker

 C_var=log(C_cv*C_cv+1);  //variance of catch
 Z_var=log(Z_cv*Z_cv+1);  //variance of Z

 //commercial + recreational catch+prop. underreported
 TC_obs=com_TC_obs*(1.+p_rec+p_under);

 //Calculate variances from CVs
 for (i=1; i<=numAdSurv; i++){
   for (y=adStartIndex; y<=adStartIndex+adTimeSteps-1; y++){
     ad_survey_var(i,y)=log(ad_survey_cv(i,y)*ad_survey_cv(i,y)+1);  //variances for adult surveys
   }
 }
 for (i=1; i<=numRecSurv; i++) {
   for (y=recStartIndex; y<=recStartIndex+recTimeSteps-1; y++){
     re_survey_var(i,y)=log(re_survey_cv(i,y)*re_survey_cv(i,y)+1);  //variances for recruitment surveys
   }
 }

 for (i=1; i<=numEnvTS; i++){
   for (y=eStartIndex; y<=endIndex; y++){
     env(i,y)=envObs(i,y);
   }
   for (y=endIndex+1; y<=endIndex+projSteps; y++){
     env(i,y)=envProj(i,y);
   }
 }

 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 << "Commercial\t" << com_TC_obs << endl;
```

```
    cout << "adults\t" <<ad_survey_obs << endl;
    cout << "recruits\t" <<re_survey_obs << endl;
    cout << "environment\t" <<env << endl;
    cout << "max F\t" <<maxF << endl;
    cout << "max M\t" <<maxM << endl;
    cout << "envMTS\t" <<envMTS << endl;
    cout << "env Lag\t" <<envMLag << endl;
    cout << "ini N\t" <<init_NIni << endl;
    cout << "steepIni\t" <<steepIni << endl;
    cout << "sel params\t" <<selParams<< endl;
    cout << "EOF test: " << test << endl;
    exit(1);
  }

 END_CALCS



//######################################################################
//######################################################################
PARAMETER_SECTION

//Copy the Parameter estimates to double vals so can put as bounds,phases below
 LOCAL_CALCS
//template: double xxxMin=log(xxxParams(1)); double xxxMax=log(xxxParams(2)); double xxxPhase=log(xxxParams(2));
 double log_init_NMin=log(init_NParams(1));            double log_init_NMax=log(init_NParams(2));
        double init_NPhase=init_NParams(3);
 double log_init_RMin=log(init_RParams(1));            double log_init_RMax=log(init_RParams(2));
        double init_RPhase=init_RParams(3);
 double log_F_qMin=log(F_qParams(1));                  double log_F_qMax=log(F_qParams(2));          double
F_qPhase=F_qParams(3);
 double log_F_devMin=log(F_devParams(1));              double log_F_devMax=log(F_devParams(2));
        double F_devPhase=F_devParams(3);
 double log_eff_cvMin=log(eff_cvParams(1));        double log_eff_cvMax=log(eff_cvParams(2));
        double eff_cvPhase=eff_cvParams(3);
 double log_rec_devMin=log(rec_devParams(1));  double log_rec_devMax=log(rec_devParams(2));          double
rec_devPhase=rec_devParams(3);
 double log_rec_cvMin=log(rec_cvParams(1));        double log_rec_cvMax=log(rec_cvParams(2));
        double rec_cvPhase=rec_cvParams(3);
 double log_S0Min=log(S0Params(1));                            double log_S0Max=log(S0Params(2));
                          double S0Phase=S0Params(3);
 double log_steepMin=log(steepParams(1));              double log_steepMax=log(steepParams(2));
               double steepPhase=steepParams(3);
 double sr_beta_envMin=sr_beta_envParams(1);       double sr_beta_envMax=sr_beta_envParams(2);       double
sr_beta_envPhase=sr_beta_envParams(3);
 double M_beta_envMin=M_beta_envParams(1);         double M_beta_envMax=M_beta_envParams(2);         double
M_beta_envPhase=M_beta_envParams(3);
 double log_M_cvMin=log(M_cvParams(1));            double log_M_cvMax=log(M_cvParams(2));
        double M_cvPhase=M_cvParams(3);
 double log_selMin=log(selParams(1));                          double log_selMax=log(selParams(2));
                    double selPhase=selParams(3);

 END_CALCS


 //initial R and N
 //template: (Min,Max,Phase)
 init_bounded_number log_init_N(log_init_NMin,log_init_NMax,init_NPhase)
 init_bounded_number log_init_R(log_init_RMin,log_init_RMax,init_RPhase)
```

```
 //Fishing mortality for each year
 init_bounded_number log_F_q(log_F_qMin,log_F_qMax,F_qPhase)
 init_bounded_vector log_F_dev(startIndex+1,endIndex-1,log_F_devMin,log_F_devMax,F_devPhase) //don't bother with terminal year deviation
 init_bounded_number log_eff_cv(log_eff_cvMin,log_eff_cvMax,eff_cvPhase)

 //Recruitment params
 init_bounded_dev_vector log_rec_dev(startIndex+1,endIndex,log_rec_devMin,log_rec_devMax,rec_devPhase)
 init_bounded_number log_rec_cv(log_rec_cvMin,log_rec_cvMax,rec_cvPhase)

 //Stock-recruitment parameters
 init_bounded_number log_S0(log_S0Min,log_S0Max,S0Phase)
 init_bounded_number log_steep(log_steepMin,log_steepMax,steepPhase)

 //S-R environmental link parameter
 init_bounded_number sr_beta_env(sr_beta_envMin,sr_beta_envMax,sr_beta_envPhase)

 //Adult environmental link parameter
 init_bounded_vector M_beta_env(1,stages,M_beta_envMin,M_beta_envMax,M_beta_envPhase)
 init_bounded_number log_M_cv(log_M_cvMin,log_M_cvMax,M_cvPhase)

 //Vulnerability at each stage
 init_bounded_vector log_sel(1,stages,log_selMin,log_selMax,selPhase)


 //############### Derived parameters ###############//

 //sdreport_matrix  for some of these
 sdreport_vector N(startIndex,endIndex+1+projSteps)   //abundance
 sdreport_vector R(startIndex,endIndex+1+projSteps)   //recruitment
 vector SP(startIndex,endIndex+projSteps) //number of spawners
 vector TC(startIndex,endIndex+projSteps)      //total catch
 vector u(startIndex,endIndex+projSteps)      //total exploitation rate
 sdreport_vector F(startIndex,endIndex+projSteps)   //fishing mortality rate
 vector effort(startIndex,endIndex+projSteps)   //fishing mortality rate
 vector sel(1,stages)                          //selectivity (partial recruitment) of recruits to the fishery
 matrix Mt(1,stages,startIndex,endIndex+projSteps)                //M at time t; don't do for years to account for seasonal M
 vector Z(startIndex,endIndex+projSteps)                          //total Z


 matrix ad_survey_est(1,numAdSurv,startIndex,endIndex)  //estimated adult survey indices
 matrix re_survey_est(1,numRecSurv,startIndex,endIndex)  //estimated recruitment survey indices
 vector qa(1,numAdSurv)   //catchability for adult surveys
 vector qr(1,numRecSurv)   //catchability for recruitment surveys


 number S0
 number steep
 number R0
 number A0
 number alpha                          //Alpha of the S-R relationship
 number beta                           //Beta of the S-R relationship
 number rec_var                 //variance for recruitment deviations
 number eff_var                        //variance for effort residuals
 number M_var                          //variance for F deviations


 //Derived variables for reference point calculations
 number Fval                                                    //F for SPR calculations
 vector SPR(1,Fval_num)                                //spawners per recruit (NOT spawning potential ratio)
```

```
number SPR0                                        //virgin SPR
number SPR1                                        //spawner per recruit per year
vector tSPR(startIndex,endIndex+projSteps) //transitional SPR
vector NPR(1,Fval_num)                    //numbers per reruit
vector YPR(1,Fval_num)                           //yield per recruit
vector SPRatio(1,Fval_num)          //spawning potential ratio
vector N_eq(1,Fval_num)                   //equilibruim numbers
vector R_eq(1,Fval_num)                   //equilibrium recruitment
vector C_eq(1,Fval_num)                   //equilibrium catch
vector C_eqSort(1,Fval_num)               //sorted equilibrium catch

//Reference points
vector u0_eq(1,Fval_num)                  //equilibrium explotation rate for age0+
vector u1_eq(1,Fval_num)                  //equilibrium explotation rate for age1+
vector uAll_eq(1,Fval_num)                //equilibrium explotation rate for age0+
vector FSPR_ref(1,nspr)                          //F%SPR reference points
vector SPRDiff(1,nspr)                           //temporary array to check if at proper F for SPR calcs
vector Fvec(1,Fval_num)                   //equilibrium explotation rate for age0+

likeprof_number MSY                              //MSY estimate
number OFL                                //Overfishing Limit (Ncurrent*uMSY)
number u0MSY                        //exploitation rate at MSY for age 0
number u1MSY                        //exploitation rate at MSY for age 1+
number uMSY                         //exploitation rate at MSY for age 0+
number FMSY                         //F rate at MSY
number RMSY                 //equilibrium recruitment at msy
number NMSY                         //Number at MSY
number FLim                         //F Limit (target)
number NLim                         //N Limit (target)
number cLim                         //c used in calculation of targets
number FCurr                        //Current F (geometric mean of last 3 years of model run, not including terminal year)
vector MCurr(1,stages)                    //Current M (geometric mean of last 3 years of model run)
number NCurr                        //Current N (geometric mean of last 3 years of model run)
number SPRCurr                      //Current SPR using FCurr and MCurr
number FMSYRatio            //Fcurr/FMSY
number NMSYRatio            //Ncurr/NMSY
number UMSYRatio            //Ncurr/NMSY
number FFLimRatio           //Fcurr/FLimit
number NNLimRatio           //Ncurr/NLim
number termToMSY  //for F calcs


//variables for likelihood function
vector Lsr(1,numRecSurv)  //likelihood components for recruit surveys
vector Lsa(1,numAdSurv)  //likelihood components for adult surveys
number Lc       //likelihood components for catch time series
number Lz       //likelihood components for adult Z estimate (anchors F/N0/R0)
number Lrdev         //likelihood for recruitment deviations
number Leff        //likelihood for effort residuals

number F_pen         //penalty for F above the max F
number M_pen          //penalty for M above the max M
objective_function_value negLL         //negative log-liklihood


//############### Starting parameter values ###############//
LOCAL_CALCS

log_init_N=log(init_NIni);
log_init_R=log(init_RIni);
```

```
 log_F_q=log(F_qIni);
 log_F_dev=log(F_devIni);
 log_M_cv=log(M_cvIni);
 log_rec_cv=log(rec_cvIni);
 log_rec_dev=log(rec_devIni);
 log_S0=log(S0Ini);
 log_steep=log(steepIni);
 sr_beta_env=sr_beta_envIni;
 M_beta_env=M_beta_envIni;
 log_sel=log(selIni);

 END_CALCS



//#####################################################################
//#####################################################################
PROCEDURE_SECTION
 set_initial_conditions();
 if (testing==1)  cout << "End set_initial_conditions()" << endl;
 calculate_abundance_and_catch();
 if (testing==1)  cout << "End calculate_abundance_and_catch()" << endl;
 calculate_predicted_indices();
 if (testing==1)  cout << "End calculate_predicted_indices()" << endl;
 calculate_objective_function();
 if (testing==1)  cout << "End calculate_objective_function()" << endl;
 mcmc();
 if (testing==1) cout << "End mcmc()" << endl;

 if (testing==1) {
  calculate_tSPR();
  obs_pred();
  MSY_estimates();
  HPD_estimates();
  general_report();

  cout << "Procedure section completed first cycle, now exiting"<< endl;
  exit(1); //exit if in testing phase -- runs model at initial parameter values
 }


//############### Main Functions ###############

FUNCTION set_initial_conditions

 //convert parameters from the log scale
 S0=exp(log_S0);
 steep=exp(log_steep);
 negLL=0.0;
 M_var=log(exp(log_M_cv)*exp(log_M_cv)+1);
 rec_var=log(exp(log_rec_cv)*exp(log_rec_cv)+1);
 eff_var=log(exp(log_eff_cv)*exp(log_eff_cv)+1);
 sel=exp(log_sel);
 F_pen=0;
 M_pen=0;


 //######## S-R Params ########

 //Calculate virgin SPR, including proportion of recruits spawning
```

```
A0=sratio*pSpawn(2)*exp(-(M(1)+sp_time*M(2)))/(1.-exp(-(M(2)))) + sratio*pSpawn(1)*exp(-(sp_time*M(1)));
R0=S0/A0;

if (SRSwitch==1)   { //Beverton-Holt
  alpha = S0*(1-steep)/(4*steep*R0);
  beta = (5*steep-1)/(4*steep*R0);
}

if (SRSwitch==2)   { //Ricker
  beta = log(5*steep)/(0.8*S0);
  alpha =(exp((5.*log(5.*steep))/4.)*R0)/S0;
}

//calculate reference points after setting S-R params so can get FMSY for F projections
calculate_reference_points();


//######## M ########

//compute the yearly M accounting for seasonal differences and environmental differences
//leave this here to deal with seasonality
for(y=startIndex; y<=endIndex+projSteps; y++) {

  //only apply deviation + bias correction if active
  Mt(1,y)=M(1);
  if (active(M_beta_env)) Mt(1,y)=M(1)*exp(M_beta_env(1)*env(envMTS(1),y-envMLag(1)))*exp(-0.5*M_var);

  if (y<=endIndex) {
    posfun(maxM-(timeSteps*Mt(1,y)),.000001,M_pen);
    negLL+=100.*M_pen;
  }

  Mt(2,y)=M(2);
  if (active(M_beta_env)) Mt(2,y)=M(2)*exp(M_beta_env(2)*env(envMTS(2),y-envMLag(2)))*exp(-0.5*M_var);


  if (y<=endIndex) {
    posfun(maxM-(timeSteps*Mt(2,y)),.000001,M_pen);
    negLL+=100.*M_pen;
  }
}


//######## F ########

if (effFlag==0) effort=1.0;
else {
  //set up effort to average and replace all missing data with average
  double avg_effort=mean(com_Eff_obs);

  //for any year prior to effort data, set to avg of all other years
  for (i=startIndex; i<=endIndex; i++) effort(i)=com_Eff_obs(i);
  for (i=endIndex+1; i<=endIndex+projSteps; i++) effort(i)=avg_effort; //effort(endIndex)+effProj(i)*termToMSY; //deviation off the
last year
  effort/=avg_effort; //scale to observed years and not including projected years
}

//If want to estimate ave. q instead of 1st year q: change F_dev to bounded_dev_vector and adjust here
F(startIndex)=exp(log_F_q+log(effort(startIndex)));
posfun(maxF-(timeSteps*F(startIndex)),.000001,F_pen);
```

```
 negLL+=100.*F_pen;

 for(y=startIndex+1; y<endIndex; y++) { //don't include terminal year estimate
  //Computed as F=q*Eff*exp(dev)
  F(y)=exp(log_F_q+log(effort(y))+log_F_dev(y));
  posfun(maxF-(timeSteps*F(y)),.000001,F_pen);
  negLL+=100.*F_pen;
 }

 //for terminal year, use estimated deviation from previous year to keep scaled together
 F(endIndex)=exp(log_F_q+log(effort(endIndex))+log_F_dev(endIndex-1));

 termToMSY=FMSY-F(endIndex); //effort range from terminal year to MSY; negative if FMSY<termF

 //no F deviations on terminal year or projected years
 for(y=endIndex+1; y<=endIndex+projSteps; y++) {
  F(y)=(F(endIndex)+effProj(y)*termToMSY);
  effort(y)=exp(log(F(y)))/exp(log_F_q);
 }

 F=F/timeSteps;


 //######## Adult Z ########

 for(y=startIndex; y<=endIndex+projSteps; y++) Z(y)=F(y)+Mt(2,y);




FUNCTION calculate_abundance_and_catch

 N(startIndex)=exp(log_init_N);
 R(startIndex)=exp(log_init_R);

 for(y=startIndex; y<=endIndex+projSteps; y++) {

  //spawners also include some animals that were recruits in the beginning of the year
  SP(y)=sratio*(N(y)*exp(-sp_time*(Mt(2,y)+sel(2)*F(y))))*pSpawn(2)
    + sratio*(R(y)*exp(-sp_time*(Mt(1,y)+sel(1)*F(y))))*pSpawn(1);

  if (SRSwitch==1) { //Beverton-Holt
   // don't use recruit deviations for projection years
   if (y<endIndex) R(y+1)=(SP(y)/(SP(y)*beta+alpha))*exp(sr_beta_env*env(envRecTS,y+1-envRecLag))*exp(log_rec_dev(y+1)-
biasAdj*0.5*rec_var);
   else R(y+1)=(SP(y)/(SP(y)*beta+alpha))*exp(sr_beta_env*env(envRecTS,y+1-envRecLag));
  }

  if (SRSwitch==2) { //Ricker
   // don't use recruit deviations for projection years
   if (y<endIndex) R(y+1)=(alpha*SP(y)*exp(-beta*SP(y)))*exp(sr_beta_env*env(envRecTS,y+1-envRecLag))*exp(log_rec_dev(y+1)-
biasAdj*0.5*rec_var);
   else R(y+1)=(alpha*SP(y)*exp(-beta*SP(y)))*exp(sr_beta_env*env(envRecTS,y+1-envRecLag));
  }

  //abundance for the next year
  N(y+1)=R(y)*exp(-(Mt(1,y)+sel(1)*F(y)))+N(y)*exp(-(Mt(2,y)+sel(2)*F(y)));

  //Baranov catch equation
  TC(y)=N(y)*((sel(2)*F(y))/(sel(2)*F(y)+Mt(2,y))*(1.-exp(-(sel(2)*F(y)+Mt(2,y)))))
```

```
    + R(y)*((sel(1)*F(y))/(sel(1)*F(y)+Mt(1,y))*(1.-exp(-(sel(1)*F(y)+Mt(1,y)))));

  u(y)=TC(y)/(R(y)*((1-exp(-sel(1)*F(y)))/(1-exp(-F(y))))+N(y));


 }


 //Calculate year-dependent F/N Reference Point components (i.e., ratios)
 NCurr=mfexp((log(N(endIndex))+log(N(endIndex-1))+log(N(endIndex-2)))/3);
 FCurr=mfexp((log(F(endIndex-1))+log(F(endIndex-2)))/2);
 FMSYRatio=FCurr/FMSY;
 NMSYRatio=NCurr/NMSY;
 UMSYRatio=mfexp((log(u(endIndex))+log(u(endIndex-1))+log(u(endIndex-2)))/3)/uMSY;
 OFL=uMSY*mfexp((log(N(endIndex))+log(N(endIndex-1))+log(N(endIndex-2)))/3);  //N is by region, so need to take mean if more

 cLim=max(1-M(2),0.5);
 NLim=cLim*NMSY;
 FLim=FMSY;
 if (NCurr <= NLim) FLim=(FMSY*NCurr)/(cLim*NMSY);
 FFLimRatio=FCurr/FLim;
 NNLimRatio=NCurr/NLim;

 MCurr(1)=mfexp((log(Mt(1,endIndex))+log(Mt(1,endIndex-1))+log(Mt(1,endIndex-2)))/3);
 MCurr(2)=mfexp((log(Mt(2,endIndex))+log(Mt(2,endIndex-1))+log(Mt(2,endIndex-2)))/3);

 SPR0=sratio*pSpawn(2)*exp(-(MCurr(1)+sp_time*MCurr(2)))/(1.-exp(-(MCurr(2))))
   + sratio*pSpawn(1)*exp(-(sp_time*MCurr(1)));
 SPR1=sratio*pSpawn(2)*exp(-(MCurr(1)+sel(1)*FCurr+sp_time*(MCurr(2)+sel(2)*FCurr)))/(1.-exp(-(MCurr(2)+sel(2)*FCurr)))
   + sratio*pSpawn(1)*exp(-sp_time*(MCurr(1)+sel(1)*FCurr));
 SPRCurr=SPR1/SPR0;


FUNCTION calculate_predicted_indices

 //########## Recruits #########
 for (i=1; i<=numRecSurv; i++){

  qr(i)=0.0;
  double counter=0.0;

  for(y=startIndex; y<=endIndex; y++) {
   if (y<recStartIndex) continue;

   if(re_survey_obs(i,y)!=-999.) { //check to make sure year is not missing
    if(!last_phase()) {
     //small constant added to recruitment in earlier stages to
     //increase numerical stability
     //NOTE: this formulation assumes survey occurs before vulnerable to harvest
     qr(i)+=log(re_survey_obs(i,y))-log(R(y)*exp(-(sr_time(i)*Mt(1,y)))+.000001);
    }
    else { //small constant not included in last estimation stage
     qr(i)+=log(re_survey_obs(i,y))-log(R(y)*exp(-(sr_time(i)*Mt(1,y))));
    }
    counter++;
   }
  }
  //calculate geometric mean
  qr(i)=exp(qr(i)/counter);
  //Calculate predicted index of abundance
```

```
  //NOTE: this formulation assumes survey occurs before vulnerable to harvest
  for(y=startIndex; y<=endIndex; y++) {
    re_survey_est(i,y)=qr(i)*(R(y)*exp(-(sr_time(i)*Mt(1,y))));
  }
 }


 //########## Adults #########
 for (i=1; i<=numAdSurv; i++){
  //calculate catchability for each sex-index combination
  double counter=0.0;
  qa(i)=0.0;

  for(y=startIndex; y<=endIndex; y++) {
    if (y<adStartIndex) continue;

    if(ad_survey_obs(i,y)!=-999.) { //check to make sure year is not missing

      qa(i)+=log(ad_survey_obs(i,y))-log(N(y)*exp(-sa_time(i)*(Mt(2,y)+sel(2)*F(y))));
      counter++;
    }
  }
  //calculate geometric mean
  qa(i)=exp(qa(i)/counter);

  //Calculate each predicted index of abundance
  for(y=startIndex; y<=endIndex; y++) {
    ad_survey_est(i,y)=qa(i)*(N(y)*exp(-sa_time(i)*(Mt(2,y)+sel(2)*F(y))));
  }
 }



FUNCTION calculate_objective_function

 double pi=3.141593;

 //calculate adult survey likelihood component
 for (i=1; i<=numAdSurv; i++){
  Lsa(i)=0.0;
  for(y=startIndex; y<=endIndex; y++) {
    if (y<adStartIndex) continue;
    if(ad_survey_obs(i,y)!=-999.) { //check to make sure year is not missing -- some holes
      Lsa(i)+=0.5*log(2.*pi)+0.5*log(ad_survey_var(i,y))+log(ad_survey_obs(i,y))+square(log(ad_survey_obs(i,y)+.000001)-
log(ad_survey_est(i,y)+.000001))/(2*ad_survey_var(i,y));
    }
  }
  Lsa(i)=sa_lambda(i)*Lsa(i);
 }


 //calculate recruit survey likelihood component
 for (i=1; i<=numRecSurv; i++){
  Lsr(i)=0.0;
  for(y=startIndex; y<=endIndex; y++) {
    if (y<recStartIndex) continue;
    if(re_survey_obs(i,y)!=-999.) { //check to make sure year is not missing
      Lsr(i)+=0.5*log(2.*pi)+0.5*log(re_survey_var(i,y))+log(re_survey_obs(i,y))+square(log(re_survey_obs(i,y)+.000001)-
log(re_survey_est(i,y)+.000001))/(2*re_survey_var(i,y));
    }
```

```
    }
    Lsr(i)=sr_lambda(i)*Lsr(i);
  }


  //calculate total catch likelihood component
  Lc=0.0;
  for(y=startIndex; y<=endIndex; y++) {
    if (y<cStartIndex) continue;
    if(TC_obs(y)!=-999.) { //check to make sure year is not missing
      Lc+=square(log(TC_obs(y)+.000001)-log(TC(y)+.000001));
    }
  }

Lc=com_lambda*(0.5*log(2.*pi)*size_count(TC_obs(startIndex,endIndex))+0.5*log(C_var)*size_count(TC_obs(startIndex,endIndex))+su
m(log(TC_obs(startIndex,endIndex)))+0.5*Lc/C_var);


  //calculate likelihood component for recruitment deviations

Lrdev=recDev_lambda*(0.5*log(2.*pi)*size_count(log_rec_dev)+0.5*log(rec_var)*size_count(log_rec_dev)+sum(log_rec_dev)+0.5*norm
2(log_rec_dev)/rec_var);


  //calculate likelihood component for effort residuals if effort time series is included
  Leff=0.0;
  if (effFlag==1) {
    for(y=startIndex; y<endIndex; y++) {
      Leff+=0.5*log(2.*pi)+0.5*log(eff_var)+log(effort(y))+0.5*square(log(effort(y))-(log(F(y))-log_F_q))/eff_var;
    }
    Leff=effort_lambda*Leff;
  }

  //calculate likelihood component for total Z of adults as prior, read from independent Z estimate
  Lz=aveZ_lambda*(0.5*log(2.*pi)+0.5*log(Z_var)+log(aveZ)+0.5*square(log(aveZ)-log(mean(Z(startIndex,endIndex-1))))/Z_var);

  negLL+=sum(Lsa)+sum(Lsr)+Lc+Lrdev+Leff+Lz;


FUNCTION calculate_reference_points

  //Reference point variables
  MSY=0.0;
  u1MSY=0.0;
  u0MSY=0.0;
  uMSY=0.0;
  i=0;
  OFL=0.0;
  SPRDiff=1e10;

  //With recruit spawners
  SPR0=sratio*pSpawn(2)*(exp(-(Myr(1)+sp_time*Myr(2)))/(1.-exp(-(Myr(2)))))
    + sratio*pSpawn(1)*(exp(-((sp_time*Myr(1)))));

  Fval=Fval_init;
  for(i=1; i<=Fval_num; i++)
  {
    Fvec(i)=Fval; //record the F values

    SPR(i)=sratio*pSpawn(2)*(exp(-(Myr(1)+sel(1)*Fval+sp_time*(Myr(2)+sel(2)*Fval)))/(1.-exp(-(Myr(2)+sel(2)*Fval))))
```

```
     + sratio*pSpawn(1)*(exp(-(sp_time*(Myr(1)+sel(1)*Fval))));

   NPR(i)=exp(-(Myr(1)+sel(1)*Fval))/(1.-exp(-(Myr(2)+sel(2)*Fval)));

   YPR(i)=(sel(1)*Fval)/(sel(1)*Fval+Myr(1))*(1.-exp(-(sel(1)*Fval+Myr(1))))
     + ((sel(2)*Fval)/(sel(2)*Fval+Myr(2))*(1.-exp(-(sel(2)*Fval+Myr(2)))))*NPR(i);

   if (SRSwitch==1)  R_eq(i)=(SPR(i)-alpha)/(SPR(i)*beta);
   if (SRSwitch==2)  R_eq(i)=(log(alpha)+log(SPR(i)))/(beta*SPR(i));

   N_eq(i) = NPR(i)*R_eq(i);
   C_eq(i)=YPR(i)*R_eq(i);

   //calculate exploitation rate
   //age 0+
   u0_eq(i)=(sel(1)*Fval)/(sel(1)*Fval+Myr(1))*(1.-exp(-(sel(1)*Fval+Myr(1))));
   //age 1+
   u1_eq(i)=(sel(2)*Fval)/(sel(2)*Fval+Myr(2))*(1.-exp(-(sel(2)*Fval+Myr(2))));
   //all ages
   if (i>1) uAll_eq(i)=C_eq(i)/(N_eq(i)+R_eq(i)*((1-exp(-sel(1)*Fval))/(1-exp(-Fval))));

   //MSY
   if (C_eq(i)>MSY) {
    MSY=C_eq(i);
    FMSY=Fval;
    NMSY=N_eq(i);
    RMSY=R_eq(i);
    u0MSY=u0_eq(i);
    u1MSY=u1_eq(i);
    uMSY=uAll_eq(i);
   }


   //loop through SPR targets and see if at the correct F for each target
   for (ispr=1; ispr<=nspr; ispr++){
    if (square(SPR(i)/SPR0-SPR_targ(ispr)) < SPRDiff(ispr)) {
     SPRDiff(ispr)=square(SPR(i)/SPR0-SPR_targ(ispr));
     FSPR_ref(ispr)=Fval;
    }
   }

   //increment the female F for the SPR
   Fval+=Fval_inc;
  }


//############### Reporting functions ###############//

FUNCTION mcmc
 //Code to write results of MCMC to file so we can access the chains
 if(mceval_phase()) {
   //Define output file stream for MCMC results
   if(iterMCMC==0) {
    ofstream mcmcout("cmsa_refs.mcmc");
    mcmcout <<"MSY\t"<<"FMSY\t"<<
"NMSY\t"<<"uMSY\t"<<"FLim\t"<<"NLim\t"<<"FMSYRatio\t"<<"NMSYRatio\t"<<"UMSYRatio\t"<<"FFLimRatio\t"<<"NNLimRatio\
t"<<"SPRCurrent"<<endl;

    //print out yearly F and N
    ofstream mcmcout2("cmsa_yearly.mcmc");
```

```
    year=fyear;
    for(y=startIndex;y<=endIndex;y++){
      mcmcout2 <<"N"<<year<<"\t";
      year=year+1.0/timeSteps;
    }

    year=fyear;
    for(y=startIndex;y<=endIndex;y++){
      mcmcout2 <<"R"<<year<<"\t";
      year=year+1.0/timeSteps;
    }

    year=fyear;
    for(y=startIndex;y<=endIndex;y++){
      if( y<endIndex) mcmcout2 <<"F"<<year<<"\t";
      else mcmcout2 <<"F"<<year << endl;
      year=year+1.0/timeSteps;
    }

    ofstream mcmcout3("cmsa_pars.mcmc");
    mcmcout3 <<"N0\t"<<"R0\t"<< "Fq\t"<<"S0\t"<<"h"<<endl;

    iterMCMC++;
  }


  ofstream mcmcout("cmsa_refs.mcmc",ios::app);
  mcmcout
<<MSY<<"\t"<<FMSY<<"\t"<<NMSY<<"\t"<<uMSY<<"\t"<<FLim<<"\t"<<NLim<<"\t"<<FMSYRatio<<"\t"<<NMSYRatio<<"\t"<
<UMSYRatio<<"\t"<<FFLimRatio<<"\t"<<NNLimRatio<<"\t"<<SPRCurr<<endl;

  //print out yearly F and N
  ofstream mcmcout2("cmsa_yearly.mcmc",ios::app);

  for(y=startIndex;y<=endIndex;y++){
    mcmcout2 <<N(y) << "\t";
  }

  for(y=startIndex;y<=endIndex;y++){
    mcmcout2 <<R(y) << "\t";
  }

  for(y=startIndex;y<=endIndex;y++){
    if (y<endIndex) mcmcout2 <<F(y) << "\t";
    else mcmcout2 <<F(y) <<endl;
  }

  //print out yearly F and N
  ofstream mcmcout3("cmsa_pars.mcmc",ios::app);
  mcmcout3 <<exp(log_init_N)<<"\t"<<exp(log_init_R) <<"\t"<<exp(log_F_q)<<"\t"<<exp(log_S0)<<"\t"<<exp(log_steep) <<
endl;

 }


FUNCTION calculate_tSPR

 ofstream ofs_tSPR("tSPR.dat");
 ofs_tSPR<< "year\ttSPR" << endl;
```

```
 year=fyear;

 for(y=startIndex;y<=endIndex+projSteps;y++){

  SPR0=sratio*pSpawn(2)*exp(-(Mt(1,y)+sp_time*Mt(2,y)))/(1.-exp(-(Mt(2,y))))
    + sratio*pSpawn(1)*exp(-(sp_time*Mt(1,y)));
  SPR1=sratio*pSpawn(2)*exp(-(Mt(1,y)+sel(1)*F(y)+sp_time*(Mt(2,y)+sel(2)*F(y))))/(1.-exp(-(Mt(2,y)+sel(2)*F(y))))
    + sratio*pSpawn(1)*exp(-sp_time*(Mt(1,y)+sel(1)*F(y)));

  tSPR(y)=SPR1/SPR0;
  ofs_tSPR << year << "\t" << tSPR(y) << endl;
  year=year+1.0/timeSteps;
 }


FUNCTION obs_pred

 ofstream ofs_op("obs_pred_results.dat");
 ofs_op << "survey year sex a_r s_c snum obs pred" << endl;
 year=fyear;

 for(y=startIndex; y<=endIndex; y++) {

  //total observed and predicted catch
  ofs_op << "0 "<< year << " t a c 0 " << TC_obs(y) << " " << TC(y) <<  endl;

  //adult surveys
  for (i=1; i<=numAdSurv; i++)
  ofs_op << i << " "<< year << " 0 a s 0 " << ad_survey_obs(i,y) << " " << ad_survey_est(i,y) << endl;

  //recruit surveys
  for (i=1; i<=numRecSurv; i++)
  ofs_op  << i << " "<< year << " 0 r s 0 " << re_survey_obs(i,y) << " " << re_survey_est(i,y) << endl;

  if (y==startIndex) ofs_op << "0 "<< year << " r r r 0 " <<  R(y) << " " << "NA"  <<  endl;
  else {
   if (SRSwitch==1) ofs_op << "0 "<< year << " r r r 0 " << R(y)<< " "   << SP(y-1)/(SP(y-1)*beta+alpha)  <<  endl;
   if (SRSwitch==2) ofs_op << "0 "<< year << " r r r 0 " << R(y)<< " "   << alpha*SP(y-1)*exp(-beta*(SP(y-1)))  <<  endl;
  } //recruitment deviations

  year=year+1.0/timeSteps;
 }


FUNCTION HPD_estimates
 ofstream ofs_hpd("HPD_results.dat");
 ofs_hpd << "year Adult Spawners Rec RecSurvey1 TC recM adM  F FMSYRatio NMSYRatio FFLimRatio NNLimRatio u0 u1 uAll SREnv
MEnvRec MEnvAd" << endl;

 year=fyear; //for outputting the year if multiple time steps per year

 for(y=startIndex;y<=endIndex+projSteps;y++){
  ofs_hpd << year << " " << N(y) << " "<< SP(y)<< " " << R(y) << " " <<R(y)*exp(-sr_time(1)*Mt(1,y)) << " " << TC(y) << " " <<
Mt(1,y) << " " << Mt(2,y) << " " << F(y)<< " " << F(y)/FMSY<< " " << N(y)/NMSY<< " "<< F(y)/FLim<< " " << N(y)/NLim<< " "<<
(sel(1)*F(y))/(sel(1)*F(y)+Mt(1,y))*(1.-exp(-(sel(1)*F(y)+Mt(1,y)))) << " "<< (sel(2)*F(y))/(sel(2)*F(y)+Mt(2,y))*(1.-exp(-
(sel(2)*F(y)+Mt(2,y)))) << " "<< u(y) << " " << env(envRecTS,y-envRecLag) << " "<< env(envMTS(1),y-envMLag(1)) << " " <<
env(envMTS(2),y-envMLag(2)) << endl;
  year=year+1.0/timeSteps;
 }
```

```
FUNCTION MSY_estimates
 ofstream ofs_msy("MSY_results.dat");
 {
  //Column headings
  ofs_msy << "Fval\t" << "C_eq\t" << "N_eq\t" << "R_eq\t" << "YPR\t" << "SPR\t" << "SPRatio\t" << "u0_eq\t" << "u1_eq\t" <<
"uAll_eq\t" << endl;

  Fval=Fval_init;
  for(i=1; i<=Fval_num; i++) {
    ofs_msy << Fval << "\t" << C_eq(i) << "\t" << N_eq(i) << "\t" << R_eq(i) << "\t" <<YPR(i) << "\t" << SPR(i) << "\t" <<
SPR(i)/SPR0 << "\t" << u0_eq(i) << "\t" << u1_eq(i)<< "\t" << uAll_eq(i) << endl;
    Fval+=Fval_inc;
  }
 }

FUNCTION general_report
 ofstream ofs_gen("gen_results.dat");
 {
  ofs_gen << "Name Value" << endl;
  ofs_gen << "negLL " << negLL <<endl;
  ofs_gen << "Lsa "<< Lsa <<endl;
  ofs_gen << "Lsr "<< Lsr << endl;
  ofs_gen << "Lc "<<  Lc << endl;
  ofs_gen << "Lz "<<  Lz << endl;
  ofs_gen << "Lrdev "<< Lrdev << endl;
  ofs_gen << "Leff "<< Leff << endl;
  ofs_gen << "init_N "<< exp(log_init_N) << endl;
  ofs_gen << "init_R " << exp(log_init_R) << endl;
  for (i=1; i<=numAdSurv; i++) ofs_gen << "qa_i"<<i <<" " << qa(i) << endl;
  for (i=1; i<=numRecSurv; i++) ofs_gen << "qr_i"<<i <<" " << qr(i) << endl;
  ofs_gen << "F_q "<< exp(log_F_q) << endl;
  ofs_gen << "rec_cv "<< exp(log_rec_cv) << endl;
  ofs_gen << "p_rec "<< p_rec << endl;
  ofs_gen << "p_under " << p_under << endl;

  ofs_gen << "SRType " << SRSwitch << endl;
  ofs_gen << "S0 " << exp(log_S0) << endl;
  ofs_gen << "steepness " << exp(log_steep) << endl;
  ofs_gen << "alpha " << alpha << endl;
  ofs_gen << "beta " << beta << endl;
  ofs_gen << "sr_beta_env " << sr_beta_env << endl;
  ofs_gen << "M_beta_env_1 " << M_beta_env(1) << endl;
  ofs_gen << "M_beta_env_2 " << M_beta_env(2) << endl;
  ofs_gen << "sel_1 " << exp(log_sel(1)) << endl;
  ofs_gen << "sel_2 " << exp(log_sel(2)) << endl;
  ofs_gen << "Mr " << Myr(1) << endl;
  ofs_gen << "Ma " << Myr(2) << endl;
  ofs_gen << "Ma " << Myr(2) << endl;
  ofs_gen << "sp_time " << sp_time <<endl;
  ofs_gen  << "MSY " << MSY << endl;
  ofs_gen  << "FMSY " << FMSY << endl;
  ofs_gen  << "FMSYRatio " << FMSYRatio << endl;
  ofs_gen  << "NMSY " << NMSY << endl;
  ofs_gen  << "NMSYRatio " << NMSYRatio << endl;
  ofs_gen  << "RMSY " << RMSY << endl;
  ofs_gen  << "u0MSY " << u0MSY << endl;
  ofs_gen  << "u1MSY " << u1MSY<< endl;
  ofs_gen  << "uMSY " << uMSY<< endl;
```

```
    ofs_gen  << "UMSYRatio " << UMSYRatio << endl;
    ofs_gen  << "FLim " << FLim << endl;
    ofs_gen  << "FFLimRatio " << FFLimRatio << endl;
    ofs_gen  << "NLim " << NLim << endl;
    ofs_gen  << "NNLimRatio " << NNLimRatio << endl;
    ofs_gen  << "cLim " << cLim << endl;
    ofs_gen  << "OFL " << OFL<< endl;
    ofs_gen  << "projYears " << projYears<< endl;


    for(ispr=1; ispr<=nspr; ispr++) {
      ofs_gen  << "F"<<SPR_targ(ispr) << "% " << FSPR_ref(ispr)<< endl;
    }
  }


//##################################################################
//##################################################################
REPORT_SECTION
//Call reporting functions
  calculate_tSPR();
  obs_pred();
  MSY_estimates();
  HPD_estimates();
  general_report();

  report << "Likelihood Components" <<endl;
  report << "negLL\t" << negLL <<endl;
  report << "Lsa\t" << Lsa <<endl;
  report << "Lsr\t" << Lsr << endl;
  report << "Lc\t" <<  Lc << endl;
  report << "Leff\t" <<  Leff << endl;
  report << "Lz\t" <<  Lz << endl;
  report << "Lrdev\t" << Lrdev << endl;
  report << "F_pen\t" << F_pen << endl;
  report << "\nParameter Estimates (NOT log space unless marked)" <<endl;
  report << "init_N\t" << exp(log_init_N) << endl;
  report << "init_R\t" << exp(log_init_R) << endl;
  report << "F\t" << F << endl;
  report << "M_rec\t" << Mt(1) << endl;
  report << "M_ad\t" << Mt(2) << endl;
  report << "AveF\t" << mean(F(startIndex,endIndex-1)) << endl;
  report << "AveZ\t" << mean(Z(startIndex,endIndex-1)) << endl;
  report << "AveU\t" << mean(u(startIndex,endIndex)) << endl;
  report << "F_q "<< exp(log_F_q) << endl;
  report << "log_F_dev\t" << log_F_dev << endl;
  report << "mean(log_F_dev)\t" << mean(log_F_dev) << endl;
  report << "rec_dev\t" << exp(log_rec_dev) << endl;
  report << "mean(log_rec_dev)\t" << mean(log_rec_dev) << endl;
  report << "mean(rec_dev)\t" << mean(exp(log_rec_dev)) << endl;
  report << "rec_cv\t" << exp(log_rec_cv) << endl;
  for (i=1; i<=numAdSurv; i++) report << "qa_i"<<i <<"\t" << qa(i) << endl;
  for (i=1; i<=numRecSurv; i++) report << "qr_i"<<i <<"\t" << qr(i) << endl;
  if (SRSwitch==1)     //Beverton-Holt
  report << "SR=Beverton-Holt\t" << endl;
  if (SRSwitch==2)     //Ricker
  report << "SR=Ricker\t" << endl;
  report << "S0\t" << exp(log_S0) << endl;
  report << "steepness\t" << exp(log_steep) << endl;
  report << "alpha\t" << alpha << endl;
```

```
 report << "beta\t" << beta << endl;
 report << "sr_beta_env\t" << sr_beta_env << endl;
 report << "M_beta_env\t" << M_beta_env << endl;
 report << "M_beta_env_rec\t" << M_beta_env(1) << endl;
 report << "M_beta_env_ad\t" << M_beta_env(2) << endl;
 report << "sel\t" << exp(log_sel) << endl;
 report << "p_rec\t" << p_rec << endl;
 report << "p_under\t" << p_under << endl;
 report << "M\t" << Myr << endl;
 report << "rec_cv\t" << exp(log_rec_cv) << endl;
 report << "sp_time\t" << sp_time <<endl;

 report << "\nReference Point Calculations" <<endl;
 report << "negLL\t" << negLL <<endl;
 report  << "MSY\t" << MSY << endl;
 report  << "uMSY\t" << uMSY<< endl;
 report  << "NMSY " << NMSY << endl;
 report  << "UMSYRatio " << UMSYRatio << endl;
 report  << "NMSYRatio " << NMSYRatio << endl;
 report  << "FMSY\t" << FMSY << endl;
 report  << "FMSYRatio " << FMSYRatio << endl;
 report  << "RMSY\t" << RMSY << endl;
 report  << "u0MSY\t" << u0MSY << endl;
 report  << "u1MSY\t" << u1MSY<< endl;
 report  << "FLim\t" << FLim << endl;
 report  << "FFLimRatio\t" << FFLimRatio << endl;
 report  << "NLim\t" << NLim << endl;
 report  << "NNLimRatio\t" << NNLimRatio << endl;
 report  << "cLim\t" << cLim << endl;
 report  << "OFL\t" << OFL << endl;
 report  << "SPRCurr\t" << SPRCurr<< endl;

 report <<"\n"<< negLL <<endl;
 report  <<MSY << endl;
 report  <<FMSY<< endl;
 report  <<NMSY << endl;
 report  <<FFLimRatio << endl;
 report  <<NNLimRatio << "\n"<< endl;

 for(ispr=1; ispr<=nspr; ispr++) {
   report  << "F"<<SPR_targ(ispr) << "%\t" << FSPR_ref(ispr)<< endl;
 }

//######################################################################
//######################################################################
GLOBALS_SECTION

 #include "admodel.h"
 //define constant variable
 const double MathPI = 3.141592654; //or using MI_PI
 const double EPS = 1e-30;
 const double MathE = 2.71828183;

//######################################################################
//######################################################################
RUNTIME_SECTION
 maximum_function_evaluations 5000,25000,20000,20000,20000,20000
 convergence_criteria 1.0e-8

 //Leave space below this line
```

Appendix A.2 ADMB Reference Data File (CMSA.dat)

Note: this file selects the stock data to run

```
#Data file name (uncomment just one filename to run):
#
CMSA_EastStock.dat
#CMSA_WestStock.dat
```

Appendix A.3 ADMB Data File for East Stock Base Run (CMSA_EastStock.dat)

```
##########################################################
##########################################################
##########################################################
# Data sources
##########################################################
##########################################################
##########################################################

#Run in testing mode: runs model at initial values and output some values to console (0=off, 1=on)
0

#first year / last year for the model simulation (should be same as catch)
1989 2011

#Retrospective NumYears
0

#Projection NumYears
0



#################################
#Catch Data
#################################

#first / last year in any region of total catch time series
1986 2011

#Total Commercial Catch (in 1 millions of crabs)
#NOAA
20.67371454	22.9730814	26.24260698	15.01907907	14.03195872	17.11797094
	18.36188837	21.14422848	19.00864186	23.81577034	29.32890872	19.81952673
	36.56660493	17.03767284	12.2078978	11.97206516	13.60857137	19.71102984
	18.2597561	18.28278544	18.58467809	8.362494842	7.267201994	10.19426815
	17.06753423	12.62101973

#Commercial catch CV (same for each year since no data on variability):
0.05

#Flag to include effort time series in calcs (adds negLL component for F-deviations)
0

#Trap Effort  (if don't have an effort time series, set all equal to 1 for the total number of years)
#From FL trip ticket program - # traps pulled
5.163355	5.08823	5.875669	4.621626	4.395232	4.483885	5.274843	6.325681	6.053532	6.861174	7.820214	6.298735	8.336047
	5.406051	4.409944	4.779467	5.031937	6.07831	5.273512	4.999432	4.992762	3.379471	3.094001	3.260352	4.252351
	3.438569



#################################
#Survey Data
#################################

###Adult surveys AND CVs###
#Number of adult surveys
```

```
1

#first / last year in adult surveys
#Note: if catch are different lengths of time, use -999. for missing values
#	Therefore, this is min and max year for any data
1989 2011

#Standardized (x/mu)

#Glf All Ad, 1990-present (otter trawls 1990-2011, 183m haul seines 1996-2011)
2.801450204	1.09128937	0.793509531	2.132091602	0.640488149	0.994606188
	0.597634102	1.452800261	0.460792438	1.916935486	0.788916559	0.413885163
	0.277185746	0.390012294	0.671310537	1.141437488	1.0203978	2.297395155
	0.738431001	0.186284873	0.235016851	1.173701304	0.7844279
#Glf All Ad CV
0.374387019	0.40079575	0.406453272	0.339944414	0.445229963	0.50854749
	0.334936697	0.144880941	0.166922492	0.116233374	0.121979485	0.15757089
	0.171345178	0.152041413	0.127601251	0.10337698	0.106676832	0.094544103
	0.114987264	0.207481909	0.177980827	0.110056199	0.118278162

#Adult survey time(s)
0.0



###recruitment surveys AND CVs###

#Number of recrtui surveys
1

#first /last year in recruit surveys
#Note: if catch are different lengths of time, use -999. for missing values
#	Therefore, this is min and max year for any data
1989 2011

#Standardized (x/mu)
#Do all surveys as rows first, then all CVs as rows 2nd
#GlfAll Rec
1.001005116	0.283812494	1.143517535	0.928502926	0.792187488	0.639873842
	0.83191239	0.706005627	0.965528699	2.013047475	1.304789755	1.075983431
	0.765711243	0.643204199	1.776157051	1.114431304	0.853290469	1.596605041
	0.829762155	0.569516693	0.727422957	1.666886277	0.770845833
#GlfAll Rec CV
0.366562411	0.440732341	0.288289062	0.297553426	0.277851454	0.242664878
	0.130397553	0.115172137	0.11952129	0.109251156	0.113825168	0.107998652
	0.112934582	0.113641943	0.091612603	0.093220916	0.09356952	0.091690735
	0.101344351	0.106715434	0.1061701	0.098185682	0.149213969

#Recruit survey time
#NOTE: assummed that recruits are surveyed before vulnerable to fishery
#E.g., re_survey_est(r,i)=qr(r,i)*(R(r)*mfexp(-(sr_time(r,i)*Mt(1)));
0.5



#################################
#Fishery params
#################################
#Proportion of recreational harvest per region
.05
```

```
#Proportion under reporting per region
#could alternative add this directly to the catch data for month and region specific
0


#Max F
4

#Max M
4


#Ave Z prior
# calculated as sum of size freq across all years for 183m haul seine and 6.1m otter trawl,
#   using eq 4.4.5.3 in Sparre and venema 1998
# based on fit to simulated data from IBM molt-process temperature
#   for both sexes combined
3.10599543

#+/- 20%
#2.174196801
#4.037794059


#Ave Z CV
.05


################################
#Life History params
################################

#Sex ratio (leave at 1)
.5

#Natural mortality per stage
#3yr mortality
1.28 .87
#2yr mortality
#1.78 1.22
#3yr constant
#1 1

#Proportion spawning per stage (1st = Recruits, 2nd = Adults)
1
1

#Proportion of the time step before spawning occurs (0=start of year, 1=end of year)
1

#SR formulation (Bev Holt=1, Ricker=2)
2


################################
#Environmental time series params/data
################################

#Number of environmental time series
```

1

#first / last year for the environmental time series
1980 2011

#GlfStream
-0.982937731 -0.858425202 1.539823242 0.916872095 -0.625035665 0.179729529
0.603164622 -0.126476777 -0.255735071 0.374830432 -0.279651943 0.094259549
0.714082581 -0.603017897 1.486887988 1.209786676 -0.394459622 2.378390258
-0.262426043 -1.043837322 -1.47568612 -0.884639379 0.532935588 0.900764451
1.256223547 0.468701733 -1.223624997 -1.287573367 -0.551710175 0.794235242
-1.015937809 -1.579512414
#AtlStream -1.371195991 -0.934229209 2.01234639 1.041339067 -0.036041279
0.306438513 -0.024093324 -0.441231402 -0.770842701 -1.189193943 -0.538279926
0.088980559 0.67933287 -0.709307014 1.752663352 1.075693309 -0.201937715
2.291092663 -0.5932093 0.204586106 -1.388224535 0.105886731 0.659193015
-0.522463434 0.849843471 1.2054167 -1.054161503 -1.176871965 0.228422422
0.456717828 -1.158008571 -0.848661184
#FLPrecip -1.676902843 0.69198606 1.344133542 0.252757366 -1.484070733 0.471032601
0.544683754 -0.693994728 -0.229322908 -0.75961121 0.908922184 -0.003013002
-0.072646819 -0.040508134 1.303960186 1.234326369 -0.148976196 0.919635079
0.116167955 -1.33141198 -0.904235292 0.349173421 1.590530127 -0.455632815
2.051184611 -1.035468256 -1.658155277 -0.336451858 0.401398784 0.310339177
-1.78938824 0.129559074

#Environment series CV
.1

#Time series which influences recruitment:
#Use 3, assumming the num of eggs are survival of early recruits are due to rain 6 months around spawn peak
1

#Lag in environment influence on recruitment (# time steps)
1

#Time series that influences mortality (one for each stage):
1 1

#Lag in enviro influence on mortality (one for each stage):
0 0

#################################
#Projections time series
#################################

#Environmental time series annomolies for projection years +1 (+1 is for recruit calc)
#Note: must be same number of series as in environment section above with mean=0 (average)
#0 0 0 0 0 0 0 0 0 0 0
0
#Effort Deviation from year before terminal yr (0) to FMSY (1)
#E.g., 0 .25 .5 .75 1 would be step increase from year before terminal yr F -> FMSY
#.25 .5 .75 1 1 1 1 1 1 1 1
0

##
##
##
#Parameters and flags

```
# Format:
#            1st row: initial parameter estimates vector by sub-stock (or stage, e.g., selectivity)
#  2nd row: min bound, max bound, phase of estimatation
# note: if phase <0, then initial value will be held constant
##########################################################
##########################################################
##########################################################

#################################
#Initial values, bounds, and phase
#################################

#init_N (first row is vector of initial parameter guesses by sub-stock)
5
.01 100 1

#init_R
#Note: only used if the SR lag (in years) is >0
50
.01 500 1

################
# F params
################
## F=(q*Effort)*exp(Fdev)  where 1st Fdev=0 so q scales to the initial year F
#F q
1
.00001 10 2

#F_dev
1
.1 5 5

#effort_cv
.2
.01 1 -1

################
# Recruit params
################

#rec_dev (expected: log(rec_dev)=0 / rec_dev=1)
1
.1  5 4

#rec_cv
.5
.3 1 -1

#Stock Recruitment S0
5
.1 10000 3

#S-R steepness
.8
.2 .9999 3


########
# Environment params
```

```
########
#sr_beta_env (environmental link parameter for recruitment: R=R*exp(sr_beta_env*env) )
0
-20 20 -3

#M_beta_env (environmental link parameter for yearly M: Mt=M*exp(M_beta_env*env) )
#note: one for each stage
0 0
-20 20 -3

#M_cv
.1
.3 1 -1

#sel (vulnerability)
#NOTE: currently the modle only accomodates surveying the recruits prior to being vulnerable
# if this is not the case (i.e., sel > (1-sr_time)), need to re-code the index calcs
0.3 1.0
0.1 1 -1


#################################
#Likelihood weights
#################################

#Landings weight(s) lambda
1.0
#Adult survey weight(s) lambda
1.0
#Recruit survey weight(s) lambda
1.0
#recruitment deviation weight(s) lambda
1.0
#effort residuals weight(s) lambda
1.0
#Z prior weight(s) lambda
1.0


#################################
#Additional param control flags not addressed in data section
#################################

#Bias correction adjustment for predicted recruitment: biasAdj*(0.5*var)
#can turn off by setting=0 or turn on to whatever proportion by setting =1
1


#################################
#Reference point calcs
#################################

#variables to control F for females used in reference point calculations
#FSPR_init FSPR_max FSPR_inc
0 6.0 0.01

#SPR targets for calculating F reference points
#number of SPR targets
5
```

```
#targets
0.05 0.1 0.2 0.3 0.4


################################
#EOF I/O test
################################
#EOF number
12345
```

Appendix A.4 ADMB Data File for West Stock Base Run (CMSA_WestStock.dat)

```
############################################################
############################################################
############################################################
# Data sources
############################################################
############################################################
############################################################

#Run in testing mode: runs model at initial values and output some values to console (0=off, 1=on)
0

#first year / last year for the model simulation (should be same as catch)
1985 2011

#Retrospective NumYears
0

#Projection NumYears
0


##################################
#Catch Data
##################################

#first / last year in any region of total catch time series
1985 2011

#Total Commercial Catch (in 1 millions of crabs)
#rows=spatial regions, columns=time steps (steps/year * years)
#NOAA
#Grand Total
98.45087442	121.6449721	159.966614	142.6423512	114.9461349	133.5054744
	135.1838977	144.407093	111.3985395	111.178993	107.7819372	117.0608488
	126.4343372	140.4308372	157.5395901	118.6543769	129.1933266	143.8513492
	127.9418075	113.460141	115.9262415	126.9902281	114.5286733	127.0669509
	108.7038416	89.52476457	89.35450346
#AL	5.435304654	6.183193021	7.115025582	9.647239535	8.342374421	8.282074419
	5.924637207	7.307462788	6.685593024	5.477879064	6.590725582	7.937344183
	7.04770465	9.082044183	11.17805116	8.583411628	5.083004651	6.036727904
	7.704506973	5.383213957	3.709179072	6.479458138	5.069918609	4.213295355
	2.554772091	3.030869774	3.545802329
#LA	69.08582093	91.41135349	122.8216488	105.7652395	86.10353721	106.1285116
	114.8085 118.7742884	88.97858139	92.92577906	84.88989534	93.86322558
	102.0428465	111.1367279	131.4285739	100.0005699	108.5660359	120.5068515
	108.7324215	97.57581307	103.8837973	114.6192514	98.28634307	115.5828393
	99.48527651	77.48651108	82.15458485
#MS	1.110269768	3.367879068	2.423293026	1.919886048	1.210693022	1.309462792
	1.017881395	0.707223256	0.482860465	0.444767442	1.031639535	0.940999999
	1.623460464	1.884706976	2.006048838	1.424160466	1.196513953	2.008011627
	2.216918607	1.757376743	1.558572093	1.903290698	1.469530232	1.275102327
	0.943355813	0.882525581	1.079120931
#TX/WestSubregion 22.81947907	20.68254651	27.60664652	25.30998604	19.28953023
	17.78542558	13.43287907	17.6181186	15.25150465	12.33056744	15.26967675
	14.31927907	15.72032558	18.32735814	12.92691628	8.646234885	14.3477721
	15.29975814	9.287960463	8.743737209	6.77469302	3.988227902	9.702881396
	5.995713951	5.720437205	8.124858144	2.574995349
```

#CentralSubregion 75.63139535 100.9624256 132.3599674 117.3323651 95.65660465
115.7200488 121.7510186 126.7889744 96.14703488 98.84842557 92.51226046
102.7415698 110.7140116 122.1034791 144.6126739 110.008142 114.8455545
128.551591 118.6538471 104.7164038 109.1515485 123.0020002 104.8257919
121.071237 102.9834044 81.39990644 86.77950811

#Commercial catch CV (same for each year since no data on variability):
0.05

#Flag to include effort time series in calcs (adds negLL component for F-deviations)
0

#Trap Effort (if don't have an effort time series, set all equal to 1 for the total number of years)
#
1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1
1 1

################################
#Survey Data
################################

###Adult surveys AND CVs###
#Number of adult surveys
1

#first / last year in adult surveys
#Note: if catch are different lengths of time, use -999. for missing values
Therefore, this is min and max year for any data
1985 2011

#Standardized (x/mu)
#Do all surveys as rows first, then all CVs as rows 2nd
#All Adults mean
1.766147166 1.768107473 1.596853607 1.10483864 0.999790093 1.526579353
1.42450192 1.039353467 1.466427913 0.939851755 0.436654142 0.613031703
0.786854207 0.964869567 0.690056536 0.641226945 0.634253061 0.78304312
0.753201752 0.786065262 0.740924042 1.358614501 0.97159447 0.728005718
0.890133492 0.786544662 0.802475432
0.064247085 0.065432786 0.061646786 0.064997891 0.068393927 0.065248206
0.065254712 0.06931112 0.065986747 0.070719855 0.082478639 0.077020954
0.070775011 0.068675335 0.073868918 0.076923252 0.073756897 0.070873845
0.071980759 0.06876141 0.076525005 0.064977194 0.068481944 0.072156128
0.068916816 0.075843186 0.073334971
#AL adults mean
#1.934161061 1.905566414 0.651811671 0.847748157 1.91460443 1.269750201
1.119446395 1.3313397 1.117875209 0.707451824 0.806645291 0.89329348
0.805844532 0.894965339 0.659924503 0.806577107 0.986254122 0.809719193
1.578323541 1.725442417 0.407125917 0.740273822 0.328870487 0.315010261
0.432551229 1.109012323 0.900411374
#0.240723558 0.209773392 0.255863755 0.263971498 0.253668936 0.24920737
0.24784996 0.241078466 0.255918017 0.287586546 0.273385335 0.309036602
0.278979121 0.274338189 0.350830256 0.32896739 0.209416765 0.244914758
0.214925863 0.191024744 0.307338662 0.268476953 0.368926996 0.381085994
0.331218081 0.270736791 0.286838964
#LS Adults mean
#1.965712926 1.844279267 1.34838459 0.894541797 0.901581753 1.714053028

```
	1.626328809	0.741896556	0.773819759	0.581447302	0.271069218	0.409413256
	0.605203225	0.656865133	0.710436113	0.756996339	0.468357536	0.802997954
	0.490993146	0.597184321	1.209127263	2.559258298	1.154544038	0.735864931
	1.191863172	0.848387437	1.139392831
#0.100009391	0.110027442	0.09829643	0.106866881	0.117501811	0.097179463
	0.096538353	0.111266888	0.110102397	0.120857132	0.1396424	0.131976617
	0.110478769	0.112045926	0.110842472	0.106775877	0.118157724	0.108309045
	0.120157497	0.114157905	0.111336732	0.100705248	0.103905552	0.107584485
	0.097738162	0.112830586	0.104688292
#MS adults	mean
#1.062864439	1.479250935	0.79254653	1.23232732	2.504375184	1.345340552
	0.22209675	0.526642023	0.689690062	0.852902055	1.009943561	2.257556179
	1.944202645	0.82824453	0.762871277	1.01176093	1.605173552	0.707178272
	0.634301661	0.670106532	0.416955051	0.816896111	0.84321792	0.262125511
	0.763117353	1.480115809	0.278197256
#0.548760991	0.410409083	0.502978494	0.4184149	0.377290973	0.706681493
	1.74194089	2.30971521	0.825390596	0.684400629	0.873328024	0.535363604
	0.576940588	0.902191271	0.929316607	0.708361791	0.60228561	0.924976488
	0.853158878	0.827994075	1.51691707	1.62494303	0.779682238	2.0457767
	2.2257102	0.642529604	2.07795042
#TX Adults	mean
#1.60360775	1.789673715	2.030992469	1.305510919	0.926925935	1.388987099
	1.298031926	1.285060252	2.184216893	1.266426715	0.531273635	0.717301929
	0.904683137	1.24191986	0.625789687	0.484048002	0.69883636	0.738857404
	0.846177418	0.770935246	0.424828449	0.424765162	0.923334521	0.764766034
	0.655271569	0.670664734	0.497113178
#0.09185961	0.083614965	0.083570045	0.086875809	0.091534378	0.08856159
	0.087259405	0.093678848	0.0844765	0.090921221	0.113393377	0.10103429
	0.094411799	0.088617666	0.103466211	0.112489994	0.103806482	0.098546766
	0.095217299	0.097702481	0.116794742	0.117793316	0.094947395	0.098760169
	0.104670116	0.104972032	0.112319954
#Central Adults	mean
#1.933002267	1.812643788	1.207798908	0.90395831	1.083142796	1.666135116
	1.561080499	0.817750948	0.824945217	0.61331737	0.347652511	0.49286234
	0.660189478	0.688459766	0.738852761	0.772606991	0.563642355	0.798951724
	0.638545961	0.777571467	1.067099317	2.264010375	1.016007994	0.678738642
	1.082610508	0.88827046	1.100152133
#0.092088354	0.096776293	0.090685224	0.096700229	0.101655466	0.091964072
	0.092193626	0.102222007	0.10255344	0.110612017	0.121496563	0.117061245
	0.102588433	0.103474237	0.106829555	0.101514333	0.10298717	0.098932384
	0.105915274	0.098676099	0.104150861	0.089676908	0.09834757	0.103682887
	0.095195677	0.103757257	0.09826679

#Adult survey time(s)
0.0



###recruitment surveys AND CVs###

#Number of recruit surveys
1

#first /last year in recruit surveys
#Note: if catch are different lengths of time, use -999. for missing values
#	Therefore, this is min and max year for any data
1985 2011

#Standardized (x/mu)
```

```
#Do all surveys as rows first, then all CVs as rows 2nd
#All Recruits	mean
1.281060449	0.961905987	1.684921265	1.366795752	1.546392544	1.888464386
	1.267444476	1.149981792	1.517864986	1.233561953	0.993402856	0.881826873
	1.393501748	0.659525956	1.128206135	0.641399509	0.55726424	0.489175454
	0.722851228	0.794348598	0.893163237	0.599717045	0.613062775	0.716521884
	0.371561463	0.671836817	0.974240592
0.082604791	0.085677496	0.082567205	0.085648035	0.087637115	0.086046495
	0.085287309	0.087673689	0.085091555	0.085467383	0.089105278	0.087590841
	0.080807254	0.083848689	0.087980306	0.092260579	0.088100563	0.087623753
	0.084544347	0.082349279	0.085764847	0.088823729	0.087530303	0.086073428
	0.094116767	0.095835502	0.118244586
#AL Recruits	mean
#2.259304668	1.362175172	2.293538512	1.228282876	1.047260519	2.038404855
	0.875922401	0.508953165	1.117391961	1.162530918	0.526935763	1.281291823
	1.694670196	0.643649025	0.836917276	0.272098583	0.507071476	0.268250578
	1.897288978	0.435408108	0.686091597	0.930567871	0.539312174	0.24214521
	0.236441482	0.743370888	1.364723925
#0.27103365	0.257760793	0.22508085	0.341360378	0.309843555	0.278263529
	0.282205007	0.300645097	0.315732484	0.293787719	0.328172826	0.273370631
	0.275979873	0.380419755	0.373862642	0.349074225	0.324320952	0.348294607
	0.255216171	0.283016542	0.283983707	0.285358928	0.310096529	0.369042991
	0.331600568	0.346818871	0.453133848
#LS Recruits	mean
#1.021414525	1.089342144	1.446027319	0.900833691	1.169274102	1.771677384
	1.046041028	0.77154291	1.617251266	1.172011336	1.063405894	0.880954991
	1.684168453	0.492378093	1.30873406	0.878713542	0.651849656	0.48353943
	0.766854474	1.15749317	1.14832627	0.718343819	0.846465708	0.738274786
	0.48622214	0.648777584	1.040082225
#0.148007688	0.166945921	0.166949606	0.145134448	0.154478846	0.147839232
	0.146847808	0.15116891	0.151881965	0.1429286	0.14093523	0.152059651
	0.136914614	0.126856454	0.132646646	0.133938077	0.12807167	0.129960964
	0.134588077	0.12312838	0.132417641	0.128362326	0.12625073	0.128244464
	0.125488848	0.150874589	0.145392029
#MS Recruits	mean
#1.744040989	1.488430434	1.384528336	1.303839497	2.199279331	2.999370682
	1.06599792	0.437624839	0.4347188	1.701416109	1.736085156	1.646329799
	1.799698261	0.423138335	0.808186704	0.277205678	0.722019716	0.718267688
	0.66186235	0.27862969	1.423439987	0.320311528	0.732136403	0.238224258
	0.079569454	0.116903794	0.258744261
#0.421007152	0.411593799	0.414375592	0.409850175	0.669082108	0.664858803
	0.729055698	0.941717094	0.917099323	0.611029607	0.712901043	0.600551221
	0.676986612	0.85396163	1.24038984	1.53801629	0.827982523	0.679869851
	0.629009647	5.10481154	0.654018038	1.4796399	0.773689055	1.57703416
	2.26935799	1.43372723	1.61123301
#TX Recruits	mean
#1.329779181	0.799638554	1.718275586	1.891654321	1.792226945	1.894603557
	1.715090415	1.717031845	1.466155363	1.297676432	0.973281401	0.743362651
	1.029551594	1.001125473	0.996484034	0.502342569	0.519036216	0.60052039
	0.551143019	0.521986637	0.577776193	0.416246246	0.390774299	0.827163645
	0.257903773	0.76197142	0.707198241
#0.099693156	0.10958801	0.095740566	0.102084033	0.096841744	0.104094755
	0.098776698	0.101428589	0.10031809	0.102181046	0.107205872	0.114912105
	0.105115803	0.100718735	0.114655565	0.127421231	0.123059898	0.111299474
	0.122000902	0.113793704	0.12364692	0.132919422	0.127831018	0.116281629
	0.155926345	0.120774904	0.247378896
#Central Recruits	mean
#1.206682086	1.144075042	1.59823793	0.951455877	1.191727807	1.845703122
	1.015123786	0.708258572	1.470794626	1.178639796	1.004934335	0.954383164
	1.690392153	0.496441075	1.30751928	0.789672838	0.627992222	0.446685439
```

```
        0.87599117      1.013097585     1.122172862     0.73213531      0.813587297     0.66405557
        0.424830258     0.638336024     1.087074777
#0.126620075    0.13393635      0.127105647     0.129497784     0.133404695     0.127576894
        0.128385577     0.133644844     0.12971474      0.126359249     0.129677474     0.13004819
        0.119709539     0.120068466     0.120271754     0.12041334      0.118559533     0.122629509
        0.118822676     0.110880573     0.116603728     0.114173279     0.115956484     0.115138876
        0.117095314     0.138605109     0.139397655

#Recruit survey time
#NOTE: assummed that recruits are surveyed before vulnerable to fishery
#E.g., re_survey_est(r,i)=qr(r,i)*(R(r)*mfexp(-(sr_time(r,i)*Mt(1)));
0.5


#################################
#Fishery params
#################################
#Proportion of recreational harvest per region
.05

#Proportion under reporting per region
#could alternative add this directly to the catch data for month and region specific
0


#Max F
4

#Max M
4

#Ave Z prior
# calculated as sum of size freq across all years for 183m haul seine and 6.1m otter trawl,
#   using eq 4.4.5.3 in Sparre and venema 1998
# based on fit to simulated data from IBM molt-process temperature
#   for both sexes combined
2.06290806

#+/- 20%
#1.444035642
#2.681780478

#Ave Z CV
.05


#################################
#Life History params
#################################

#Sex ratio (leave at 1)
.5

#Natural mortality per stage
#3yr mortality
1.46 0.77
#2yr mortality
#1.95 1.05
#3yr constant mortality
```

```
#1 1

#Proportion spawning per stage (1st = Recruits, 2nd = Adults)
1
1

#Proportion of the time step before spawning occurs (0=start of year, 1=end of year)
1

#SR formulation (Bev Holt=1, Ricker=2)
2


################################
#Environmental time series params/data
################################

#Number of environmental time series
1

#first / last year for the environmental time series
1980 2011

#These are for adjusted year, not calendar year (July->June)
#TXPrecip0.222751937	0.426310576	-0.652901173	-1.144249611	0.519315816	0.143785224
	1.500257877	-1.079321424	-0.001864492	-0.60727596	0.670229979	2.411007303
	0.170107462	-0.803815336	0.503522473	-1.553121704	1.681003909	-0.779247914
	0.772009298	-1.005619159	-0.198403867	-0.501987009	0.594772898	0.891336776
	0.326286072	-1.270596352	1.5581668	-0.428284744	-0.700281201	0.84746638
	-1.556631336	-0.954729499
#LAPrecip-1.649545417	-1.182987328	2.184253182	-0.287871355	-0.334316052	0.009796928
	0.463688282	-0.407149781	1.187803326	0.311687457	1.681806009	0.542855379
	0.894357288	-0.585539638	0.598800127	-0.916985883	1.262748178	-0.189704155
	0.473188334	-1.767768281	0.148075457	-0.048258943	1.006246784	1.130803016
	-0.534872697	-1.353988256	0.179742296	-0.4229832	-0.640428825	0.54391094
	-2.040103094	-0.257260078
#ALPrecip-1.391722302	-0.107246552	1.630768315	-0.027794444	-0.874180097	-1.046326332
	0.356224079	-1.878366465	1.211437744	1.327305402	0.586855893	-0.792520986
	0.526163311	0.105729238	0.147662295	0.813073701	0.939976374	0.525059809
	0.287806986	-1.71284124	-0.026690943	-0.711965376	1.64180333	-0.038829459
	0.94439038	-0.588373208	-1.530763492	-0.655686799	0.640927467	1.48731312
	-1.105915413	-0.683274337
#MSPrecip	-1.432329829	-0.864596177	2.769103051	-0.181684961	-0.635260321	-
0.728013934	0.370759634	-1.599490186	1.261602025	0.973148482	1.520496725	-
0.499697348	0.321834651	0.186271679	0.273928939	-0.326421368	1.010861489	-
0.182704232	0.043573813	-1.56381572	-0.322344286	0.464532517	1.559229002
	0.639847038	-0.126644356	-0.730052475	-1.173435129	-0.447714554	0.398279936
	0.748908978	-1.337537675	-0.390635408
#WestPrecip	-1.395710381	-0.87110158	1.80866847	-0.506862226	-0.230291985	-
0.07259123	0.759587832	-0.793846979	1.071281146	0.243041627	1.588571371
	0.90657151	0.780987342	-0.621123762	0.606726586	-1.044038179	1.495057617
	-0.310402757	0.567398784	-1.807325494	0.043010926	-0.169393174	1.120751788
	1.120089603	-0.282425741	-1.426624491	0.333825233	-0.497343014	-0.590969438
	0.761895721	-2.094163042	-0.493252083
#centralSubPrecip(LA,AL,MS)	-1.677173766	-1.125848061	2.273670734	-0.271847519	-0.409562225
	-0.123619227	0.466442223	-0.621971142	1.240770462	0.448534606	1.654655135
	0.385919284	0.857351226	-0.497838981	0.56382881	-0.781208528	1.268167936
	-0.144869475	0.444394671	-1.815595503	0.104407341	-0.057936253	1.133815232
	1.051417119	-0.416786265	-1.30190849	-0.042416946	-0.45790163	-0.491426897
	0.648800001	-1.996006399	-0.308257474
```

```
#westStream
-1.347464185	-0.082128462	0.370539104	-0.267880573	-0.59635016	-0.675992103
	0.528157922	-0.501676926	-1.023916844	0.757663959	0.320985794	2.53148789
	0.747354456	0.022446003	0.822725918	-0.912776692	0.421701302	1.106280384
	0.65159242	-1.804756843	-0.774402102	0.694138381	1.310355869	0.878248549
	1.355458641	-1.387474055	-0.691620993	0.259773332	-0.827719572	0.674032765
	-1.43384874	-1.124934438
#westSubStream(TX)	-1.026546614	0.547815074	-0.406801755	-0.505120733	-0.555864394
	-0.834193296	0.262860576	-0.30828085	-0.839352363	0.049416073	0.329000755
	3.391508469	0.648105836	-0.251591495	0.87952503	-1.094468658	0.198289033
	0.248161334	0.918544526	-1.214136636	-0.145692527	0.765279979	1.030129782
	0.410535577	1.199249487	-1.471811055	0.058375104	1.122777218	-1.13004559
	0.119587471	-1.182695121	-1.21256024
#centralSubStream(LA,AL,MS)	-1.285957009	-1.649637591	2.030513586	0.463535429	-0.318126139
	0.068515657	0.697193704	-0.623317207	-0.849597059	1.526897843	0.145243638
	0.015577809	0.533204293	0.405464709	0.330015972	-0.238104586	0.519194734
	1.655179695	0.049346883	-1.794872443	-1.246813314	0.300862681	1.079385525
	1.084774939	0.973407425	-0.740561339	-1.385348872	-0.97985674	-0.116039912
	1.115943775	-1.202570581	-0.563455505


#Environment series CV
.1

#Time series which influences recruitment:
1

#Lag in environment influence on recruitment (# time steps)
1

#Time series that influences mortality:
1 1

#Lag in enviro influence on mortality
0 0


################################
#Projections time series
################################

#Environmental time series annomolies for projection years +1 (+1 is for recruit calc)
#Note: must be same number of series as in environment section above with mean=0 (average)
#0 0 0 0 0 0 0 0 0 0 0
0
#Effort Deviation from year before terminal yr (0) to FMSY (1)
#E.g., 0 .25 .5 .75 1 would be step increase from year before terminal yr F -> FMSY
#.25 .5 .75 1 1 1 1 1 1 1 1
0


##########################################################
##########################################################
##########################################################
#Parameters and flags
# Format:
#	1st row: initial parameter estimates vector by sub-stock (or stage, e.g., selectivity)
#  2nd row: min bound, max bound, phase of estimatation
# note: if phase <0, then initial value will be held constant
##########################################################
```

```
##########################################################
##########################################################

#################################
#Initial values, bounds, and phase
#################################

#init_N (first row is vector of initial parameter guesses by sub-stock)
100
.01 500 1

#init_R
#Note: only used if the SR lag (in years) is >0
50
.01 1000 1

################
# F params
################
## F=(q*Effort)*exp(Fdev)  where 1st Fdev=0 so q scales to the initial year F
#F q
1
.00001 10 2

#F_dev
1
.1 5 5

#effort_cv
.2
.01 1 -1


################
# Recruit params
################

#rec_dev (expected: log(rec_dev)=0 / rec_dev=1)
1
.1  5 4

#rec_cv
.5
.3 1 -1

#Stock Recruitment S0
100
.1 1000 3

#S-R steepness
.8
.2 .9999 3


########
# Environment params
########
#sr_beta_env (environmental link parameter for recruitment: R=R*exp(sr_beta_env*env) )
0
-20 20 -3
```

```
#M_beta_env (environmental link parameter for yearly M: Mt=M*exp(M_beta_env*env) )
#note: one for each stage
0 0
-20 20 -3

#M_cv
.1
.3 1 -1

#sel (vulnerability)
#NOTE: currently the modle only accomodates surveying the recruits prior to being vulnerable
# if this is not the case (i.e., sel > (1-sr_time)), need to re-code the index calcs
0.3 1.0
0.1 1 -1


################################
#Likelihood weights
################################

#Landings weight(s) lambda
1.0
#Adult survey weight(s) lambda
1.0
#Recruit survey weight(s) lambda
1.0
#recruitment deviation weight(s) lambda
1.0
#effort residuals weight(s) lambda
1.0
#Z prior weight(s) lambda
1.0



################################
#Additional param control flags not addressed in data section
################################

#Bias correction adjustment for predicted recruitment: biasAdj*(0.5*var)
#can turn off by setting=0 or turn on to whatever proportion by setting =1
1



################################
#Reference point calcs
################################

#variables to control F for females used in reference point calculations
#FSPR_init FSPR_max FSPR_inc
0 6.0 0.01

#SPR targets for calculating F reference points
#number of SPR targets
5

#targets
0.05 0.1 0.2 0.3 0.4
```

```
#################################
#EOF I/O test
#################################
#EOF number
12345
```

Appendix B.1 Input data and parameters for ASPIC surplus production model base configuration for Eastern GOM Stock

```
FIT  ## Run type (FIT, BOT, or IRF)
"sp-01"
LOGISTIC  YLD    SSE
103  ## Verbosity
1000  90  ## Number of bootstrap trials, <= 1000
1  2000000  ## 0=no MC search, 1=search, 2=repeated srch; N trials
1.0000E-08  ## Convergence crit. for simplex
3.0000E-08  20  ## Convergence crit. for restarts, N restarts
1.0000E-04  24  ## Conv. crit. for F; N steps/yr for gen. model
6.0000  ## Maximum F when cond. on yield
1.0  ## Stat weight for B1>K as residual (usually 0 or 1)
1  ## Number of fisheries (data series)
1.0000E+00    ## Statistical weights for data series
0.75  ## B1/K (starting guess, usually 0 to 1)
9.89205E+06  ## MSY (starting guess)
9.89205E+07  ## K (carrying capacity) (starting guess)
4.6081E-08    ## q (starting guesses -- 1 per data series)
1  1  1  1    ## Estimate flags (0 or 1) (B1/K,MSY,K,q1...qn)
9.89205E+05  1.97841E+08  ## Min and max constraints -- MSY
9.89205E+06  1.97841E+09  ## Min and max constraints -- K
3921295  ## Random number seed
62  ## Number of years of data in each series
"Florida Index"
CC
   1950    -2.439024E+00     7.186200E+05
   1951    -2.439024E+00     2.184000E+06
   1952    -2.439024E+00     2.098740E+06
   1953    -2.439024E+00     3.314115E+06
   1954    -2.439024E+00     3.048465E+06
   1955    -2.439024E+00     5.202645E+06
   1956    -2.439024E+00     3.915975E+06
   1957    -2.439024E+00     5.577180E+06
   1958    -2.439024E+00     9.128910E+06
   1959    -2.439024E+00     1.459353E+07
   1960    -2.439024E+00     1.958513E+07
   1961    -2.439024E+00     1.799133E+07
   1962    -2.439024E+00     1.087433E+07
   1963    -2.439024E+00     1.381002E+07
   1964    -2.439024E+00     1.478558E+07
   1965    -2.439024E+00     2.163966E+07
   1966    -2.439024E+00     1.737540E+07
   1967    -2.439024E+00     1.468173E+07
   1968    -2.439024E+00     9.458505E+06
   1969    -2.439024E+00     1.216341E+07
   1970    -2.439024E+00     1.552593E+07
   1971    -2.439024E+00     1.289264E+07
   1972    -2.439024E+00     1.120697E+07
   1973    -2.439024E+00     1.007843E+07
   1974    -2.439024E+00     1.064049E+07
   1975    -2.439024E+00     1.344851E+07
```

1976	-2.439024E+00	1.265093E+07
1977	-2.439024E+00	1.662381E+07
1978	-2.439024E+00	1.228596E+07
1979	-2.439024E+00	1.176797E+07
1980	-2.439024E+00	1.185724E+07
1981	-2.439024E+00	1.555080E+07
1982	-2.439024E+00	9.370517E+06
1983	-2.439024E+00	9.841806E+06
1984	-2.439024E+00	1.358693E+07
1985	-2.439024E+00	1.290458E+07
1986	-2.439024E+00	8.036358E+06
1987	-2.439024E+00	1.094588E+07
1988	-2.439024E+00	1.092292E+07
1989	6.832805E+00	8.607252E+06
1990	2.661681E+00	7.260622E+06
1991	1.935389E+00	5.496715E+06
1992	5.200223E+00	8.036314E+06
1993	1.562166E+00	8.949551E+06
1994	2.425869E+00	8.887131E+06
1995	1.457644E+00	9.219875E+06
1996	3.543415E+00	1.309866E+07
1997	1.123884E+00	9.787235E+06
1998	4.675452E+00	1.350592E+07
1999	1.924187E+00	1.172794E+07
2000	1.009476E+00	6.901276E+06
2001	6.760628E-01	4.878993E+06
2002	9.512495E-01	5.845369E+06
2003	1.637343E+00	7.586642E+06
2004	2.783994E+00	8.487322E+06
2005	2.488775E+00	7.738503E+06
2006	5.603403E+00	9.040658E+06
2007	1.801051E+00	6.415316E+06
2008	4.543533E-01	2.796251E+06
2009	5.732118E-01	3.532425E+06
2010	2.862686E+00	6.046601E+06
2011	1.913239E+00	7.174866E+06

Appendix B.2 Input data and parameters for ASPIC surplus production model base configuration for Western GOM Stock

```
FIT  ## Run type (FIT, BOT, or IRF)
"sp-01"
LOGISTIC  YLD    WTDSSE
103  ## Verbosity
1000  90  ## Number of bootstrap trials, <= 1000
0  2000000  ## 0=no MC search, 1=search, 2=repeated srch; N trials
1.0000E-08  ## Convergence crit. for simplex
3.0000E-08  8  ## Convergence crit. for restarts, N restarts
1.0000E-04  24  ## Conv. crit. for F; N steps/yr for gen. model
6.0000  ## Maximum F when cond. on yield
1.0  ## Stat weight for B1>K as residual (usually 0 or 1)
1  ## Number of fisheries (data series)
1.0000E+00    ## Statistical weights for data series
0.75  ## B1/K (starting guess, usually 0 to 1)
4.64508E+07  ## MSY (starting guess)
4.64508E+08  ## K (carrying capacity) (starting guess)
2.7894E-09    ## q (starting guesses -- 1 per data series)
1  1  1  1    ## Estimate flags (0 or 1) (B1/K,MSY,K,q1...qn)
4.64508E+06  9.29016E+08  ## Min and max constraints -- MSY
4.64508E+07  9.29016E+09  ## Min and max constraints -- K
3921295  ## Random number seed
62  ## Number of years of data in each series
"Western Combined INDEX"
CC
1950  -2.43902439 19420380    0
1951  -2.43902439 14866530    0
1952  -2.43902439 13140750    0
1953  -2.43902439 15443085    0
1954  -2.43902439 13703445    0
1955  -2.43902439 21088725    0
1956  -2.43902439 17469480    0
1957  -2.43902439 19427835    0
1958  -2.43902439 23627415    0
1959  -2.43902439 30842595    0
1960  -2.43902439 37169790    0
1961  -2.43902439 37686390    0
1962  -2.43902439 27557670    0
1963  -2.43902439 28199535    0
1964  -2.43902439 26782665    0
1965  -2.43902439 39086145    0
1966  -2.43902439 32633790    0
1967  -2.43902439 29066205    0
1968  -2.43902439 27345990    0
1969  -2.43902439 35055195    0
1970  -2.43902439 35795025    0
1971  -2.43902439 35340270    0
1972  -2.43902439 37062375    0
1973  -2.43902439 45771810    0
1974  -2.43902439 42471975    0
1975  -2.43902439 40771605    0
```

1976	-2.43902439	38482185	0
1977	-2.43902439	46780230	0
1978	-2.43902439	40245393.3	0
1979	-2.43902439	45835585.95	0
1980	-2.43902439	45005747.85	0
1981	-2.43902439	44549579.55	0
1982	-2.43902439	38793170.85	0
1983	-2.43902439	42494597.25	0
1984	-2.43902439	59143614.6	0
1985	4.307676015	58644988.5	242.2663769
1986	4.312457251	55665646.05	233.5657594
1987	3.894764895	82389458.55	263.135305
1988	2.69472839	83244848.4	236.7017504
1989	2.438512422	58425216.15	213.7789398
1990	3.723364276	61263699	234.8890922
1991	3.474394927	69124282.5	234.8422569
1992	2.535008456	73283362.95	208.1585081
1993	3.576653446	68840932.65	229.6606352
1994	2.292321354	55904844.45	199.9480978
1995	1.065010102	57094206.75	146.9998962
1996	1.495199276	65535013.95	168.5707476
1997	1.919156602	67307339.4	199.6365743
1998	2.353340407	70958647.2	212.0305436
1999	1.683064722	72445591.05	183.2637313
2000	1.563968159	72342378.15	168.9992307
2001	1.546958685	57225395.85	183.8208311
2002	1.909861268	69319649.7	199.0801737
2003	1.837077444	67158598.5	193.0043763
2004	1.917232346	63609825.3	211.5000395
2005	1.80713181	52543234.8	170.7627998
2006	3.313693905	70855203.3	236.8525663
2007	2.36974261	60862579.05	213.2297706
2008	1.775623702	51722924.4	192.0673567
2009	2.171057298	64335784.8	210.5472585
2010	1.918401615	43301931.75	173.8468649
2011	1.957257151	58385875.8	185.9421083

Appendix C

GDAR 01 Stock Assessment Report for Gulf of Mexico Blue Crab

Reviewers Report

Prepared by:
Sean P. Powers, Romuald N. Lipcius, Thomas J. Miller and Genevieve Nesslage

for the Gulf States Marine Fisheries Commission

July 15, 2013

I. Executive Summary

The GDAR 01 (Blue Crab) review panel (RP) met from June 11 to June 13, 2013 where the Stock Assessment Analytical Team (AT) presented the assessment. Overall, the RP was impressed with the quality of the assessment. After examination of additional sensitivity runs of the model, the panel felt the assessment represented the best available science to evaluate the status of GOM blue crab populations. All five Terms of Reference (ToR) were evaluated by the RP, which provided comments and recommendation for each ToR. In summary, the GOM blue crab stock status was determined to be not overfished and overfishing was not occurring; however, the stock assessment report demonstrates that these benchmarks have been exceeded in some recent years.

II. Participants:

Dr. Sean Powers, USA/DISL, Mobile, AL - *Chair*
Dr. Romuald Lipcius – VIMS, Gloucester Point, VA - *Reviewer*
Dr. Thomas Miller – UMCES, Solomons, MD - *Reviewer*
Dr. Genevieve Nesslage – ASMFC, Arlington, VA - *Reviewer*
Dr. Robert Leaf - GCRL, Ocean Springs MS - *Analyst*
Dr. Wade Cooper – FWC, St. Petersburg FL - *Analyst*
Mr. Joe West – LDWF, Baton Rouge LA - *Analyst*
Mr. Glen Sutton – TPWD, Rockport TX - *Analyst*

Ms. Traci Floyd – MDMR, Biloxi, MS - *Blue Crab TTF*
Dr. Ryan Gandy – FWRI/FWC, St. Petersburg, FL - *Blue Crab TTF*
Mr. Jason Hermann – ADCNR/AMRD, Gulf Shores, AL - *Blue Crab TTF*
Mr. Jeff Marx – LDWF, New Iberia, LA - *Blue Crab TTF*
Ms. Harriet Perry – GCRL/USM, Ocean Springs, MS - *Blue Crab TTF*

Dr. Behzad Mahmoudi – FWRI/FWC, St. Petersburg, FL
Dr. Ralf Riedel – GCRL, Ocean Springs MS

Mr. Steve VanderKooy – GSMFC, Ocean Springs MS - *Rapporteur*
Ms. Debbie McIntyre – GSMFC, Ocean Springs MS – *GDAR Staff Assistant*

III: Workshop Agenda, GDAR01 RW for GOM Blue Crabs

Tuesday

8:30 am Convene
8:30 – 9:00 am Introductions and Opening Remarks Coordinator
- Agenda Review, ToRs, Task Assignments

9:00 am – 11:30 am Assessment Presentations
11:30 am – 1:30 pm Lunch Break
1:30 pm – 3:00 pm Continue Assessment Presentations
3:00 pm – 3:15 pm Break
3:15 pm – 5:00 pm Panel Discussion Chair
- Assessment Data & Methods
- Identify additional analyses, sensitivities, corrections

Tuesday Goals: Initial presentations completed, sensitivities and modifications identified.

Wednesday

8:30 am – 11:30 am Panel Discussion Chair
- Review additional analyses, finalize sensitivities

11:30 am – 1:30 pm Lunch Break
1:30 pm – 5:00 pm
Panel Discussion Chair
- Consensus recommendations and comments
- Projections reviewed.

Wednesday Goals: Projection approaches approved, Summary report drafts begun; Complete assessment work and discussions.

Thursday

8:30 am – 11:30 am Panel Discussion Chair
- Review Consensus Reports

11:30 am – 1:30 pm Lunch Break
1:30 pm – 5:00 pm Panel Discussion or Work Session Chair
- Final results available. Draft Summary Report reviewed.

5:00 pm ADJOURN

IV. Comments by Terms of Reference (ToRs)

ToR 1. Evaluate the data used in the assessment.

a. Are data decisions made by the DW and AW sound and robust?

The RP found the decisions made by the DW and AW to be sound, well-reasoned and robust. The RP did express a concern about the division point between the Eastern and Western stocks within the Gulf. Whether the division point between east and west should be near Apalachicola Bay (as is currently the case), the Mississippi River (as is the case for red snapper), Mobile Bay (a biogeographic break), or some other location remains debatable. Genetic and oceanographic circulation data appear ambiguous on this point. Because the status of the stock (not overfished or experiencing overfishing) remains the same regardless of the break point or whether the stock is modeled as one mixed population, the RP was not concerned with the break point. However, there is a clear need to resolve the issue of stock subdivision before the next stock assessment.

A second concern of the RP was the lack of a Gulf-wide fishery independent index to monitor the spawning stock biomass. Towards the end of the RW, the RP investigated the potential for the NMFS SEAMAP ground fish survey to fill this void. This is a topic that should be further explored for the next stock assessment. The development and inclusion of state specific fishery independent indices is a major development and the AT should be applauded for integrating these indices into the modeling framework. As mentioned under ToR 2, an issue arises when state indices are juxtaposed and a Gulf-wide (or region-wide if the stock is split) index would greatly inform the model. At a minimum, if a spatially-explicit assessment is maintained, a greater consistency among the fishery-independent surveys within each spatial region is to be encouraged.

A third concern was the lack of a continuous and reliable time series on effort. A strong recommendation from the RP is to continue to sustain and improve trip-level effort monitoring in the fishery. Ideally, these data may be reconciled with past effort time series (e.g, NMFS port agent time series) in some states.

b. Are data uncertainties acknowledged, reported, and within normal or expected levels?

In general yes, specific comments and recommendations regarding uncertainties are made under ToR 4.

c. Are data applied properly within the assessment model?

Yes, specific comments and recommendations regarding data inputs are made under ToR 2.

d. Are input data series reliable and sufficient to support the assessment approach and findings?

The current data and model configuration are sufficient to provide stock status determination.

ToR 2. Evaluate the methods used to assess the stock, taking into account the available data.

The assessment integrated three sources of data (life history, fishery-dependent and fishery-independent) into one of two unified assessment models. The RP addressed this term of reference with regard to each assessment model.

Catch Survey Model

Background. A Catch-Survey Analysis was the principal approach used to assess blue crab in the GOM. This approach was developed by Collie and Sissenwine (1983) and applied to fish stocks in New England. It is a stage-based approach that divides an exploited population into pre-recruited (not available to the fishery) and recruited (available to the fishery) stages. The approach was reviewed by Mesnil (2003). In summary, a simple structured population model is statistically fit to observed time series of abundances of pre-recruit and fully-recruited individuals to yield estimated time series of population recruitments, abundances of fully-recruited stages and fishing mortality rates. In the original formulation, catch was assumed to be known without error and no management reference points were estimated.

Catch-Survey Analysis has been applied successfully to a range of crustacean fisheries including northern shrimp in the northwest Atlantic (Cadrin 2000), king crab in Alaska (Zheng et al. 1997), and blue crab in both Delaware Bay (Coakley 2004, Wong 2008) and Florida (Murphy et al. 2007). The approach was modified by Miller et al. (2005) to allow incorporation of the multiple fishery-independent surveys available in the Chesapeake Bay. This application of the renamed Catch-Multiple Survey Analysis was reviewed by an international panel of assessment scientists with expertise in crustacean fisheries and was found to be a sound scientific foundation for management (http://hjort.cbl.umces.edu/crabs/Assessment05.html). Miller et al. (2011) further refined the Catch-Multiple Survey Analysis to relax the assumption that catches were reported without error, to estimate management reference points internally in the model, and to estimate sex-specific abundances and exploitation rates. This revised Catch-Multiple Survey Analysis was applied in an updated assessment of the blue crab stock in the Chesapeake Bay. The assessment was reviewed by a second independent panel of international assessment experts and found to provide a sound basis for management (http://hjort.cbl.umces.edu/crabs/Assessment.html).

a. Are methods scientifically sound and robust?

The RP evaluated the Catch-Multiple Survey Analysis developed to assess the blue crab population in the GOM and concluded that the Catch-Multiple Survey Analysis presented in the 2013 Stock Assessment of Blue Crab in the GOM is scientifically sound and robust. This finding is based on several lines of evidence:

- The stage-based structure of Catch-Survey Analysis is appropriate for crustaceans for which ageing is difficult, thereby precluding age-based models, and for which the absence of fishery-dependent length data preclude length-based models,

- The recent modification of the Catch-Survey methodology (Miller et al. 2011) that allows for uncertainty in reported landings has been reviewed by an independent panel of experts and found to provide a reliable basis for management, and
- Adequate survey data are available throughout the stock range.

A sufficient number of sensitivity runs were conducted to permit the RP to understand the pattern and magnitude of sensitivities of the model to changes in inputs.

The RP commends the analytical team on the level of detail provided in the assessment document and the care taken in the development and implementation of the assessment model.

b. Are assessment models configured properly and used consistent with standard practices?

The model uses an annual time step and a reference date of July 1 for the model year. Modeling blue crab populations in the GOM is more difficult than populations in the mid-Atlantic because of the faster growth rates of crabs in the Gulf. The consequence of this faster growth is that a substantial number of crabs born at the beginning of the model year, and represented as pre-recruits in the model, are likely to grow sufficiently within the annual time step to both attain the legal size AND mature within the annual time step of the model. Although this is appropriately captured within the model, it does complicate partitioning of fishery-dependent and fishery-independent data, which are compiled on a calendar year basis.

The model uses appropriate expressions for estimating population parameters, and time series of abundances of pre-recruit and fully-recruited stages. The model specifies appropriate error distributions for observation models. Sufficient simulations were conducted by the assessment team to understand the effects of alternative weightings of likelihood components on model results and conclusions.

The base models included in the assessment report recognized an Eastern and a Western stock of blue crab in the GOM, with a dividing line at the St. Joseph Bay/Apalachicola Bay Peninsula. This spatially-structured approach is reflected in the selection of base runs in the assessment document. The RP views this as a strong hypothesis regarding the stock structure of blue crab. The RP was concerned over tension in model fits at the regional level whereby fishery-independent patterns in Texas surveys were not well captured by the model results (Fig. ToR2.1). Strong residual patterns are evident for the Texas data, suggesting that crab abundances in this region are not well described by the stock dynamics estimated for the Western portion of the range. This and other statistical issues with the regional models led the RP to question the reliability of the geographic split of the blue crab stock in the Gulf into two management units.

However, the RP notes that sensitivity runs were presented that represented a single well-mixed population of blue crab in the Gulf, and an additional run was presented that included a division of the Western GOM stock into a central and Western component. Single state models were also presented in the assessment document. In general all of these models do not differ in the fundamental conclusion that the blue crab stock in the GOM is not overfished and overfishing is not occurring.

The RP recommends that additional work be conducted to more fully understand the stock structure of blue crab in the GOM. The RP notes that this recommendation cannot be addressed by modeling work alone, but will require additional hydrodynamic, genetic and mark-recapture studies. We elaborate on this in our response to ToR 5.

The base models presented in the assessment report use a single pair of indices for pre-recruit and fully-recruit crabs for the presumed Eastern and Western GOM stocks. The indices used are derived from the results of a two-stage general linear model (GLM) applied to fishery-independent data from the individual states. This is certainly a commonly-used approach. However, the RP noted that the Catch-Multiple Survey Analysis used in the assessment was designed specifically to allow multiple surveys to be used in model fitting. The RP recommends that the assessment team evaluate the potential of using multiple state surveys in future modeling exercises. In the current approach the degree to which individual state surveys are explained by the model is somewhat opaque because the levels of the "state" classes from the GLM are not included directly in the model. In sensitivity runs that were conducted during the workshop, the use of multiple state surveys was shown to be feasible.

The Catch-Multiple Survey Analysis implemented for this assessment uses an informative prior on average total mortality rates (Z) to obtain the correct "scale" of the population response. This approach is defensible but the RP notes that the model estimates are sensitive to assumptions regarding Z. We return to this point in ToR 4: Uncertainties.

c. Are the methods appropriate for the available data?

Following extensive discussions with the assessment team and amongst themselves, the RP concludes that the methods employed in the assessment are generally appropriate for the data that were available.

The RP also questioned the application of the two-stage general linear model approach. This approach is certainly of value when the survey data includes a high number of null catches. However, when this is not the case, other error distribution models (e.g., negative binomial) can be used in a single-stage model to effectively describe the survey data. The RP recommends that the efficacy of such single-stage, general linear models be explored in survey standardization.

<u>Surplus Production (ASPIC) model</u>

Background. Surplus production models have seen widespread application since they were first derived (Schnute and Richards 2002). Important extensions have been developed to the original formulation that relaxes the equilibrium assumption and provides the option of including covariates into model fitting (Prager 1994). Surplus production models have few data needs and limited assumptions. However, the assumptions required are strong and sufficient temporal contrast must be present in the data if parameter estimates are to be reliable.

Because of their simplicity, surplus production models are often used as supporting analyses in assessments that use more structured models. Indeed the most recent stock assessment for blue crab in the Chesapeake Bay (Miller et al. 2011) used a surplus production model in this vein.

a. Are methods scientifically sound and robust?

The surplus production modeling conducted for the assessment of blue crab in the GOM was conducted within ASPIC (A Surplus Production model Incorporating Covariates – Prager 1994). This is a widely used package, the performance and reliability of which has been thoroughly documented. A substantial array of diagnostics is available for this model that assist in evaluating the degree of fit of the model to the data. The RP concluded that the surplus production methodology employed in the assessment of blue crab in the Chesapeake Bay is scientifically sound and robust.

b. Are assessment models configured properly and used consistent with standard practices?

The application of the ASPIC models in the assessment closely followed the application of the Catch-Multiple Survey Analyses implemented in the assessment. As a result many of the conclusions drawn above regarding the stock definitions, the use of aggregate indices, and the contribution of newly born crabs to the fishery and to the reproductive population within the year in which they are born are relevant to the ASPIC modeling as well.

The structural covariance in estimates of the instrinsic rate of increase (r), and the population carrying capacity (K) has been well described. This covariation in parameter estimates means that the scale of the population estimated in the model can be difficult to validate. For example, some model fits yielded estimates of parameter pairs reflecting a low r and high K, whereas others that fit the data equally well were characterized by high r and low K. There is little information in the model to select between these alternatives. This limits the utility of the ASPIC modeling as a check on the validity of the Catch-Multiple Survey Analyses.

Nothing in the comments above suggests that the models were not configured properly, nor that the ASPIC modeling was conducted contrary to standard practices.

c. Are the methods appropriate for the available data?

The RP concludes that the methods employed in the assessment were appropriate for the available data.

C. ToR 3. Evaluate the assessment findings with respect to the following:

a. Are abundance, exploitation, and biomass estimates reliable, consistent with input data and population biological characteristics, and useful to support status inferences?

Overall, the data inputs and current model configuration of the Catch Survey Model are sufficient to produce robust estimates of the stock status. Although caution should be exercised in using the absolute value for F outside this modeling framework, stock determinations can be made using the base model configuration. The values for F are extremely low in absolute terms, and likely underestimate fishing mortality; however, the relative change in F values over time likely captures changing exploitation patterns.

(i) Are abundance, exploitation and biomass estimates reliable and consistent with input data?
The Catch-Multiple Survey Analysis model estimates were generally consistent with the input data, though there were exceptions as indicated by residuals between abundance indices and base model predictions.

For the Western GOM stock, these indicated that the base model underestimated juvenile abundance in the 1980s through 1995 when abundance was high, and overestimated abundance after 1996 when abundance was low. These patterns in residuals would potentially produce risk-prone estimates of N_{MSY} and F_{MSY}. When the base model was revised and rerun (e.g., with different parameter estimates or starting values), some of the runs reduced the deviations of the model predictions from observed values. Despite these differences between the model runs, the conclusions about stock status and fishing mortality rates necessary to achieve MSY for the Western GOM stock were not qualitatively different among model scenarios, which promoted confidence in the conclusions that the stock is not overfished and overfishing is not occurring.

For the Eastern GOM stock, the model predictions fit the data well.

(ii) Are the estimates consistent with biological characteristics?

In general, the estimates of abundance and exploitation were consistent with biological characteristics. The blue crab is characterized by high fecundity (average of about 2 x 10^6 eggs per brood), a relatively short life span in the GOM (about 3-4 yrs), and a moderate intrinsic rate of increase ($r \approx 0.5$), which allow for relatively high fishing mortality rates. Moreover, the life history features also promote fishery yield dependent on newly-recruited and 1+ year classes, high variability in recruitment, and density dependence, as was observed in the stock-recruit relationship. In addition, the long-term variability or phases observed in the time series of abundance and landings are potentially associated with regime shifts driven by environmental variation, such as river flow, and which modify demographic rates rapidly in this short-lived species.

(iii) Are the estimates useful to support status inferences?

The data inputs and current model configuration of the Catch-Multiple Survey Analysis are sufficient to produce robust estimates of the stock status. Although caution should be exercised in using the absolute value for F outside this modeling framework, stock determinations can be made using the base model configuration or one of its alternative derivations. The values for F are extremely low in absolute terms, and likely underestimate fishing mortality; however, the relative change in F values over time likely captures changes in exploitation patterns.

b and c. Is the stock overfished? Is the stock undergoing overfishing? What information helps you reach this conclusion?

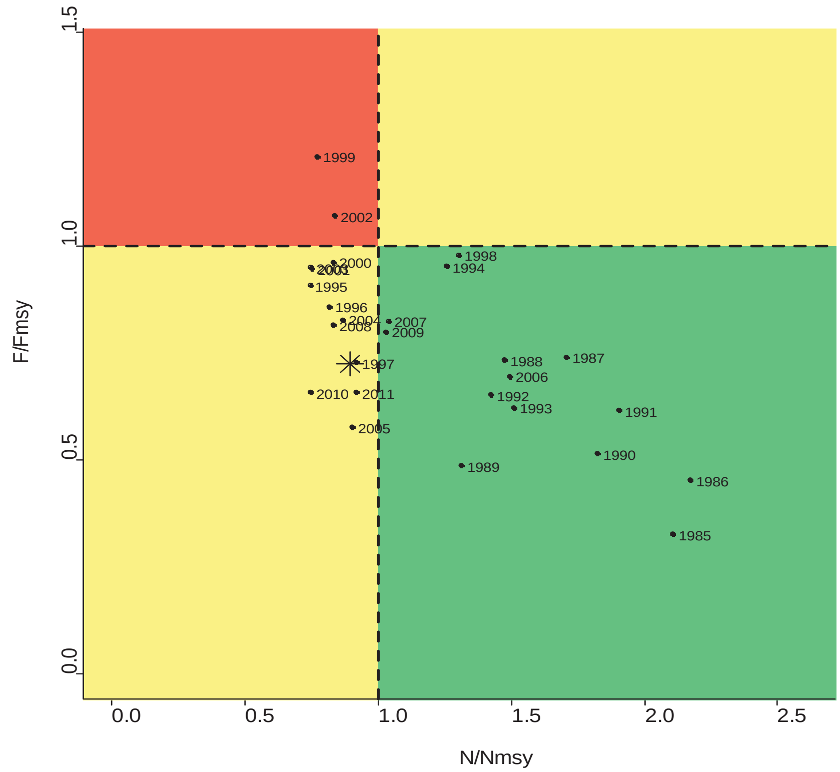
To determine whether or not the blue crab stock is overfished or whether or not overfishing is occurring, we referred to the proposed limits and reference points (F_{Limit}, N_{Limit}, F_{MSY}, N_{MSY}) as outlined in the Assessment report. As stated in the report, these reference points are accepted standards for federally managed stocks in US waters, and were viewed as robust indicators by the RP team. The RP team was also in agreement with the Assessment team that judging the status of the stock with reference only to fishing may not be appropriate for this species because of the probable effects of environmental conditions on the population. Thus, a risk-averse approach to stock management is advised, and further investigations of environmental and hydrodynamic drivers of demographic rates are recommended.

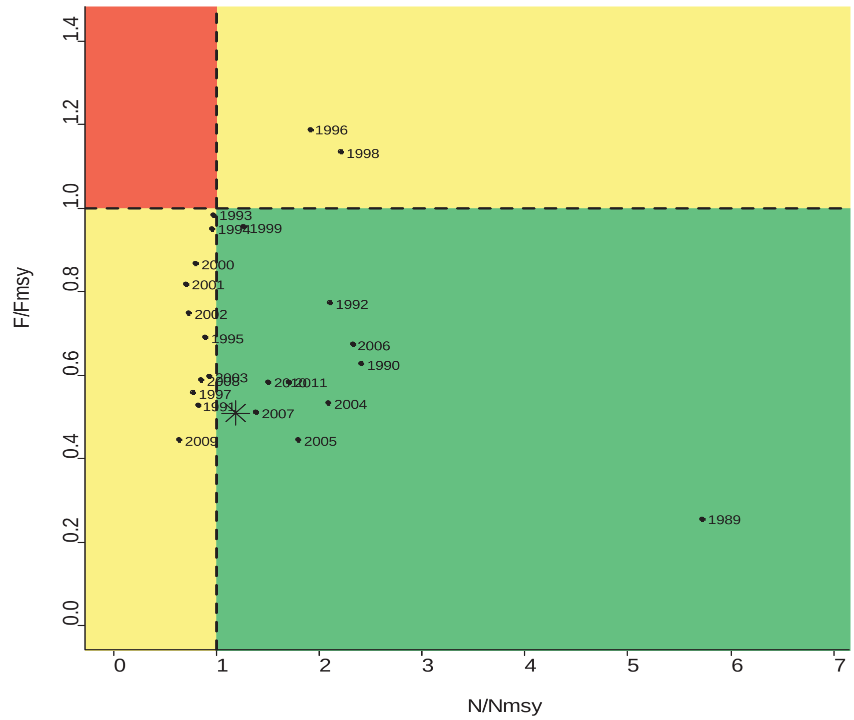
For the Western GOM stock, the terminal year of the assessment indicated an overfished stock (current $N/N_{MSY} < 1.0$), although N_{Limit} was not exceeded in the recent time period. Both the base model and multiple sensitivity runs of the Catch-Multiple Survey Analysis model indicated that the overfished threshold has at times been exceeded in the past and current exploitation rates are approaching or exceeding maximum values (see Figures 8.1 and 8.3 in Assessment report derived from Catch-Multiple Survey Analysis). Furthermore, the stock had $N/N_{MSY} < 1.0$ for most of the last decade. Despite variability in abundance and exploitation estimates from the different Catch-Multiple Survey Analysis model runs, all of the runs resulted in abundance estimates supporting the conclusion that the stock is not overfished at present. However, it appears that abundance has been trending towards the overfished limit since 1996, in contrast to the previous two decades, suggesting that the stock is drawing close to being overfished. In terms of overfishing, the current F/F_{MSY} and F/F_{Limit} were < 1.0 in both the base model fits and the MCMC analyses, suggesting that the stock is currently not undergoing overfishing. However, the stock did experience overfishing in 1999 and 2002.

For the Eastern GOM stock, the stock status determinations for the terminal year of the assessment (2011) did not indicate an overfished stock (N/N_{MSY} and N/N_{Limit} were > 1.0); however, in the most recent decade, the stock was overfished ($N/N_{MSY} < 1.0$) in three years. In terms of overfishing, the most recent F/F_{MSY} and F/F_{Limit} were < 1.0 in both the base model fits and the MCMC analyses, suggesting that the stock is currently not undergoing overfishing, although the stock did experience overfishing in 1996 and 1998.

Results of the ASPIC model runs indicated a similar pattern, although ASPIC models indicate poorer overall conditions of the stocks. For both stocks, the mid to late 1990s were a period during which stock trajectories changed. Following this break point, stock condition approached the overfished limit in many years.

As noted earlier in this report, the assessment team provided the RP with numerous additional sensitivity runs using the Catch-Multiple Survey Analysis model and the ASPIC model. In addition to the original runs with Eastern and Western GOM stocks, the Assessment team conducted supplemental runs assuming either (i) a single Gulf-wide stock of blue crab in the Gulf or (ii) a division of the Western GOM stock into a central and Western component. Single state models were also presented in the assessment document. In general the results of all of these models did not provide evidence against the basic conclusion that the blue crab stock in the GOM is not overfished and overfishing is not occurring. The variability and sporadic inconsistency in the results for the different stock scenarios (Eastern and Western GOM stocks, Gulf-wide stock, etc.) also led the team to conclude that determination of the actual stock structure is a critical research need. This includes not only stock structure of blue crab subpopulations in US waters, but also the role of subpopulations along the Mexican coast.





Figures 8.1 and 8.3 from the Stock Assessment Report. Stock status for the Western GOM stock (left panel) and Eastern GOM stock (right panel) of GOM blue crabs.

Finally, the control rule plots (above) were also consistent with the general conclusion that overfishing is not occurring and that the stock is not overfished, but also with the conclusion that the stock is nearing overfishing and being overfished such that a risk-averse management approach is warranted.

d. Is there an informative stock recruitment relationship? Is the stock recruitment curve reliable and useful for evaluation of productivity and future stock conditions?

There is an informative stock recruit relationship. Although the data points on the ascending limb of the curve are sparse, compared to many other managed fisheries in the GOM, the relationship is well defined. The stock recruit relationship may, however, have to be reformulated based on (i) investigations of stock structure throughout the GOM, (ii) determination of the role of environmental drivers upon the stock recruit relationship, and (iii) assessment of the most reliable surveys to estimate spawning stock and recruitment throughout the Gulf.

5. Are the quantitative estimates of the status determination criteria for this stock reliable? If not, are there other indicators that may be used to inform managers about stock trends and conditions?

The current stock determinations are reliable based on sensitivity runs and uncertainty analyses.

D. ToR 4. Consider how uncertainties in the assessment, and their potential consequences, are addressed.

Uncertainties in parameter estimates, data sources, and model configurations were presented for both the Catch-Survey Analysis (CSA) and the surplus production (ASPIC) model. Several consequences of these uncertainties with regard to stock magnitude and status were not explicitly stated in the report, but were discussed among participants at the RW and are described in detail below. Overall, the assessment team did an outstanding job using modern statistical methods to characterize parameters estimate uncertainty and providing the RP with sensitivity analyses upon request.

Catch-Survey Analysis

a. Comment on the degree to which methods used to evaluate uncertainty reflect and capture the significant sources of uncertainty in the population, data sources, and assessment methods

Uncertainty in CSA parameter estimates was appropriately addressed through the generation of asymptotic standard errors for each estimated parameter and MCMC posterior distributions for each estimated parameter and reference point (MSY, F_{MSY}, N_{MSY}, F_{Limit}, N_{Limit}). Asymptotic standard errors produced tight confidence intervals (as is typical for such models) and likely did not capture the true uncertainty in parameter estimates. To obtain a more realistic set of confidence intervals, the analysts also generated MCMC posterior distributions for each parameter and reference point calculation. MCMC analyses indicated there was no evidence that the base model had settled at a local minimum.

In addition, a retrospective analysis was conducted for both the Western and Eastern GOM stocks by peeling away the terminal years of 2011 to 2007 and plotting the resulting change in fishing mortality and adult abundance estimates. Retrospective pattern for both Western and Eastern GOM stocks was minimal.

The impact of using alternative input data sources and model configurations on model fit, reference point calculations, and stock status was assessed using sensitivity analyses. Prior to the RW, 24 sensitivity runs were conducted for the Western GOM stock and 16 sensitivity runs were conducted for the Eastern GOM stock as described in Section 6.2.1.6 of the assessment report. An additional 32 alternative runs were conducted at the request of the RP at the RW.

Western Stock										
	Run #	Run	negLL	MSY	FMSY	NMSY	F/FLim	N/NLim	Overfishing	Overfishe
	bc-00-west	**Base**	179.33	164.35	1.70	78.54	0.72	1.79	NO	NO
	bc-RW1-west	Juvenile IOA 30-50mm	174.004	164.067	1.69	78.9595	0.724962	1.79696	NO	NO
	bc-RW2-west	Juvenile IOA 50-80mm	146.532	163.592	1.73	76.5791	0.7224	1.83728	NO	NO
	bc-RW3-west	Blocking q (FIM)	94.9632	193.926	2.7	51.6506	0.398405	3.1786	NO	NO
	bc-RW4-west	Linear q	118.024	173.028	2.02	67.136	0.541191	2.39583	NO	NO
	bc-RW5-west	Constant IOA CV=.2	75.5436	163.697	1.6	84.0116	0.786172	1.71459	NO	NO
	bc-RW6-west	Constant IOA CV=.4	83.9735	161.251	1.5	89.1909	0.853524	1.57962	NO	NO
	bc-RW7-west	Multiple IOAs (landing weights)	174.283	176.622	2.09	65.6908	0.531554	2.49341	NO	NO
	bc-RW8-west	Multiple IOAs (habitat weights)	229.37	168.703	1.86	72.4051	0.634418	2.12721		
	bc-RW9-west	Multiple IOAs, block q	133.393	188.622	2.22	65.0164	0.386355	3.32896	NO	NO
	bc-RW10-west	Hoenig 4.22/maxAge	170.957	179.526	1.4	81.4798	0.649845	1.90869	NO	NO
	bc-RW11-west	Landings CV=.1	159.569	164.051	1.74	76.2697	0.683829	1.68138	NO	NO
	bc-RW12-west	Landings CV=.2	114.113	167.535	1.6	85.9813	0.623171	1.47069	NO	NO
	bc-RW13-west	Z Prior CV=.2	180.687	163.949	1.76	75.1918	0.7315	1.7758	NO	NO
	bc-RW14-west	Z Prior CV=.4	181.319	163.446	1.84	71.0704	0.74217	1.75661	NO	NO
All w/ 4.22/maxAge	bc-RW15-west	base model (1 index)	170.957	179.526	1.4	81.4798	0.649845	1.90869	NO	NO
Z Prior=2.06	bc-RWFinal2-west	Multipe IOAs (equal weights)	202.336	173.422	1.24	91.0784	0.75901	1.7073	NO	NO
	bc-RWFinal3-west	Multiple IOAs (landings)	177.59	193.792	1.84	62.4574	0.491688	2.59114	NO	NO
	bc-RWFinal4-west	Multiple IOAs (habitat)	228.304	183.601	1.59	71.2371	0.583232	2.21963	NO	NO
	bc-RWFinal5-west	Multiple IOAs (equal), block q	167.414	217.671	2.25	53.6659	0.382185	3.21191	NO	NO
	bc-RWFinal6-west	Multiple IOAs (landings), block q	140.069	207.116	1.94	62.303	0.367237	3.38918	NO	NO
	bc-RWFinal7-west	Multiple IOAs (habitat), block q	176.306	212.376	2.19	54.3316	0.363318	3.45823	NO	NO
Entire Gulf Stock										
	Run #	Run	negLL	MSY	FMSY	NMSY	F/FLim	N/NLim	Overfishing	Overfishe
	bc-Rev1-all	Multiple IOAs	203.789	199.608	2.07	75.1353	0.538092	2.44141	NO	NO
All w/ 4.22/maxAge	bc-RWFinal2-east	With Streamflow on M	52.7796	35.9639	2.69	8.02099	0.356028	1.80068	NO	NO
Z Prior=3.11	bc-RWFinal3-east	base model with effort	138.728	23.4395	2.87	4.75959	0.511855	2.42383	NO	NO
East Stock										
	Run #	Run	negLL	MSY	FMSY	NMSY	F/FLim	N/NLim		
	bc-00-east	**Base**	140.21	23.16	3.48	4.75	0.51	2.37	NO	NO
	bc-RW1-east	Z Prior CV=.2	139.725	22.5484	3.57	4.44787	0.562167	2.1361	NO	NO
	bc-RW2-east	Z Prior CV=.4	140.17	22.5024	3.58	4.41981	0.568549	2.1084	NO	NO
M=4.22/maxAge	bc-RWFinal1-gulf	Multipe IOAs (equal weights)	268.502	193.735	1.84	66.9829	0.735088	1.71546	NO	NO
Z=2.58	bc-RWFinal2-gulf	Multiple IOAs (landings)	202.181	206.37	2.28	53.8044	0.558648	2.39618	NO	NO
	bc-RWFinal3-gulf	Multiple IOAs (habitat)	262.469	199.611	2.13	57.0344	0.619455	2.05288	NO	NO
	bc-RWFinal4-gulf	Multiple IOAs (equal), block q	227.868	202.64	2.33	51.2891	0.56043	2.33276	NO	NO
	bc-RWFinal5-gulf	Multiple IOAs (landings), block q	172.55	218.658	2.5	50.1874	0.428563	3.13661	NO	NO
	bc-RWFinal6-gulf	Multiple IOAs (habitat), block q	228.435	210.004	2.52	47.663	0.495539	2.61296	NO	NO

Sensitivity runs conducted at the RW consisted of one or more of the following changes to inputs or model configuration:

1. Alternative size classifications for the generation of juvenile indices
2. Alternative assumptions about changes over time in survey catchability
3. Application of larger CVs for fishery-independent data sources, landings data, and the Z prior
4. Use of multiple surveys (all individual state surveys) in place of one index that combined all state data sources
5. Alternative calculation of M using 4.22/max age
6. Combination of Western and Eastern data sources into one GOM model
7. Use of lambda weighting of state indices using landings or habitat area percentages by state.

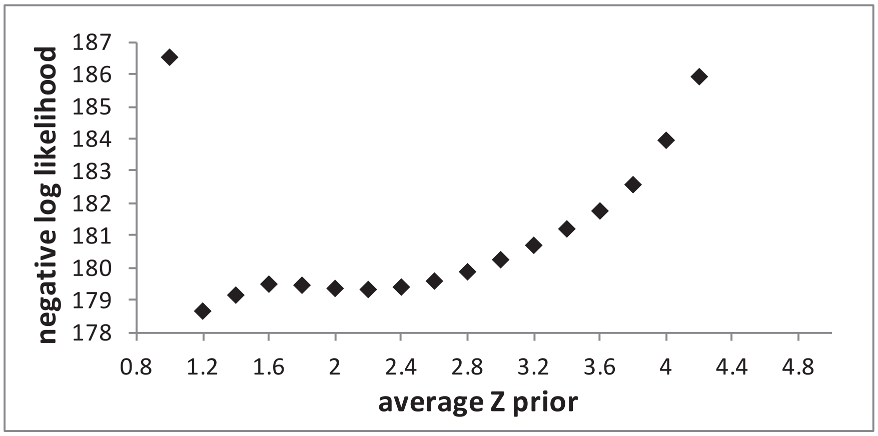
The RP encourages the assessment team to explore and refine model performance during future assessments by exploration of these and other alternative model configurations. The RP noted, however, that the overwhelming majority of alternative CSA model runs demonstrated that stock status was insensitive to available input data and model configurations. **With few exceptions, sensitivity analyses indicated that the status of the GOM blue crab stock is not overfished and overfishing is not occurring in the terminal year of the assessment.**

The panel cautioned that individual states exhibited different trends in landings and relative abundance indices (Table 7.5) which suggests that sub-stock dynamics may differ from regional or Gulf-wide trends. The extent to which an individual state's stock dynamics are affected by larval transport, migration, and fisheries in other Gulf States or countries is unknown at this time and should be a high priority for future blue crab research.

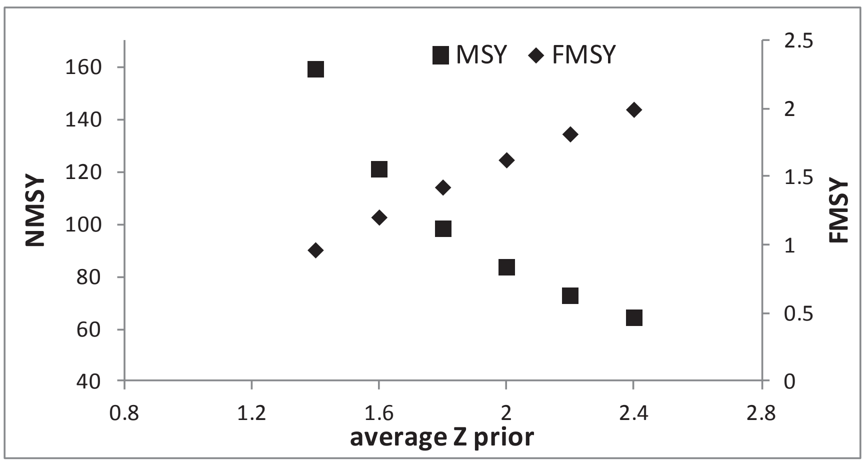
b. Ensure that the implications of uncertainty in technical conclusions are clearly stated.

One area of uncertainty not discussed at length in the assessment was the effect of the average Z prior on model estimates. Acceptable performance of the CSA relied on the use of an informative prior for the average total mortality rate (Z) on adult crabs. This prior helped limit initial abundance, recruitment, and fishing mortality to a set of realistic values. The average value for Z was estimated from a length-based catch curve analysis of fishery independent size frequency data using growth parameters estimated from an individual-based molt-process model. A small error value (CV = 0.05) applied to the average Z prior was required to produce the biologically reasonable results presented in this assessment. The assessment team indicated that larger error values resulted in the model hitting up against the maximum fishing mortality bounds.

As mentioned previously in this report, the assessment team's approach was appropriate and defensible. However, the RP stressed the importance of communicating to fishery managers that the magnitude of certain CSA model reference points (e.g., F_{MSY} and N_{MSY}) are sensitive to the assumptions made regarding the average Z prior. To demonstrate the consequences of using such an informative prior, a likelihood profile was produced displaying negative log likelihood values for total model fit across a range of average Z prior values for the base Western GOM stock model. The best fit (i.e., lowest negative log likelihoods) versions of the base model that converged without hitting parameter bounds used average Z prior values ranging from 1.4 to 2.4.



Thus, a wide range of values for the average Z prior produced similar model fits, indicating that the magnitude of N_{MSY} and F_{MSY} could span a wide range of values as well and thus the magnitude of these benchmarks was highly uncertain.



Given the ultimate status of the stock relative to these benchmarks did not change with a change in average Z prior, the RP believes that stock status is not highly uncertain. **However, uncertainty in the average Z prior would need to be addressed before managers would be able to consider applying management measures that utilized absolute estimates of stock size or fishing mortality (e.g., catch quotas, population abundance targets).**

Surplus Production (ASPIC) model

a. Comment on the degree to which methods used to evaluate uncertainty reflect and capture the significant sources of uncertainty in the population, data sources, and assessment methods.

Uncertainty in estimated parameters and reference points generated by the surplus production model was presented as confidence intervals derived from the non-parametric bootstrap procedure in ASPIC. Resulting 90% confidence intervals were extremely wide (more so for the

Western than Eastern GOM stock). The RP suggests caution when interpreting point estimates from these models.

In addition, a retrospective analysis was conducted for both the Western and Eastern GOM stocks by peeling away the terminal years of 2011 to 2007 and plotting the resulting change in fishing mortality and stock biomass. Retrospective runs significantly changed the magnitude of stock biomass and fishing mortality for the Eastern GOM stock (less so for the Western GOM stock).

Model sensitivity to data inputs and stock definition was also tested with the generation of 8 alternative runs of the Western GOM stock and 4 alternative runs of the Eastern GOM stock model as described in detail in section 6.2.2. An additional 12 runs were performed at the RW, a subset of which are shown below.

Model Name	Fmsy	MSY	F/Fmsy	B/Bmsy	BMSY	K (lbs)	r	Start Landings TS	End Landings TS	Model Shape	Indices
sp-01	0.24	60,943,214	1.05	0.92	250,318,630	500,637,260	0.487	1950	2011	LOGISTIC	Western Combined INDEX
sp-21	0.19	58,519,676	1.3	0.76	309,260,570	618,521,140	0.378	1950	2011	LOGISTIC	Western Combined INDEX Rec0-80
sp-22	0.16	56,641,456	1.58	0.64	348,081,910	696,163,830	0.325	1950	2011	LOGISTIC	Western Combined INDEX Rec30-80
sp-23	0.16	56,406,015	1.65	0.61	350,574,570	701,149,130	0.322	1950	2011	LOGISTIC	Western Combined INDEX Rec50-80
sp-24	0.03	100,909,400	0.28	2.05	3,186,208,900	6,372,417,700	0.063	1985	2011	LOGISTIC	Western Combined INDEX Rec0-80
sp-25	0.02	65,659,884	0.37	2.4	3,130,887,300	6,261,774,700	0.042	1985	2011	LOGISTIC	Western Combined INDEX Rec30-80
sp-26	0.02	74,069,858	0.34	2.3	3,087,478,700	6,174,957,500	0.048	1985	2011	LOGISTIC	Western Combined INDEX Rec50-80

These runs consisted of one or more of the following changes to inputs or model configuration:

1. use of multiple and alternative indices, including juvenile indices of abundance
2. truncation of the time series to match that of the CSA (1985+).

Biomass, fishing mortality, intrinsic growth rate, and resulting stock status determinations varied widely among sensitivity runs for both stocks, indicating ASPIC is highly sensitive to the indices and the length of landings time series used to inform the model. Similar to the CSA, the Western GOM stock ASPIC model also had difficulty fitting the indices of abundance and exhibited residual pattern. However, the ASPIC model often suffered from several additional problems, including extremely wide confidence intervals, unrealistically low values for F_{MSY}, biologically counterintuitive (low) values for intrinsic growth rate, and significant retrospective pattern. This intrinsic growth rate estimates, in particular, were counterintuitive given published research on GOM blue crab which tends to be highly productive, short-lived, and able to withstand at least moderate levels of fishing pressure.

The panel encourages the assessment team to continue refining this model for comparison with stage- or length-based models in future assessments. Exploring the option of surplus production modeling within in a Bayesian framework using informative priors (if defensible ones can be developed) may help constrain the model in a more reasonable parameter space so that it can play a stronger role in the assessment.

b. Ensure that the implications of uncertainty in technical conclusions are clearly stated.

Although two models were used in this assessment, an overarching discussion of the differences between their results and the implications of those differences was not provided in the report. A comparison of model performance between the preferred CSA model and the supplementary ASPIC model provided valuable information about the potential impact of time series length in this assessment. The two models often yielded conflicting views about the status of the stock. Unlike the CSA, base ASPIC model runs indicated that overfishing was occurring in the Western GOM stock and that the Eastern GOM stock was overfished and overfishing was occurring. One reason for this discrepancy may be that the ASPIC runs utilized the full landings time series (1950 to 2011). Therefore, the ASPIC model was given information that the stock has the potential to be far more productive than it currently is. If that is true, the CSA, which used a shorter landings time series, is not being given enough information about the historical productive capacity of the stock. This was confirmed by sensitivity runs of the ASPIC model using a shorter time series (1985-2011); these runs produced stock status determinations for the Western GOM stock similar to the CSA (not overfished and overfishing was not occurring). Given the shorter time period used in the CSA, there is a chance that the CSA results may be overly optimistic about current stock conditions. However, there appears to be growing evidence that the stock may have experienced an environmental regime shift which could make comparison of the present stock condition with that of the 1950s inappropriate. Analysts should carefully consider whether the use of a longer landings time series is appropriate in future assessments.

Ideally, abundance indices with longer time series would be developed to provide a fisheries-independent view of stock trends over time. In the absence of such rare data sets, it may be a worthwhile exercise to compare landings data in years where data collection systems overlapped (e.g., general canvass vs. trip ticket systems) to determine if it is appropriate to combine historical landings from the 50s-70s with current landings data.

E. ToR 5. Research Recommendations

The RP agrees with the research recommendation in the assessment report. Further, we encourage research under several themes:

1. Stock identity; examine the biological and physical data available to determine if the GOM should be managed as a single or mixed stock. Identify future efforts that may resolve related questions such as a large scale tagging study of adults and biophysical transport modeling of juveniles.
2. Development of a Gulf-wide fishery independent index of spawning stock abundance.
3. Monitor effort in the fishery.
4. Determine the role of environmental drivers upon spawning stock and recruitment.

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