The 2014 stock assessment update for striped mullet, *Mugil cephalus*, in Florida

By

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Executive Summary

- Total statewide landings for striped mullet in Florida were 12,039,430 lb in 2013, with about 80% made by the commercial fishery and on the west coast. Since the last assessment in 2008, total landings on the west coast have been stable around an average of 9,896,539 lb. From 1930 to 1993 west coast landings averaged 26,715,585 lb/yr but due to the net ban they fell below 6,613,860 lb in 1995 and have only increased slightly to 10,465,331 lb in 2013. On the east coast since 2008, total landings have been stable around an average of 2,112,026 lb. Prior to the net ban landings on the east coast averaged 3,816,197 lb/yr, then fell to 1,895,973 lb in 1995 and have remained at that level ever since.

- Since 2008, the percentage of total landings occurring during roe season (September-December on the east coast and October-January on the west coast) has increased on the east coast from 66.2% to 76.8% in 2013. On the west coast the percentage has remained relatively stable since 2008 around an average of 70.9%.

- Fisheries independent surveys of juvenile striped mullet indicate a strong year class in 2010 on the east coast, and 2010-2011 on the west coast.

- The data used in the stock assessment models were current through 2013. We applied five modeling approaches ranging from a “data poor” method (i.e., depletion-based stock reduction analysis) to more complex approaches (i.e., stochastic stock reduction analysis, surplus production model, a two-age delay-difference model, and a fully age- and size-structured stock synthesis model). Models were developed separately for the east and west coasts.

- All models indicate that striped mullet on both coasts are currently neither overfished ($B_{current}/B_{SPR35\%} > 1$ or $B_{current}/B_{msy} > 1$) nor undergoing overfishing ($F_{current}/F_{SPR35\%} < 1$ or $F_{current}/F_{msy} < 1$). The delay-difference and stock synthesis models both predicted the current SPR to be above the management target of $SPR_{35\%}$.

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1 Introduction

We developed five different stock assessment models (i.e., depletion-based stock reduction analysis, stochastic stock reduction analysis, non-equilibrium surplus production, delay-difference, and stock synthesis) each for the east and west coasts of Florida. The depletion-based stock reduction analysis (DBSRA) method relies solely on removals data. The stochastic stock reduction (SSRA) and surplus production (ASPIC) models both include landings as well as indices of abundance and catch rate data. The delay-difference model (DD) is a simple age structured model that includes two ages, recruits and adults. This move towards non-age structured models is because the fishery-independent monitoring (FIM) trammel-net survey, which provided the age samples, was terminated and the spatial and temporal coverage from fishery-dependent sampling was inadequate. Lastly, we constructed a stock synthesis model that includes historical removals, indices of abundance, length composition, and age composition data when available.

1.1 Life History

Striped mullet are distributed worldwide in most coastal waters and estuaries of tropical and subtropical seas. They have a loosely defined catadromous life cycle, i.e., they reside in fresh waters but spawn in the sea. Beginning in the early fall, large schools of mullet aggregate in preparation for a migration from fresh and estuarine waters to offshore spawning grounds. Environmental cues such as the occurrence of cold fronts and decreases in water temperature and barometric pressure are thought to initiate aggregation and subsequent migration (Mahmoudi 2000). Spawning occurs in deep, offshore waters from mid-October through late January, with peak spawning occurring in November and December (Ditty and Shaw 1996). A single mullet can produce 45,000 to >4 million eggs, depending on the female's length (Greely et al. 1987). Juveniles actively recruit to estuaries in Florida and ascend toward freshwater rivers. Striped mullet grow to about 6.1–7.3 inches fork length (FL) in one year and can reach 9–13 years of age (Mahmoudi 1991). Typically they get no larger than about 20 inches total length (TL) (Leard *et al.* 1995). Females mature at 2–3 years old when about 11.5 inches FL (Leard *et al.* 1995).

In general, mullet do not move or migrate extensively, and the greatest distance moved occurs during fall and winter spawning migration (Broadhead and Mefford 1956). Tagging experiments during the spawning season in Tampa Bay and Charlotte Harbor showed that the majority of adults return to the same system in which they were tagged (Mahmoudi 1990, 1991). The lack of long-range movement suggests that several sub-groups may exist. Based on meristic data, de Sylva *et al*. (1956) hypothesized that distinct northern and southern stocks of mullet exist along the east and west coasts of Florida. However, Campton and Mahmoudi (1991) found no genetic basis for the separation of stocks, suggesting that the morphometric differences found may be based on ecophenotypic characters. Despite the genetic homogeneity, there are regional morphological differences influenced by environmental and habitat conditions. In this report, assessments were conducted separately for each coast of Florida.

1.2 Regulations

Since 1989 when Striped Mullet was designated as restricted, the species has been regulated by a combination of size limits, bag and trip limits, gear restrictions, and weekend closures. Prior to the net ban there were numerous county and season specific regulations on gear types and restricted areas. Below is an abbreviated version of the more important regulations affecting Striped Mullet. A complete version can be found at myfwc.com/fishing/saltwater/recreational/history/.

1989 CH 46-39, F.A.C. (Effective October 19, 1989)

- Designates mullet as a "restricted species"
- Establishes a daily recreational bag limit of 50 fish per person
- Creates a statewide commercial minimum size limit of 11 inches fork length and retains the 10% undersized allowance, and all commercially harvested mullet must be landed in a whole condition
- Prohibits harvest of commercial quantities of black mullet from sunrise Saturday to sunset Sunday between October 1 and January 15
- County and season specific minimum mesh sizes

1993 CH 46-39, F.A.C. (Effective November 16, 1993)

- Prohibits the commercial harvest of mullet from noon Friday through noon Monday each week from July through January
- Prohibits all harvest of mullet during a ten day period beginning at 12 noon on the fourth Friday of December each year
- Establishes a 500 pound daily commercial trip limit for mullet from July through September each year

1996 Emergency Rule, CH 46ER96-3, F.A.C. (Effective July 1 - September 28, 1996)

- Prohibits the simultaneous possession of any species of mullet in excess of the recreational bag limit (50 fish) and any gill or entangling net
- Eliminates the July through September 500 pounds commercial daily vessel harvest limit for mullet

1997 CH 46-39, F.A.C. (Effective March 3, 1997)

- Establishes the only allowable gear that may be used to harvest mullet as cast nets with a radius no greater than12 feet/7 inches; beach or haul seines; certain non-bottom fishing skimmer nets; hook and line gear; and gigs
- Prohibits the simultaneous possession of any species of mullet in excess of the daily recreational bag limit (50 fish) and any gill or entangling net, including on separate vessels or vehicles operating together
- Eliminates the July through September 500 pounds commercial daily vessel harvest limit for mullet

2000 CH 68B-39, F.A.C. (Effective March 30, 2000)

- Increases the vessel limit for black mullet from 50 fish to 100 fish daily if two or more licensed persons are aboard during the period Feb. 1 through Aug. 31 each year

2001 CH 68B-39, F.A.C. (Effective October 7, 2001)

- Establishes the weekend closure to commercial mullet fishing as 12:01 a.m. Saturday until 12:01 a.m. Monday.

2008 CH 68B-39, F.A.C. (Effective July 13, 2008)

- Allows the commercial harvest of striped mullet on weekends.

1.3 Stock Assessments History

The most recent stock assessment for striped mullet in Florida waters was completed in 2008. In that assessment, a non-equilibrium surplus production model (ASPIC), statistical forward-projecting age structured model (ASAP), and statistical forward projecting length-based model (SCALE) were used. The ASPIC model indicated that F/F_{MSY} was consistently below 1 and B/B_{MSY} above 1 after the net ban in all regions. The ASAP and SCALE models showed that fishing mortality rates dropped sharply after the 1995 net ban and that fishing mortality in recent years (2005-2007) was below the $F_{35\%}$ and $F_{40\%}$ reference points. Spawning potential ratio was above the 35% SPR target in all regions. The 2005 stock assessment used ASPIC and ASAP and also found that the stock was not overfished or undergoing overfishing as of 2004.

2 Fishery-Dependent Data Sources

Analyses of fishery-dependent data were based on commercial landings reports (1978-1984) from the NMFS general canvass database, commercial landings and trip information (1985-2013) from the FWC-FWRI's Marine Fisheries Information System (Trip ticket) database, biostatistical information (e.g., lengths) from the Trip Information Program (TIP, 1991-2013) database, and recreational landings estimates and length information from the NMFS-MRFSS (1981-2003) and NMFS-MRIP (2004-2013) databases. Additionally, commercial landings (1870-1977) reports were compiled from various sources including the U.S. Commissioner of Fisheries and Florida State Board of Conservation.

2.1 Commercial Fishery

The commercial fishery contributed to 82% of the total striped mullet landings during 2004-2013 in Florida (Table 1). In 2013, commercial landings of striped mullet totaled about 9.9 million pounds (86% of the 2013 total landings). Landings were greater on the gulf coast, where about 85% of the statewide landings were made during 2004-2013. The majority of coastal counties reported commercial landings of striped mullet during 2013. Eighty percent of the striped mullet landings on the gulf coast of Florida came from the central and southwest portions of the state near Tampa Bay and Charlotte Harbor. Landings data by county showed no noticeable regional shift in landings after the net ban or in more recent years. The roe season (spawning season: September-December on the east coast and October-January on the west coast) landings during 2004-2013 accounted for 66% and 68% of the total annual landings on the east and west coasts, respectively. Major changes have occurred in the mullet fishery with the fishing gears and fishing practices after the net ban. Types of fishing gears used in fishery shifted from large entangling nets (i.e., gill nets and trammel nets

ranging from 600 to 1,200 yards in length and from 2-1/2 to 4-1/4 inches in stretched-mesh size) and large haul seines (1,000 to 1,200 yards in length) to cast nets and small seines (limited to 500 square feet in area and a maximum of 2 inches in stretched-mesh size). Since the net ban, mullet production is impacted by other factors, i.e., market demand and dollar value, changes in number of participants, boat and engine size, and fishing practices.

2.1.1 Commercial Landings Trends

The first recorded commercial catch of striped mullet was in 1879, when 3.5 million pounds of striped mullet were landed in Florida (U.S. Commission of Fisheries report 1880). Landings gradually increased to about 30 million pounds from 1880 to 1900 and fluctuated at that level from 1900 to 1940 (Figure 1). Landings reached a historical peak at about 50 million pounds during 1941-1942 when the demand for fish protein sharply increased during World War II. Mullet production dropped back to the historical level of 30 million pounds during 1945-1966. Mullet landings further dropped to a new production level during 1967-1991, averaging about 25 million pounds annually. Landings declined during 1992-1994 to an annual average of 18 million pounds, primarily due to the regulations that were adopted in 1992. Striped mullet harvest was severely restricted by Florida's 1995 constitutional amendment eliminating the use of entangling nets in Florida waters. This caused a rapid decline in landings, especially on the gulf coast, in 1995. The total landings slowly increased from 1995 to 2002 reaching an annual average of about 8.1 million pounds. The annual landings in more recent years (2004-2013) averaged about 9.1 million lbs, a 64% reduction in landings if compared to the historical (1967-1990) annual average landings of 25 million lbs.

Commercial landings for striped mullet are primarily influenced by changes in market demand, environmental and ecological conditions, gear compositions, and regulations. The regulatory measures adopted for the management of the mullet fishery in Florida can be found at myfwc.com/fishing/saltwater/recreational/history/. Important regulations included: seasonal closures in the early 1950s; minimum-size restrictions in 1989; gear restrictions and time closures in the early 1990s; and finally the elimination of the use of entangling nets (net ban) that became effective in July 1995.

Commercial landings of striped mullet and fishing effort dropped sharply following the 1995 net ban on both coasts (Figure 2a). Mullet landings declined from an average of 21.3 million lbs annually during the pre net ban period (1978-1994) to an average of 7.4 million lbs annually after the net ban (1995-2013) on the west coast (a 65% drop in landings). East coast landings declined from an average of 2.4 million lbs annually during 1978-1994 to an average of 1.3 million lbs annually during 1995-2013 (a 45% drop in landings). Similarly, the average number of fishing trips dropped by 62% and 35% annually after the net ban in the west and east coast regions, respectively (Figure 2b).

The average roe season landings declined from 12.3 million pounds annually during the pre net ban period (1978-1994) to 5.0 million pounds annually after the net ban (1995-2013) on the west coast (a 59% drop), and from 1.4 million pounds annually during the pre net ban period to 0.9 million pounds annually after the net ban on the east coast (a 37% drop) (Figure 3a). The average non-roe season landings declined

from 9.1 million pounds annually during the pre net ban period (1978-1994) to 2.4 million pounds annually after the net ban (1995-2013) on the west coast (a 74% drop), and from 1.0 million pounds annually during the pre net ban period to 0.5 million pounds annually after the net ban on the east coast (a 55% drop) (

Figure 3b). Since 1978, the proportion of striped mullet caught in the roe season has generally increased on both coasts (Figure 4).

The length-frequency data collected from the commercial fishery appear to indicate shifts toward larger fish on the east and west coasts after the net ban, with a much stronger shift on the west coast (Figure 5). It is not clear that the shift toward the larger fish on the west coast reflected the potential changes in the market condition and or the population age structure.

2.1.2 Commercial CPUE

Trends in commercial catch rates for mullet are strongly influenced by changes in quotas, gear restrictions, time closures, and by the net ban. Standardized commercial catch rates (pounds/trip) were calculated for the pre- and post-net ban periods using a general linear model that adjusts trip catches for year, month, county, and trip duration in days. Commercial catch rates from both coasts showed a gradual, long-term increase since 1995, which may reflect the increase in mullet abundance (Figure 6). The catch rates were generally stable on the east coast and generally declined on the west coast during the pre net ban period during 1984-1994.

2.2 Recreational Fishery

Recreational fishermen use cast nets almost exclusively to harvest striped mullet for food and bait. Both MRFSS and MRIP data were used to derive a time series of recreational landings of striped mullet, where the early MRFSS data were calibrated to the overlapping years of MRFSS/MRIP data following the procedures outlined by the MRFSS/MRIP Calibration Ad Hoc Working Group (Salt *et al*. 2012). The statewide recreational landings of striped mullet were relatively small (around 18% of the total statewide striped mullet landings during 2004-2013) and fluctuated from year to year. The MRFSS/MRIP adjusted estimated annual landings on Florida's east coast ranged from 10 thousand pounds in 1987 to 2.5 million pounds in 1992; and from 0.5 million pounds in 1995 to 4.5 million pounds in 1986 on Florida's west coast (Figure 7). The annual recreational harvests in more recent years (2004-2013, Figure 8) have averaged 973,268 fish (727,323 pounds) on the east coast and 880,779 fish (1,296,101 pounds) on the west coast.

Recreational catch estimates are imprecise for striped mullet. Adjusted proportional standard errors (PSE) calculated for MRFSS/MRIP landings estimates from 1981-2013 average around 30%. Few length measurements are taken in the fishery; yearly total statewide sample sizes ranged from 21-244 individual lengths from 1981-2013. Available data showed that median fork varied between 200 to 390 mm on the east coast and from 300 to 380 mm on the west coast (Figure 9). Median fork length showed a slight increasing trend on the east coast over the time series, while the west coast remained fairly stable throughout the time series.

3 Fishery-Independent Survey Data

The fishery-independent data for striped mullet includes the coastal juvenile (YOY) abundance indices. The juvenile survey is conducted by the Fish and Wildlife Research Institute's Fisheries Independent Monitoring (FIM) program in major estuaries along the east and west coasts of Florida. The juvenile sampling is conducted monthly via a 70-ft seine. Catch rates for YOY striped mullet were standardized using a general linear model (GLM) analyzing Florida's east (1997-2013) and west (1995-2013) coasts (Figure 10). For each region, the full GLM models adjusted the number of YOY fish per set for bay, gear, year, month, salinity, temperature, depth, bottom vegetation, and shore type; however, not all of these terms were significant in each coast; therefore, a reduced model with just the significant terms was used to estimate the adjusted number of YOY striped mullet per set for each year.

The FIM surveys of adult striped mullet included the monthly haul seine (183 m) sampling in major estuaries on the east and west coasts of Florida and the trammel net survey (September-February) in Tampa Bay-Charlotte Harbor region. Few adult striped mullet were captured in the 183 m haul seine because a significant proportion of mullet jump over the net. The small and sporadic catches of striped mullet from this survey precluded the generation of realistic estimates of adult catch rates that could be used to examine trends in relative abundance. The directed trammel-net survey has generated valuable information on size composition since 1993 and age composition since 1995. Inconsistencies associated with searching and capturing methods and schooling behavior prevented us from using this survey to develop relative abundance estimates. The size-frequency distributions from the trammel-net survey indicated strong recruitment pulses in 1998 and 2006 in Tampa Bay and in 1996, 2003-2005, and 2011-2012 in Charlotte Harbor (Figure 11).

4 Stock Assessments Models

A suite of analytical models of various forms were used to assess the status of striped mullet in Florida. The assessment models varied from data poor methods (depletion-based stock reduction analysis) to more complex models such as a non-equilibrium surplus production model (ASPIC), delay difference, stochastic stock reduction analysis, and stock synthesis.

4.1 Depletion Based Stock Reduction Analysis (DBSRA)

4.1.1 Methods

The DBSRA is a catch-based model developed by Dick and MacCall (2011). The DBSRA is primarily used in "data poor" stock assessments. The input data are limited to time series of harvest, estimates of age at maturity, an initial value of unfished biomass (K), and prior distributions of four leading parameters: natural mortality rate (M), the ratio of F_{MSY} to M (F_{MSY}/M), the relative biomass at maximum latent productivity ($B_{mnpl} = B_{MSY}/K$), and assumed current depletion level ($B_{current}/K$). The DBSRA incorporates the uncertainty associated with leading parameters using Monte Carlo simulation routine. This is accomplished by randomly drawing many sets of plausible alternatives from respective prior probability distributions (i.e., lognormal, beta, uniform**)** of the four leading parameters**.** For the model to track the historical catch, the stocks must have

had certain productivity, which is represented by maximum sustainable yield (*MSY*). The *MSY* is calculated as the product of $U_{MSY,}$ estimated from $F_{MSY} = M*(F_{MSY}/M)$ and $B_{MSY}*(K*(B_{MSY}/K))$. The Monte Carlo simulation proceeds by drawing many (e.g. 10,000) combinations of the four leading parameters from their distributions and using them to parameterize the delay-difference model of the form (see Dick and MacCall 2011 for details on model formulations).

$$B_t = B_{t-1} + P(B_{t-a}) - C_{t-1}$$

Where, C is the catch, B_t is biomass at time t, and P is latent annual production based on parental biomass (median age at entry to the reproductive biomass). At each step, only those cases where combinations of four leading parameters did not cause the population to crash or exceed carrying capacity are accepted and used for estimating the management parameters. The DBSRA provides estimates of several important management reference points ($U_{MSY} = (F_{MSY} /M + F_{MSY})*(1-exp(-M + F_{MSY}))$ and $MSY = U_{MSY}* B_{mnpl} *K$) for a given stock depletion level.

For this assessment, the DBSRA model was based on the total harvest (commercial and recreational) of striped mullet during 1956-2013 in the east coast and during 1930-2013 in the west coast (Table 1). Prior probability distributions of the four leading parameters were the same for both coasts. The natural mortality (*M*) was based on a lognormal distribution equal to the point estimate of 0.4 and a CV of 0.25. The ratio of F_{MSY} to *M* was set at 1.0 based on lognormal distribution with a CV of 0.3. The ratio of target biomass to unfished biomass (B_{MSY}/K) was assumed at 0.4 (a proxy biological reference point chosen by the Pacific Fishery Management Council for groundfish species),which is similar to the management standard chosen by the Commission for striped mullet in Florida. Since the estimates of model parameters depend strongly on the relative depletion parameter ($B_{current}/K$), the model performance was tested for a range of relative depletion levels (poor = 0.2, moderate = 0.4, and good = 0.6). The $B_{current}/K$ probability distribution was based on a beta distribution with a CV offset at 0.05. Sensitivity runs were performed for a lower and higher values of *M* (0.3 and 0.5) and different landings time series.

4.1.2 West Coast

Trajectories of the exploitation rate (*U*) and stock biomass (*B*) estimates under various assumptions about the stock condition (i.e., poor, moderate, and good) are shown in Figure 12. The exploitation (*U*) increased gradually to peaks during mid-1990s when fishing effort was expanding, declined sharply after the 1995 net-ban under all three depletion scenarios. The estimates of exploitable biomass showed an opposite trend, declining gradually during early period (1930-mid 1990) and increasing after 1995 for all model runs.

The probability distributions of U_{MSY} and B_{MSY} estimates are shown in Figure 13. The center of distribution for U_{MSY} was estimated at 0.2. The recent exploitation rate estimates have been below the U_{MSY} in all three model runs (Figure 12). The B_{MSY} estimate was between 70,000 and 90,000 mt depending on assumed stock condition. The rejection rates (combinations of four leading parameters estimates causing the population to crash or exceed *K*) from the Monte Carlo simulation were 41%, 32%, and

19% based on model runs assuming poor, moderate, and good stock conditions, respectively.

Model results were fairly robust to the assumptions about natural mortality at a lower (M=0.3) or higher (M=0.5) rate (Figure 14) and using the shorter catch time series (1968-2013) had no effect (Figure 15). The trajectories of exploitation rate from these sensitivity runs showed negligible differences when compared to the base run.

4.1.3 East Coast

Trajectories of the exploitation rate (*U*) and stock biomass (*B*) estimates based on various assumptions about the stock condition (i.e., poor, moderate, and good) are shown in Figure 16. The exploitation rate on the east coast increased gradually to peaks during mid-1990s, declined sharply after the 1995 net-ban from model runs assuming moderate and good stock conditions. Estimates of exploitable biomass showed an opposite trend, declining during early period (1956-mid 1990) and increasing after 1995 at different rates depending on the assumption about the stock condition.

The probability distributions of U_{MSY} and B_{MSY} estimates are shown in Figure 17. The center of distribution for U_{MSY} was estimated at 0.3. The recent exploitation rates have been below the U_{MSY} for the model runs assuming moderate or good stock conditions (Figure 16). The B_{MSY} estimates were between 5,000 and 6,000 mt depending on assumed stock condition.

The rejection rates from the Monte Carlo simulation were 10%, 5%, and 3% based on model runs assuming poor, moderate, and good stock conditions, respectively. Model results were fairly robust to the assumptions about natural mortality at a lower (M=0.3) or higher (M=0.5) rate (Figure 18). The trajectories of exploitation rate from these sensitivity runs showed negligible differences when compared to the base run.

4.2 Stochastic Stock Reduction Analysis (SSRA)

4.2.1 Methods

The SSRA is essentially an exploratory tool used to derive likely estimates of important management parameters, e.g. F_{MSY} and *MSY*, given the observed persistence of the exploited population through time. The estimated trends in exploitable biomass are contrasted with the available overall fishery catch rates to help estimate the likely management parameters. In this approach, an age structured population model with Beverton-Holt stock-recruitment function is simulated forward in time from the beginning of the catch time series, removing annual harvest, adding recruitment and subtracting mortality, so as to produce a cumulative prediction of current stock size (Walters et al. 2006). The model generates a large number of simulation runs with anomaly sequences chosen from normal prior distributions of leading management parameters (MSY and F_{MSY}). The recruitment estimates in particular are then adjusted until the simulations produce stock size or exploitation rate values close to those estimated from fishery-independent surveys. The resulting sample of possible historical stock trajectories is resampled using importance resampling (SIR) method, or a large sample is taken using Monte Carlo - Markov Chain (MCMC) routine. Details of the

SSRA modeling formulation of various forms are presented in Kimura and Tagart (1982), Walters et al. (2006), Forrest et al. (2008), and Martell et al. (2008).

We used an ADMB version of SSRA developed at FWRI (Cooper, personal communication) largely based on computer codes developed by Walters et al. (2006) and Martell et al. (2008). The SSRA is parameterized by taking F_{MSY} (annual fishing mortality rate producing MSY at equilibrium) and MSY as leading parameters, then calculating the Beverton-Holt stock-recruit parameters from these and from per-recruit fished and unfished eggs and vulnerable biomasses. Given a spawner-recruit function, an initial population age structure, and a lognormal set of recruitment anomalies, an age-structured population model can be constructed for projecting abundance of the population each year, given the observed harvest is removed. This is repeated many, many times so that a set of F_{MSY} and MSY pairs are determined that do not lead the population to extinction over the course of the projection, while supporting the observed annual catches and fitting a series of recent abundance indices. MCMC is employed so that the choice of each new pair of F_{MSY} and MSY values is effected by the likelihood that these values will result in a fit to the abundance indices series (as measured in all earlier trials). This way the relative distribution of these "accepted" pairs describe the likelihood profiles for F_{MSY} and MSY.

The input data and parameters used in the SSRA included historical annual harvest (1930-2013 combined commercial and recreational landings for each coast); fishery age composition data (1993-2013); tuning indices (standardized commercial fishery CPUE reflecting relative abundance of adult population and standardized juvenile survey CPUE reflecting the YOY abundance); life history information (vectors of length-at-age, weight-at-age, maturity-at age, fecundity-at-age, and age specific natural morality rate); fishery selectivity-at-age (two selectivity blocks representing the pre and post net-ban regulation periods); estimates of current fishing mortality rate and associated coefficient of variations (CV); and priors for F_{MSY}, MSY, and compensation ratio.

4.2.2 West Coast

The SSRA model for striped mullet on the west coast fit the commercial CPUE and juvenile survey index reasonably well but did not capture the fine scale variability (Figure 19). Stock biomass was below B_{MSY} from 1973 to 1995 and has been increasing ever since with a current value (B_{2013}/B_{MSY}) of 2.08 (Figure 20). The stock was experiencing overfishing during the 1940s and for most of the time period of 1957 to 1994 before dropping sharply after the net ban (Figure 20). The current fishing mortality rate ratio (F_{2013}/F_{MSY}) was estimated at 0.25 indicating that the west coast stock is currently neither overfished nor undergoing overfishing.

4.2.3 East Coast

The SSRA model for striped mullet on the east coast fit the commercial CPUE and juvenile survey indices, which were relatively flat over time, reasonably well but did not capture the fine scale variability (Figure 21). Stock biomass was at or below B_{MSY} from 1954 to 1995 and has been increasing ever since with a current value (B_{2013}/B_{MSY}) of 1.50 (Figure 22). The stock was experiencing overfishing for almost the entire time series prior to 1995 when it dropped sharply to an average of 0.58 (Figure 22). The

current fishing mortality rate ratio (F_{2013}/F_{MSY}) was estimated at 0.40 indicating that the east coast stock is currently neither overfished nor undergoing overfishing.

4.3 A Stock Production Model Incorporating Covariates (ASPIC)

4.3.1 Methods

Surplus production models are used to describe the dynamics of a fished stock in terms of biomass by simply using the previous year's biomass, growth in biomass in that year, and catch

$$B_{t+1} = B_t + r\, B_t\,(1 - B_t / K) - C_t$$

where B_t = biomass at time t, r=rate of growth in biomass, K= maximum population size, C_t = catch during time t. The predicted CPUE was calculated by the model,

$$\mathrm{CPUE}_{\mathrm{pred}} = q\, B_t$$

where q = catchability coefficient linking CPUE to biomass. We used the logistic formulation available in ASPIC (v5) to solve for biomass B_1, K, and q by minimizing the differences between observed and predicted CPUE. ASPIC then calculates the biological reference points such as maximum sustainable yield (*MSY*), B_{MSY} (the biomass that could produce maximum sustainable yield), F_{MSY} (the fishing mortality rate that would produce the maximum sustainable yield), and F/F_{MSY} and B/B_{MSY} ratios.

Separate model runs were developed for each coast. Input data for each run included total landings (commercial and recreational,1985-2013), standardized commercial CPUE for the pre (1985-1994) and post (1995-2013) net ban periods, and initial starting values for B_1/K, K, q, and MSY. The qs were estimated for each fishery for different time periods. This was accomplished by putting the periods of time in separate data series of catch and standardized CPUE. This approach allowed q to change reflecting changes in the gear composition after the net ban. Only estimates of ratios F/F_{MSY}, and B/B_{MSY} were used to evaluate the condition of mullet stocks. These relative measures are the most robust parameters generated by the model for evaluating the stock condition (Prager 2004).

The ASPIC model measures the uncertainty associated with the F/F_{MSY} and B/B_{MSY} estimates using a bootstrapping routine. In this routine, the catch and residual estimates from the initial run are used to generate new predicted catches using randomly-chosen adjusted residuals. The model is then refit and process is repeated 1000 times to generate a bias corrected 80% confidence intervals. Sensitivity of the model runs was tested for a long catch time series (1968-2013 for the west coast and 1956-2013 for the east coast).

4.3.2 West Coast

The surplus production method predicted the variability in the west coast commercial catch rate series fairly well (Figure 23). The estimates of fishing mortality rate were generally at or above F_{MSY} (F/F_{MSY} >1) and biomass estimates were at or below B_{MSY} during the pre net ban period (Figure 24). The F/F_{MSY} and B/B_{MSY}

trajectories showed a different condition of striped mullet stock after the 1995 net-ban. The F/F_{MSY} were consistently below 1 and the B/B_{MSY} were consistently above 1 during the 1996-2013 period, which seems to indicate that striped mullet stock on the west coast was no longer overfished and overfishing was not occurring in recent years. The likelihood estimates for F/F_{MSY} ratios in 2013 suggest with a fairly high level of certainty that the F_{2013}/F_{MSY} was less than 1 (Figure 25). The ASPIC model parameters estimates were robust based model runs using the long catch time series (1968-2013) (Figure 24).

4.3.3 East Coast

The surplus production method predicted the variability of the commercial catch rate fairly well (Figure 26). The F/F_{MSY} and B/B_{MSY} trajectories showed that the fishing mortality rates were estimated at or below the F_{MSY} level through most of the time series and biomass estimates were above B_{MSY} throughout the time series (Figure 27). The likelihood estimates of F/F_{MSY} ratio in 2013 suggest with a fairly high level of certainty that the F_{2013}/F_{MSY} was less than 1 (Figure 28). The ASPIC model parameters estimates were robust based model runs using the long catch time series (1956-2013).

4.4 Delay-Difference Model (DD)

4.4.1 Methods

The DD is an intermediate (partially age-structured) modeling approach developed initially by Deriso (1980) and further modified (generalized) by Schnute (1985). It allows age-structured population dynamics to be simplified to a single equation involving total biomass and numbers. The DD requires information on body growth, recruitment, and survival. The body growth of the exploitable stock is represented by the Brody linear equation ($w_\alpha = \alpha + \rho\, w_{\alpha+1}$, where w_a is body weight at age a, and α and ρ are constants). The Brody equation states that after a certain age, the typical von Bertalanffy model of growth in weight can be represented by a linear equation of weight-at-age a against weight-at-age a+1. The recruitment to the harvested population is knife-edge (i.e., fishing mortality rate is independent of age for fish aged a and older). The natural mortality is assumed constant.

The discrete time delay-difference model (as presented by Carl Walters, personal communication) for total biomass B_t and numbers N_t, summed over mature ages is given by

$$B_t = s_{t-1} * (\alpha N_{t-1} + \rho B_{t-1}) + w_k R_t$$
$$N_t = s_{t-1} * N_{t-1} + R_t$$

where the overall survival rate s_t for year t is given by

$$s_t = e^{-M} * (1-U_t) \text{ or } s_t = e^{-M-F}$$

Here, U_t is the harvest rate in year t, and F is the instantaneous fishing mortality rate applied over a short discrete time at the start of year t. The main advantage of the delay difference equations over full age-structured accounting is that they can be solved very quickly for very large numbers of populations, e.g. in spatial grid models, without loss of

age-structure effects on average size of fish harvested and on fecundity. The continuous version of delay-difference model was also applied under the assumptions that reproduction, recruitment, growth, and mortality rates are all varying continuously over time. We were unable to obtain a stable version of the continuous delay difference model. Also, mullet do not exhibit continuous processes and the discrete version was preferred.

4.4.2 West Coast

The DD model results on the west coast showed generally good fits to pre and post net-ban commercial landings series as well as to the FIM YOY index (Figure 29). The model overpredicted landings in 1992 and underpredicted them from 1989-1994. The average fishing mortality rate from 1981 to 1994 was 0.72. The *F* declined sharply after the 1995 net-ban to an annual average of 0.15 (Figure 30). Biomass followed the opposite pattern going from a mean of 13,592 mt from 1981-1994 to 27,117 mt on average since 1995 (Figure 30). According to these predictions, the stock was experiencing overfishing from 1982 to 1994 and was also overfished from 1990-1994 (Figure 31). Currently, the biomass ratio $B_{2013}/B_{35\%SPR}$ is equal to 2.58 and the fishing mortality rate ratio ($F_{2013}/F_{35\%SPR}$) is 0.27 indicating that striped mullet on the west coast is neither overfished nor undergoing overfishing.

4.4.3 East Coast

The DD model results on the east coast showed generally good fits to pre and post net-ban commercial landings as well as to the FIM YOY index (Figure 32). The average fishing mortality rate from 1981 to 1994 was 0.48 after which it has averaged 0.23 (Figure 33). Biomass followed the opposite pattern going from a mean of 2,816 mt from 1981-1994 to 3,653 mt on average since 1995 (Figure 33). According to these predictions, the stock was experiencing overfishing in 1982, 1988, 1991, 1992, and 1994 and was overfished in 1995 and 1996 (Figure 34). Currently, the biomass ratio B_{2013}/B_{msy} is equal to 1.26 and the fishing mortality rate ratio (F_{2013}/F_{msy}) is currently 0.43 indicating that striped mullet on the east coast is neither overfished nor undergoing overfishing.

4.5 Stock Synthesis *v3* (SS3)

Stock synthesis, SS, is a forward projecting age and size structured assessment model that can be fit to various fishery and survey data (Methot 2000). The model has been used for many stock assessments of west coast and Alaska groundfish species. It has evolved into a flexible tool capable of handling multiple fleets, surveys, genders, seasons, time blocks, and regions; each with different selectivity patterns and biological characteristics (mortality and growth). Growth parameters are specified explicitly, selectivity patterns can be a function of size and/or age, and weight-at-age is determined from size-selectivity and size-at-age probability.

The population model controls the rate at which new individuals recruit to the population, the mortality rates (fishing and natural), the growth rates, and reproduction. Optionally, the total population can be divided into morphs to represent, for example, slow-, medium-, and fast-growing entities. Variability in growth (size-at-age) can be a function of age or mean length. The initial population (in first year of model) is assumed

to be at equilibrium in either an unfished or fished state. Growth can follow several patterns, usually the von Bertalanffy function, and can be gender or morph specific. A stock recruitment relationship of several forms (usually Beverton-Holt) is used to relate the number of age-0 fish to spawning biomass calculated on a yearly basis and can included deviations. Natural mortality can be constant or time-varying and age specific with functions to relate it to environmental inputs. Maturity can be calculated as a logistic function of either length or age with eggs proportional to body weight or length. Fishing mortality is modeled using either Pope's approximation, as continuous *F*, or a hybrid approach. There are numerous patterns available to model age and/or size selectivity including fixed constant selectivity, logistic, and the double normal. It is also possible to model discards explicitly using retention functions.

Stock synthesis then fits the model to observed catch-at-age and –length data from the surveys and fleets as well as indices of abundance from fishery independent or dependent sources. It accounts for the influence of sample size and factors such as aging error on relationship between samples and actual observations. The objective function can include likelihood components for catch, indices of abundance, length and age compositions, mean size-at-age, and priors. The weight of each component can be adjusted to put more or less influence on the different sources of input data. SS is capable forecasting population sizes under various levels of fishing mortality. Three reference points are calculated: the *F* at target SPR, the target SPR accounting for spawner-recruit relationship, and the *F* that maximizes equilibrium yield including the *S-R* function. Accompanying biomass, catch, and recruitment are provided for each *F* reference point. The forecast module can be used to calculate the overfishing limit (OFL) and acceptable biological catch (ABC).

4.5.1 Methods

We applied SS3 to striped mullet on the east and west coasts of Florida. Both models consisted of 1 combined gender, 2 fleets (commercial and recreational), 1 survey (FIM juvenile index), age-specific natural mortality, von Bertalanffy growth, a Beverton-Holt stock-recruit function with deviations, and separate selectivity patterns for the commercial fishery pre- and post-net ban. The west coast model included harvest removals back to 1930 and the east coast model included removals back to 1956 (Figure 35). Both models were fit to commercial age and length compositions, recreational length compositions, commercial cpue, and a fisheries independent juvenile survey. In both models, 7 parameters were estimated that included the initial recruitment (R_0) and size selectivity parameters. On the west coast, recruitment deviations were estimated separately for an early time period (1930-1969) when only catch data were available and main recruitment deviations were estimated from 1970-2013. On the east coast, only recruitment deviations for the main time period of 1976-2013 were estimated. The input data and control files necessary to execute the SS3 models for the east and west coasts are available in the appendices.

The steepness parameter was fixed at 0.8 in both models. This value was arrived at through numerous iterations at values ranging from 0.2 to 0.99 and was deemed appropriate for this species based on life history traits. We were unable to find a stable solution in either model when steepness was an estimated parameter. Because steepness largely determines the productivity of the stock, other parameters

(estimated and fixed) were not robust such that changing steepness required adjustments in other parameter values and bounds. The adjustments required for better known parameters were not easily justified.

The SS3 models were also very sensitive to the variability in recruitment deviations (σR). We attempted to run the SS3 models with σR values around 0.6, which is a general rule-of-thumb for recruitment variability in fisheries models. However, we found through numerous iterations that the models were only stable at much lower values (0.2 on the west coast and 0.05 on the east coast). Allowing the model to solve for σR produced warnings that parameters were estimated at their defined bounds and led to unrealistic biomass and fishing mortality trajectories. Also, how the deviations were phased into the model had a significant effect on model outcomes. This is most pronounced on the west coast where a strong negative recruitment deviation was always predicted in 1991-1992, which coincided with the arrival of commercial age and length data. Both models show peculiar patterns of recruitment deviation with positive deviations during the early data-poor period and negative deviations during the later data-rich period. This is concerning because recruitment deviations are expected to be variable around zero with no obvious patterns.

We also found the models to be sensitive to the assumed depletion in the first year of the model. The initial depletion is determined based on input values for initial equilibrium catch and the initial fishing mortality parameters. For example, a high initial catch and/or high initial F lead to a highly depleted stock in the first year of the model. We calculated initial equilibrium catch based on the average historical landings that occurred before the model start year. Because of uncertainty in the initial equilibrium catch, we removed this term from the objective function so the model did not attempt to fit to that value. The model could not converge when estimating the initial fishing mortality rates for each fleet and therefore those were fixed at reasonably low values.

Lastly, the model was surprisingly sensitive to growth parameters k, L_{max}, and coefficients of variation (growth CV) in young and old ages. An advantage of SS3 is the ability to estimate growth and selectivity parameters simultaneously. However, we did not possess the required data to do so. Instead we fixed all growth parameters at values estimated empirically from observed age samples.

4.5.2 West Coast

The model was able to fit the commercial cpue and FIM juvenile survey indices quite well (Figure 36). Fits to length composition from the commercial (Figure 37) and recreational fisheries (Figure 38) were also good, especially when aggregated across years (Figure 39). The model did not fit the age data very well, which was expected because the age samples were down weighted in the objective function account for uncertainty in the data (Figure 40 and Figure 41). The model tended to predict fewer one and two year olds in the catch than what the data suggested.

Predicted total biomass declined sharply from 78,845 mt in 1930 to 39,051 mt in 1944 (Figure 42A). Biomass was then variable along a gradual decline before dropping sharply again from 35,476 mt in 1990 to 16,604 mt in 1995. Total biomass has increased steadily ever since and is currently estimated to be 38,152 mt. Spawning biomass was predicted to follow a similar pattern but with a more steep decline from

1930 to the 1950s (Figure 42B). The spawning stock was assumed to be lightly depleted in 1930 with SSB equal to 0.95 unfished *SSB* (Figure 42C). Depletion fell sharply to 0.28 in 1944 then declined, with some variability, to a value of 0.15 in 1995. The spawning biomass has since recovered to a depletion level of 0.40 which is above the depletion level at target $SPR_{35\%}$. The fishing mortality ratio $F/F_{SPR35\%}$ (for ages 2-8) was predicted to be 0.52 in 1930, exceeded 1 in 1939 and increased sharply to 2.62 in 1943 (Figure 42D). The *F* ratio then declined to 1.11 in 1951 and remained variable around an average of 1.56 until 1994. In 1995 the *F* ratio dropped sharply below 1 to 0.66, has average 0.59 since the net ban, and is currently at 0.57 indicating that the stock is not undergoing overfishing.

Recruitment deviations were positive during the early era (1930-1969) and then became variable before declining sharply in 1991-1993 (Figure 43A). Recruitment deviations were predicted to be negative in almost every year since. The spawner-recruit relationship shows the same pattern with points far above the Beverton-Holt curve from earlier years and those below the curve from more recent years (Figure 43B). The *SPR* ratio fell below the target of $SPR_{35\%}$ in 1939 and remained below the target until after the net ban in which it jumped from 0.24 in 1994 to 0.46 in 1995 (Figure 44A). The ratios of phase plot of *SPR* and biomass ratios indicate that striped mullet on the west coast are neither overfished nor undergoing overfishing (Figure 44B).

4.5.3 East Coast

The predicted survey indices captured the overall trend for both the commercial catch rate index and the FIM juvenile survey index (Figure 45). The model also performed well in predicting the length-frequency distributions for the commercial fishery (Figure 46, Figure 48). However, the model had issue with poorer fits to length-frequency distributions for the recreational fishery, under-predicting proportions in the 24-28 cm FL range and over-predicting proportions in the 34-44 cm FL range according to fits (Figure 47, Figure 48). The model did a fair job of predicting the age distributions for the commercial fishery (Figure 49). Although it may have under-predicted the age-3 proportion and over-predicted ages 5-9, according to fits (Figure 49).

Predicted total biomass exhibited an initial decrease from 1956 through 1983, increased through 1988, decreased through 1996, and increased through 2004 (Figure 50A). Since then, total biomass has since remained relatively stable. Predicted spawning biomass shows the same pattern with spawning biomass initially decreasing from around 5,500 mt in 1956 to 1,926 mt in 1983, with current 2013 estimates around 3,400 mt (Figure 50B). The spawning stock was assumed to be moderately depleted in 1956 with *SSB* equal to 0.66 virgin *SSB* (Figure 50C). Depletion fell sharply to 0.30 in 1970 then declined, with some variability, to a value of 0.22 in 1983. The spawning biomass has since recovered to a depletion level of 0.40 which is above the depletion level at target $SPR_{35\%}$. The fishing mortality ratio $F/F_{SPR35\%}$ (for ages 2-8) was predicted to be 0.65 in 1956, exceeded 1 in 1963, then increase sharply to 1.96 in 1982 (Figure 50D). The *F* ratio then declined to 0.36 in 2002 and has remained variable around an average of 0.58 ever since with a current value of 0.49 indicating that the stock is not undergoing overfishing.

Predicted recruitment deviations exhibited a high level of uncertainty, and displayed a shift between positive deviations (1976 to 1991) to largely negative

deviations (1992-2012) (Figure 51A). Predicted *SPR* ratios (Figure 52A) fell below the management target of $SPR_{35\%}$ in 1963 and hovered around the target before falling to 0.18 in 1982 followed by a steep increase. Ratios then fell below the management target again in 1989 and hovered around the target until 1995. Since then, SPR ratios have been above the management target, and the current 2013 SPR ratio was estimated to be 0.55. Current reference points for fishing mortality and biomass ratios in regards to $F_{SPR35\%}$ were estimated to be $F_{2013}/F_{SPR35\%}$ = 0.41 and $B_{2013}/B_{35\%}$ = 1.74 (Figure 52B, Table 7).

5 Conclusions, Stock Status, and Research Recommendations

All five modeling approaches used in this assessment show that fishing mortality rates declined sharply after the 1995 net-ban and have remained at low levels in recent years in both coasts of Florida. This is consistent with significant drops in landings and fishing effort since the 1995 net-ban. Commercial landings have declined from an annual average of 28 million pounds during 1930-1994 to an annual average of 8.8 million pounds during 1995-2013, a 70% reduction in landings after the net-ban. The fishing effort (number of one-day trips) declined from an annual average of 59,399 trips during 1985-1994 to an annual average of 25,288 trips during 1995-2014, a 57% reduction in fishing effort after the net-ban.

Presently, the Florida Fish and Wildlife Conservation Commission, has adopted a target spawning potential ratio (*SPR*) of 35% ($F_{SPR35\%}$) for striped mullet in Florida. The estimates of current fishing mortality rates relative to $F_{SPR35\%}$ ($F/F_{SPR35\%}$) or relative to F_{MSY} (F/F_{MSY}) were below 1 from all five models, suggesting that overfishing is not occurring in either coast of Florida (Table 8). Estimates of current biomass relative to the biomass level at $F_{SPR35\%}$ or relative to B_{MSY} (B/B_{MSY}) were above 1 from all five models, suggesting that mullet stocks are not considered to be overfished in Florida (Table 8). Estimates of the *SPR* from the SS3 model showed that *SPR* varied between 15% and 25% prior to the 1995 net-ban and then increased sharply to above the 35% target level after 1995, varying around 0.45 on the east coast and around 0.5 on the west coast (Figure 44A and Figure 52A). Phase plots from the delay difference and SS3 models (Figure 31, Figure 34, Figure 44B, and Figure 52B) indicated that mullet stocks are considered healthy in both coasts of Florida given recent fishing mortality rates and biomass levels.

The SSRA, ASPIC, delay difference, and SS3 models assumed that the standardized CPUE were a reliable index of adult population abundance, although greater weighting was allowed for the catch. Results from these models were heavily dependent on the trends observed in the catch and CPUE indices given lack of strong signals in the length and age composition data. Because of limited direct aging data from the fishery, the catch-at-age matrices were constructed primarily based on age length keys (ALK) derived from biological studies and fishery-independent samplings. Consequently, the age structures to which the models were fit for this assessment may not be representative of a particular year because the pooled ALK would tend to minimize apparent differences among years. In addition, the pooled ALK would under-estimate apparent decline in older age over time and or the influence of weak or strong year classes. Thus, it is critical that future sampling and data collection for striped mullet assessment include direct age sampling of the commercial and recreational catches

with sufficient spatial and temporal resolutions. Since the net ban, commercial gill nets of various mesh sizes have been replaced by cast nets and small seines. The age data from various sectors of the fishery should be incorporated into assessment for accurate measurements of the gear selectivity patterns. Future data collection should also include comprehensive on-board observations for characterizing the spatial and temporal patterns in fishing activities and effort in the mullet fishery. Finally, fishery-independent samplings should be conducted to update estimates of biological and population parameters needed for calibrating the stock assessment models.

Because mullet are important in the flow of energy through estuarine and coastal communities and are exposed to high level of predation, future modeling approaches should include predation-prey interactions and the influence of the bottom-up processes. An ecosystem-based or multispecies approach will provide quantitative estimates of predation and natural mortality rates, important parameters estimates for a forage species such as mullet.

Findings from all five modeling approaches support the general conclusion that while there is uncertainty about model outputs, the SPR estimates have been above the 35% *SPR* target in recent years in Florida. The future condition of mullet stocks depends on market demand, landings levels and fishing effort, and environmental condition affecting the stock and recruitment fluctuations. Commercial landings levels in the past ten years seem to indicate that landings have stabilized between 1-1.5 million pounds annually on the east coast and between 8-9 million pounds annually on the west coast. Given recent landings and fishing effort levels, fishing mortality rates should stabilize or decline further if recoveries of mullet stocks continue at the present rate.

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7 Tables

Table 1. Commercial and recreational landings of striped mullet on the east and west coasts of Florida from 1930-2013.

Year	west coast			east coast		
	commercial	rec	total	commercial	rec	total
1930	8,672	98	8,770	1,317	24	1,341
1931	8,392	106	8,498	1,746	28	1,774
1932	8,556	114	8,670	1,034	31	1,065
1933	13,095	122	13,218	2,282	34	2,316
1934	8,589	130	8,720	2,282	38	2,320
1935	9,603	138	9,741	2,282	41	2,323
1936	11,837	146	11,984	2,388	44	2,432
1937	9,603	155	9,757	2,282	48	2,330
1938	8,839	163	9,002	2,282	51	2,333
1939	12,652	171	12,822	2,282	55	2,337
1940	13,013	179	13,192	2,282	58	2,340
1941	15,590	187	15,777	2,282	61	2,343
1942	23,014	195	23,209	2,282	65	2,347
1943	23,098	203	23,301	2,282	68	2,350
1944	15,707	211	15,918	2,282	72	2,354
1945	13,396	219	13,615	2,282	75	2,357
1946	14,452	227	14,679	2,282	78	2,360
1947	10,660	236	10,895	2,282	82	2,364
1948	13,895	244	14,139	2,282	85	2,367
1949	13,203	252	13,455	2,282	88	2,370
1950	10,095	260	10,355	3,214	93	3,307
1951	8,246	268	8,514	3,028	96	3,124
1952	9,392	276	9,668	1,849	99	1,948
1953	10,284	284	10,568	2,178	102	2,280
1954	10,224	292	10,517	2,380	105	2,485
1955	10,925	300	11,225	2,095	108	2,203
1956	11,658	308	11,967	1,309	111	1,420
1957	13,790	317	14,106	802	113	915
1958	14,670	325	14,995	1,513	116	1,629
1959	13,900	357	14,258	1,184	128	1,312
1960	14,014	366	14,380	925	131	1,056
1961	14,952	405	15,358	1,199	145	1,344
1962	14,887	382	15,269	1,296	137	1,433
1963	14,793	391	15,183	1,505	140	1,645
1964	15,874	409	16,283	1,273	147	1,420
1965	14,228	432	14,661	1,293	155	1,448
1966	12,228	444	12,672	1,406	159	1,565
1967	10,561	482	11,044	1,314	173	1,487
1968	9,237	485	9,722	1,036	174	1,210
1969	11,556	510	12,065	1,082	183	1,265
1970	10,496	550	11,046	922	197	1,119
1971	10,804	690	11,493	956	247	1,203
1972	12,185	715	12,900	903	256	1,159
1973	12,090	755	12,846	1,191	271	1,462
1974	11,394	816	12,210	1,254	292	1,546
1975	10,509	851	11,360	1,171	305	1,476
1976	7,599	803	8,402	875	288	1,163
1977	8,531	723	9,253	1,265	259	1,524
1978	11,013	653	11,666	1,009	234	1,243
1979	10,792	700	11,492	843	251	1,094

Year	west coast			east coast		
	commercial	rec	total	commercial	rec	total
1980	12,351	576	12,927	1,081	206	1,287
1981	12,875	287	13,161	1,182	75	1,257
1982	10,788	283	11,072	1,186	786	1,972
1983	10,089	1,150	11,239	770	55	825
1984	8,121	2,470	10,591	847	137	984
1985	8,379	2,059	10,438	713	51	764
1986	9,315	2,066	11,381	994	168	1,162
1987	9,207	841	10,048	1,193	4	1,197
1988	9,431	947	10,378	1,207	281	1,488
1989	10,663	303	10,965	1,395	308	1,703
1990	10,496	427	10,923	1,140	192	1,332
1991	9,037	1,358	10,395	989	553	1,542
1992	8,176	642	8,819	1,101	1,137	2,238
1993	7,887	460	8,347	1,359	191	1,550
1994	5,647	553	6,199	1,146	486	1,632
1995	2,065	247	2,312	486	374	860
1996	1,934	408	2,342	658	67	725
1997	3,259	540	3,798	645	208	853
1998	3,358	475	3,833	764	429	1,193
1999	3,767	624	4,391	624	62	686
2000	3,337	726	4,063	563	135	698
2001	4,036	813	4,849	606	55	661
2002	3,592	461	4,053	513	29	542
2003	2,889	611	3,500	679	31	710
2004	2,966	606	3,572	499	495	994
2005	2,520	581	3,101	503	218	721
2006	3,499	521	4,020	640	421	1,061
2007	2,513	322	2,835	585	225	810
2008	3,139	620	3,758	667	297	964
2009	4,129	327	4,456	568	436	1,004
2010	3,212	873	4,086	629	195	824
2011	5,129	474	5,604	634	693	1,327
2012	3,694	589	4,282	665	249	914
2013	3,882	866	4,747	613	101	714

Table 2. Fixed and estimated parameters of the SS3 model of striped mullet on the west coast of Florida.

Parameter	Estimated Value	Bounds (low,high)	Fixed value
	growth		
Length at A1	-	NA	15
Length at A2	-	NA	46
von Bertalanffy K	-	NA	0.35
CV of length at A1	-	NA	0.1
CV of length at A2	-	NA	0.1
	weight at length		
a	-	NA	6.40E-06
b	-	NA	3.14E+00
	fecundity at length		
Mat 50%	-	NA	34.2
slope	-	NA	-0.2
	stock-recruitment		
Ln(R0)	12.8	(1,20)	-
steepness	-	NA	0.8
recruitment SD	-	NA	0.2
main recruit devs (start-stop)	1970-2012	(-5,5)	-
rec devs bias adjust.	NA	NA	0.5
	initial fishing mortality		
commercial	-	NA	0.05
recreational	-	NA	0.001
	selectivity		
commercial (logistic)			
size at inflection pre-1996	29.6	(20,50)	-
slope pre-1996	3.5	(1,10)	-
size at inflection 1996-2013	29.2	(20,50)	-
slope 1996-2013	5.2	(1,20)	-
recreational (logistic)			
size at inflection	30.1	(20,50)	-
slope	8.5	(1,10)	-
FIM juv survey (age range)			
min age	-	NA	0.1
max age	-	NA	1

Table 3. Reference points estimated by the SS3 model of striped mullet on the west coast.

reference point	value	standard deviation
unfished *SSB* (mt)	56,381	1,262
unfished total biomass (mt)	82,453	1,845
unfished recruitment (R0)	355,423	7,955
SSB at $B_{35\%}$ (mt)	19,733	442
SPR resulting in $B35_{\%}$ ($SPR_{35\%}$)	0.39	1.37E-18
F at $B_{35\%}$	0.17	7.44E-04
Yield at $B_{35\%}$ (mt)	6,796	141
SSB at $SPR_{35\%}$ (mt)	17,290	387
F at $SPR_{35\%}$	0.19	8.57E-04
Yield at $SPR_{35\%}$ (mt)	7,017	146

Table 4. Fixed and estimated parameters of the SS3 model of striped mullet on the east coast of Florida.

Parameter	Estimated Value	Bounds (low,high)	Fixed value
	growth		
Length at A1	-	NA	15
Length at A2	-	NA	43
von Bertalanffy K	-	NA	0.48
CV of length at A1	-	NA	0.1
CV of length at A2	-	NA	0.1
	weight at length		
a	-	NA	1.19E-05
b	-	NA	3.04E+00
	fecundity at length		
Mat 50%	-	NA	34.2
slope	-	NA	-0.2
	stock-recruitment		
Ln(R0)	10.7	(1,20)	-
steepness	-	NA	0.8
recruitment SD	-	NA	0.05
main recruit devs (start-stop)	1976-2012	(-5,5)	-
rec devs bias adjust.	NA	NA	5.2
	initial fishing mortality		
commercial	-	NA	0.1
recreational	-	NA	0.001
	selectivity		
commercial (logistic)			
size at inflection pre-1996	28.5	(20,50)	-
slope pre-1996	3.4	(1,10)	-
size at inflection 1996-2013	28.0	(20,50)	-
slope 1996-2013	4.2	(1,20)	-
recreational (logistic)			
size at inflection	21.0	(10,50)	-
slope	6.8	(1,10)	-
FIM juv survey (age range)			
min age	-	NA	0.1
max age	-	NA	1

Table 5. Reference points estimated by the SS3 model of striped mullet on the east coast.

reference point	value	standard deviation
unfished *SSB* (mt)	8,643	138
unfished total biomass (mt)	13,105	209
unfished recruitment (R0)	44,228	707
SSB at $B_{35\%}$ (mt)	3,025	48
SPR resulting in $B_{40\%}$ ($SPR_{35\%}$)	0.39	1.47E-18
F at $B_{35\%}$	0.21	1.08E-03
Yield at $B_{35\%}$ (mt)	1,154	17
SSB at $SPR_{35\%}$ (mt)	2,651	42
F at $SPR_{35\%}$	0.24	1.28E-03
Yield at $SPR_{35\%}$ (mt)	1,193	18

Table 6. Estimated reference points from the various model configurations for striped mullet on the west coast. The median values are provided from the DBSRA, and SSRA model iterations which calculate U_{msy}. The ASPIC model calculates F_{msy} and reference points are determined using bootstrapping. The proxy for F_{msy} in DD and SS3 is $F_{SPR35\%}$.

model	configuration	Fmsy or proxy	B2013/Bmsy or proxy	F2013/Fmsy or proxy
DBSRA	depletion = 0.2, M = 0.4	0.13	0.52	0.85
	depletion = 0.4, M = 0.4	0.14	1.05	0.41
	depletion = 0.6, M = 0.4	0.15	1.60	0.27
SSRA	start 1930, com cpue 1995-2013	0.20	2.08	0.25
	start 1930, com cpue 1985-2013	0.15	2.15	0.24
	start 1968, com cpue 1995-2013	0.32	2.53	0.23
ASPIC	start 1985	0.14	1.69	0.30
	start 1968	0.15	1.70	0.30
	start 1968, with fim adult index	0.03	0.97	0.34
DD	1980-2013	0.53	2.58	0.27
SS3	1956-2013, h=0.8,σr=0.2	0.25	1.74	0.57

Table 7. Estimated reference points from the various model configurations for striped mullet on the east coast. The median values are provided from the DBSRA and SSRA models which calculate U_{msy}. The ASPIC model calculates F_{msy} and reference points are determined using bootstrapping. The proxy for F_{msy} in DD and SS3 is $F_{SPR35\%}$.

model	configuration	Fmsy or proxy	B2013/Bmsy or proxy	F2013/Fmsy or proxy
DBSRA	depletion = 0.2, M = 0.4	0.11	0.52	0.89
	depletion = 0.4, M = 0.4	0.12	1.06	0.42
	depletion = 0.6, M = 0.4	0.14	1.60	0.27
SSRA	start 1930, com cpue 1995-2013	0.17	1.50	0.40
	start 1930, com cpue 1985-2013	0.15	1.66	0.36
	start 1956, com cpue 1995-2013	0.75	3.02	0.19
ASPIC	start 1985	0.17	1.50	0.40
	start 1956	0.15	1.66	0.36
	start 1956, with fim adult index	0.75	3.02	0.19
DD	1980-2013	0.55	1.26	0.44
SS3	1956-2013, h=0.8,σr=0.05	0.32	1.74	0.49

Table 8. Stock status from the five models used in the stock assessment. The median values are provided from the DBSRA, and SSRA model iterations which calculate U_{msy}. The ASPIC model calculates F_{msy} and reference points are determined using bootstrapping. The proxy for F_{msy} in DD and SS3 is $F_{SPR35\%}$.

Model	West Coast		East Coast	
	B_{2013}/B_{msy} or proxy	F_{2013}/F_{msy} or proxy	B_{2013}/B_{msy} or proxy	F_{2013}/F_{msy} or proxy
DBSRA	1.05	0.41	1.06	0.42
SSRA	2.15	0.24	1.66	0.36
ASPIC	1.69	0.30	1.50	0.40
DD	2.58	0.27	1.26	0.44
SS3	1.74	0.48	1.74	0.41

8 Figures

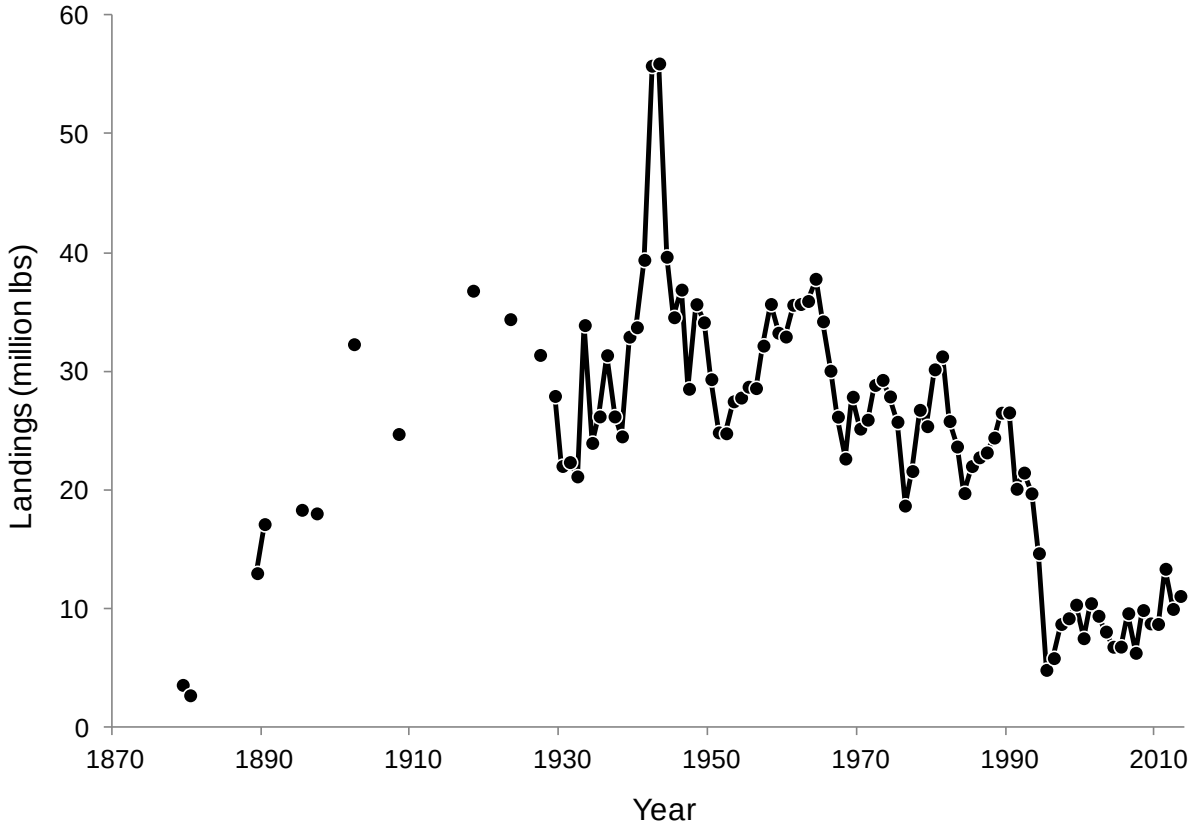


Figure 1. Historical commercial landings of striped mullet in Florida, 1879-2013.

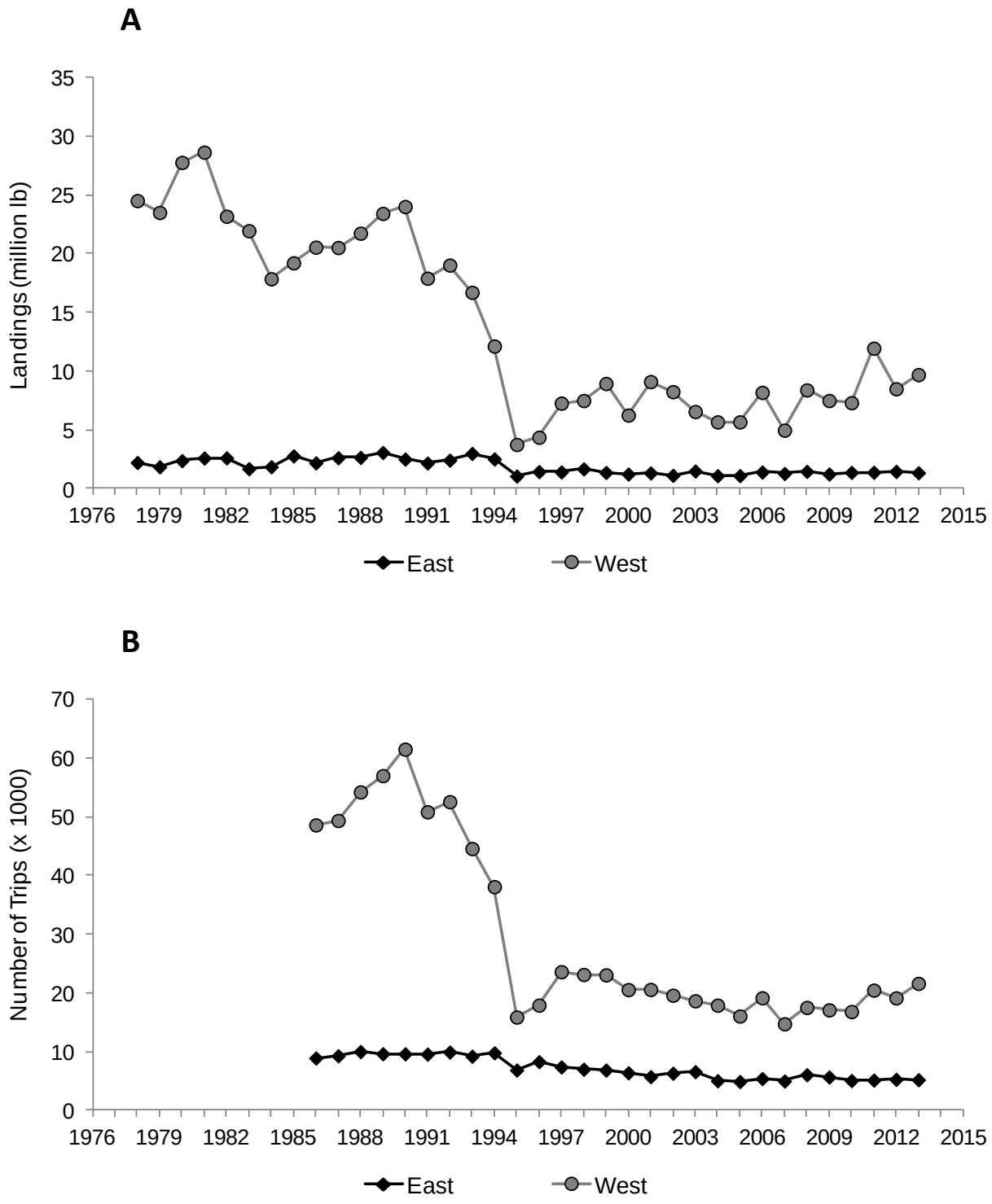


Figure 2. Annual commercial landings (A) and number of fishing trips (B) in the striped mullet fishery on the east and west coasts of Florida.

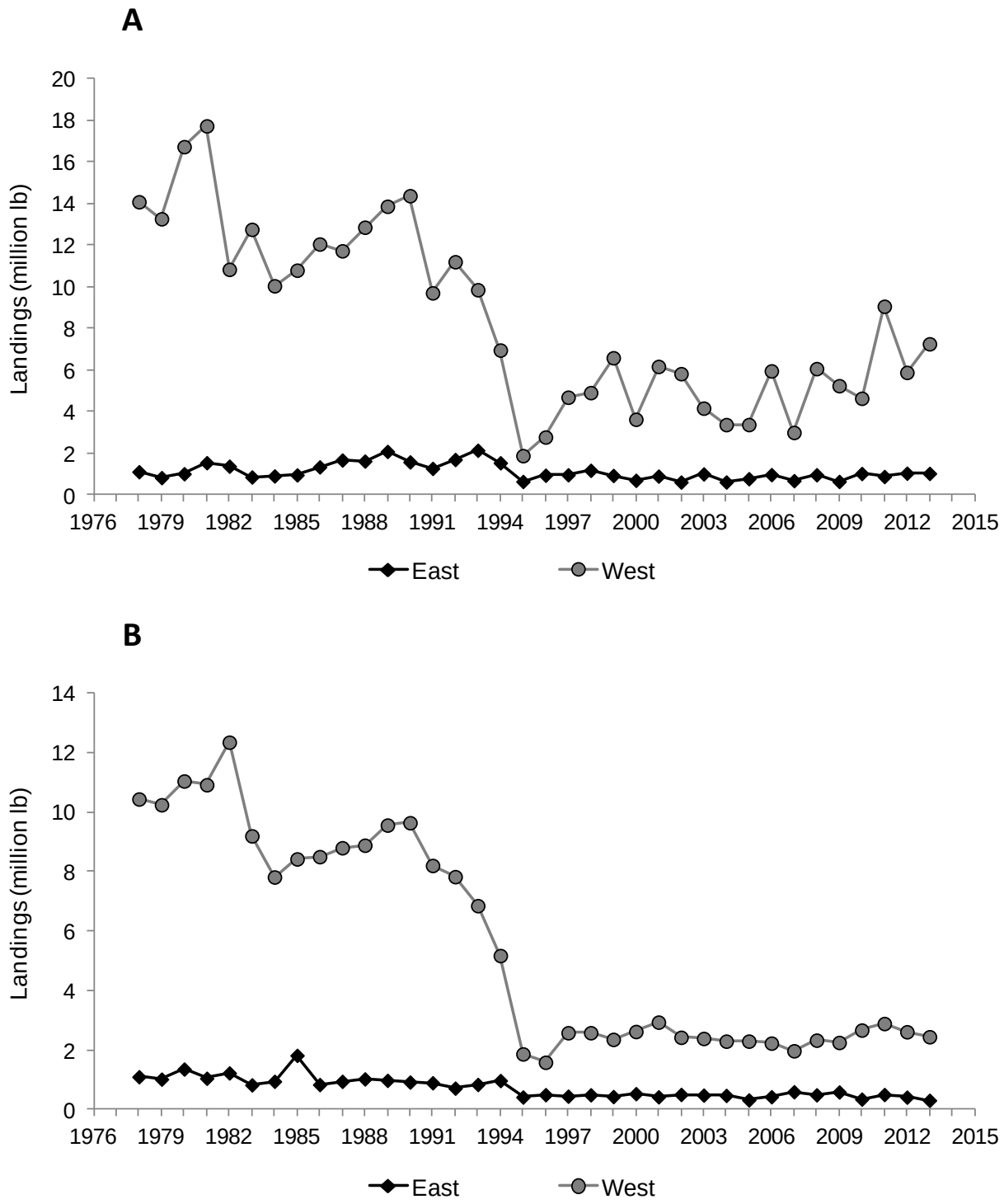


Figure 3. Annual commercial landings of striped mullet for the roe (A) and non-roe (B) seasons on the east and west coasts of Florida.

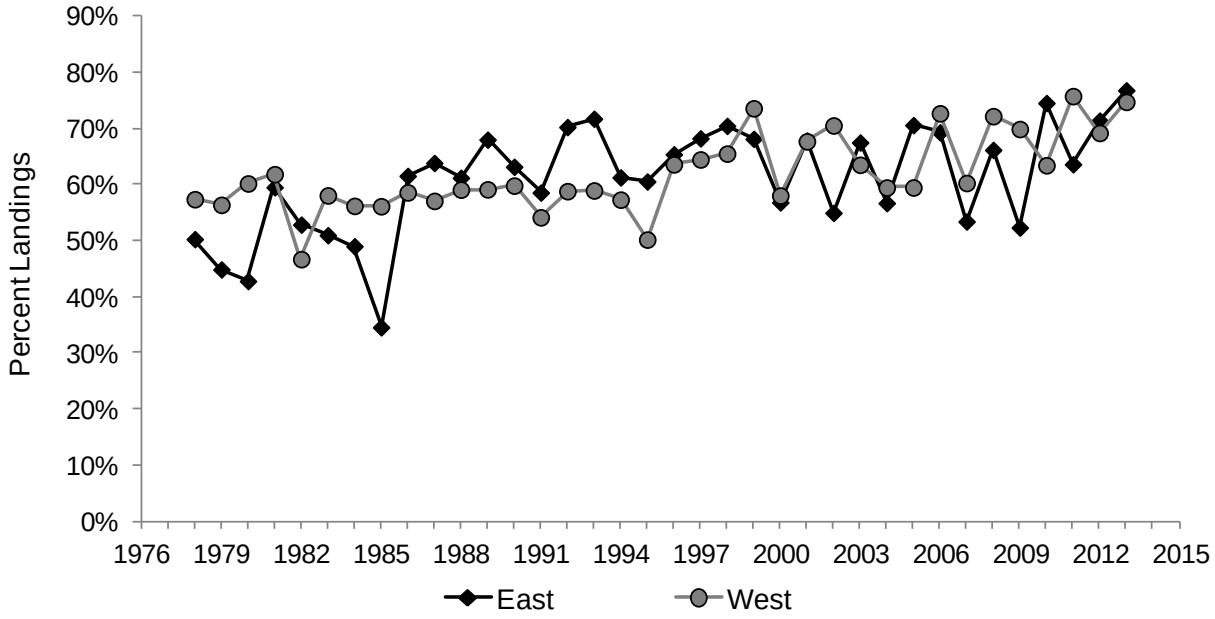


Figure 4. The proportion of striped mullet caught commercially during the spawning (roe) season on the east and west coasts of Florida.

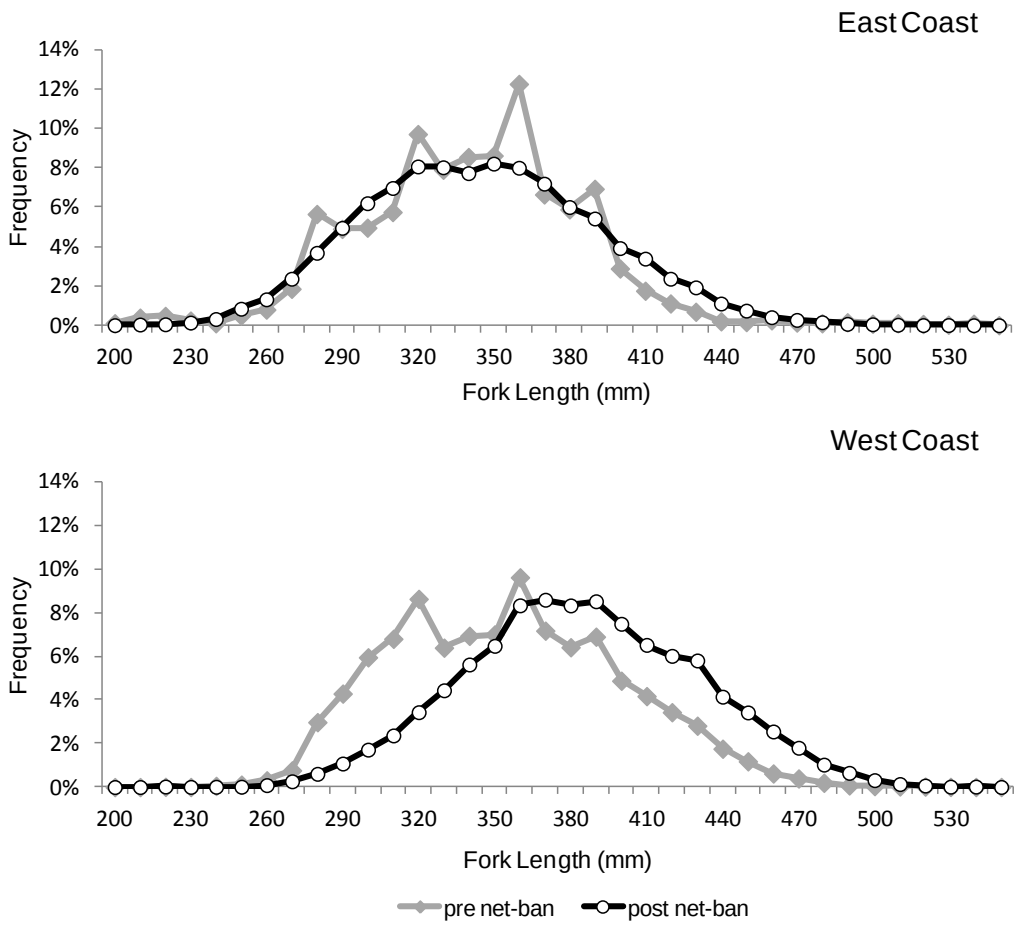


Figure 5. The length-frequency distributions of striped mullet caught commercially during the pre (1991-1994) and post (1995-2013) net ban periods on the east and west coasts of Florida.

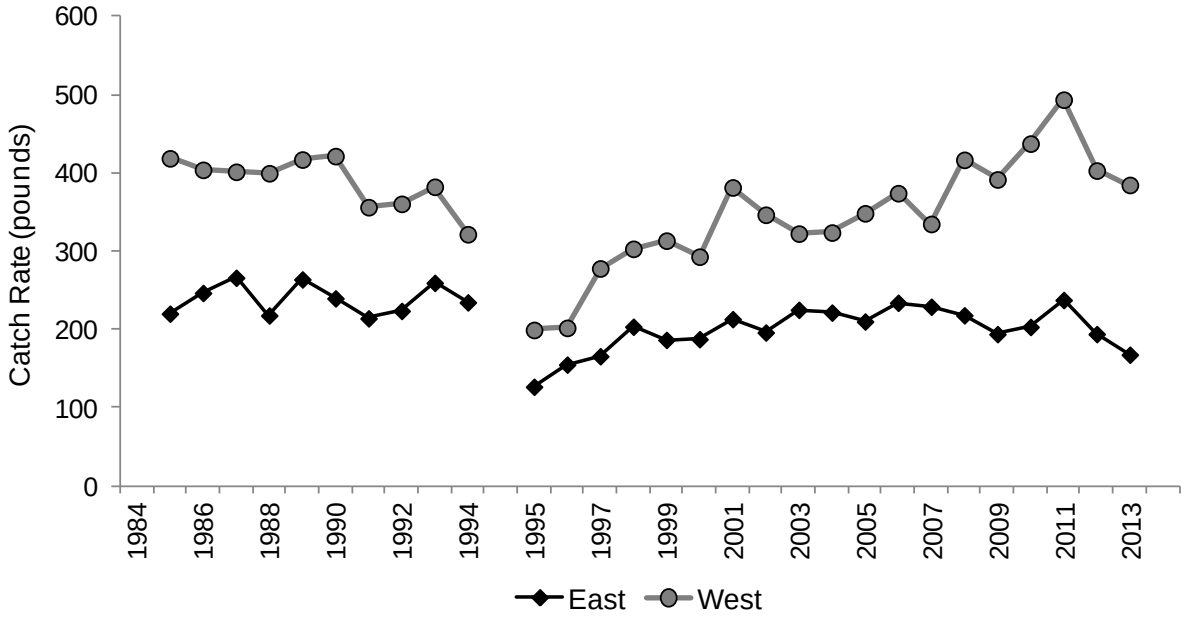


Figure 6. Standardized commercial catch rates for striped mullet during the pre (1985-1994) and post (1995-2013) net ban periods on the east and west coasts of Florida.

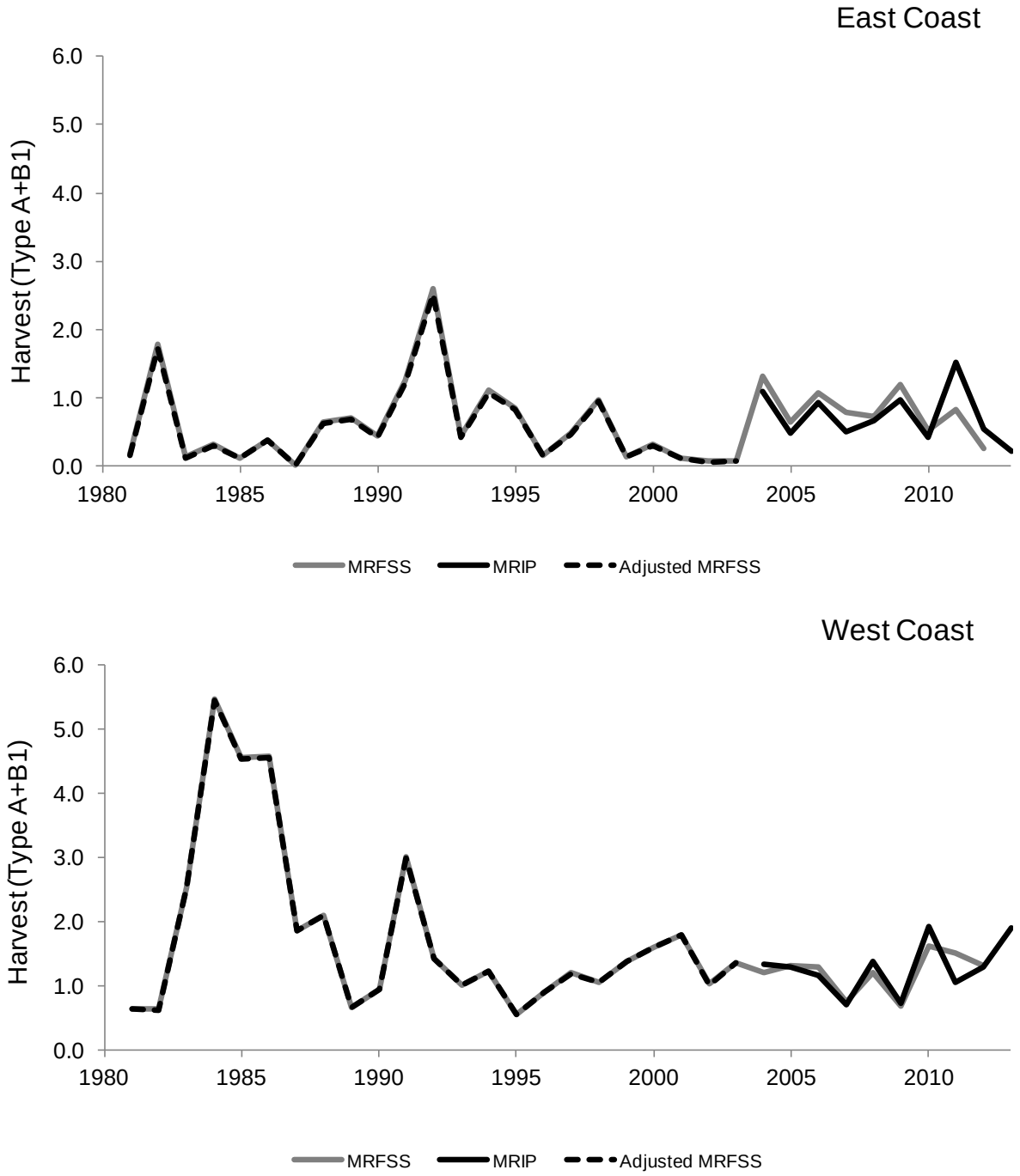


Figure 7. Calibrated recreational landings (millions of pounds) estimate for striped mullet using adjusted MRFSS/MRIP recreational landings estimates during 1981-2013 for the east and west coasts of Florida.

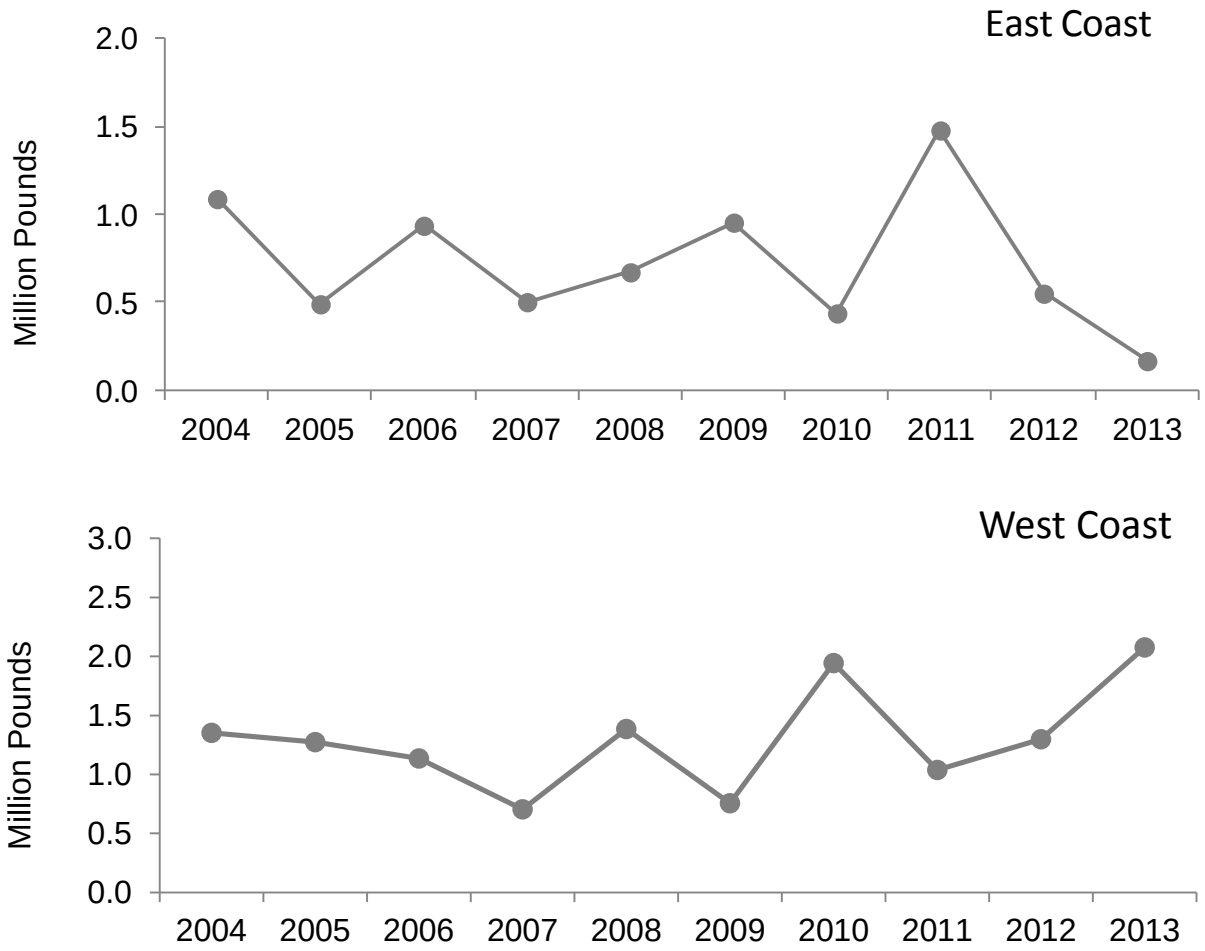


Figure 8. Recreational landings estimate for striped mullet from the MRIP database during 2004-2013 for the east and west coasts of Florida.

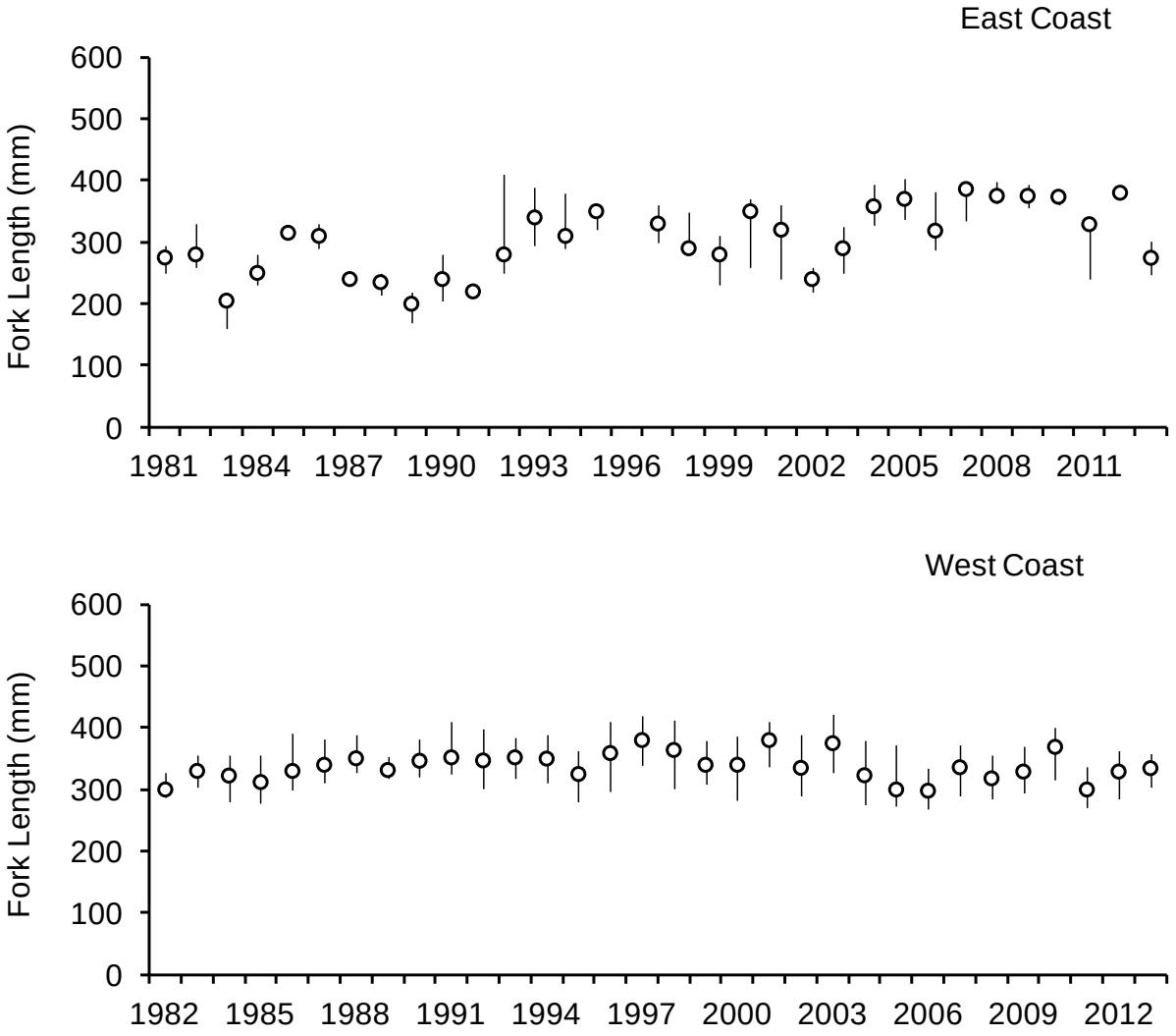


Figure 9. Median fork length estimates (MRFSS/MRIP) for recreationally caught striped mullet on the east and west coasts of Florida. The vertical line is the inter-quartiles (25 to 75 percentiles).

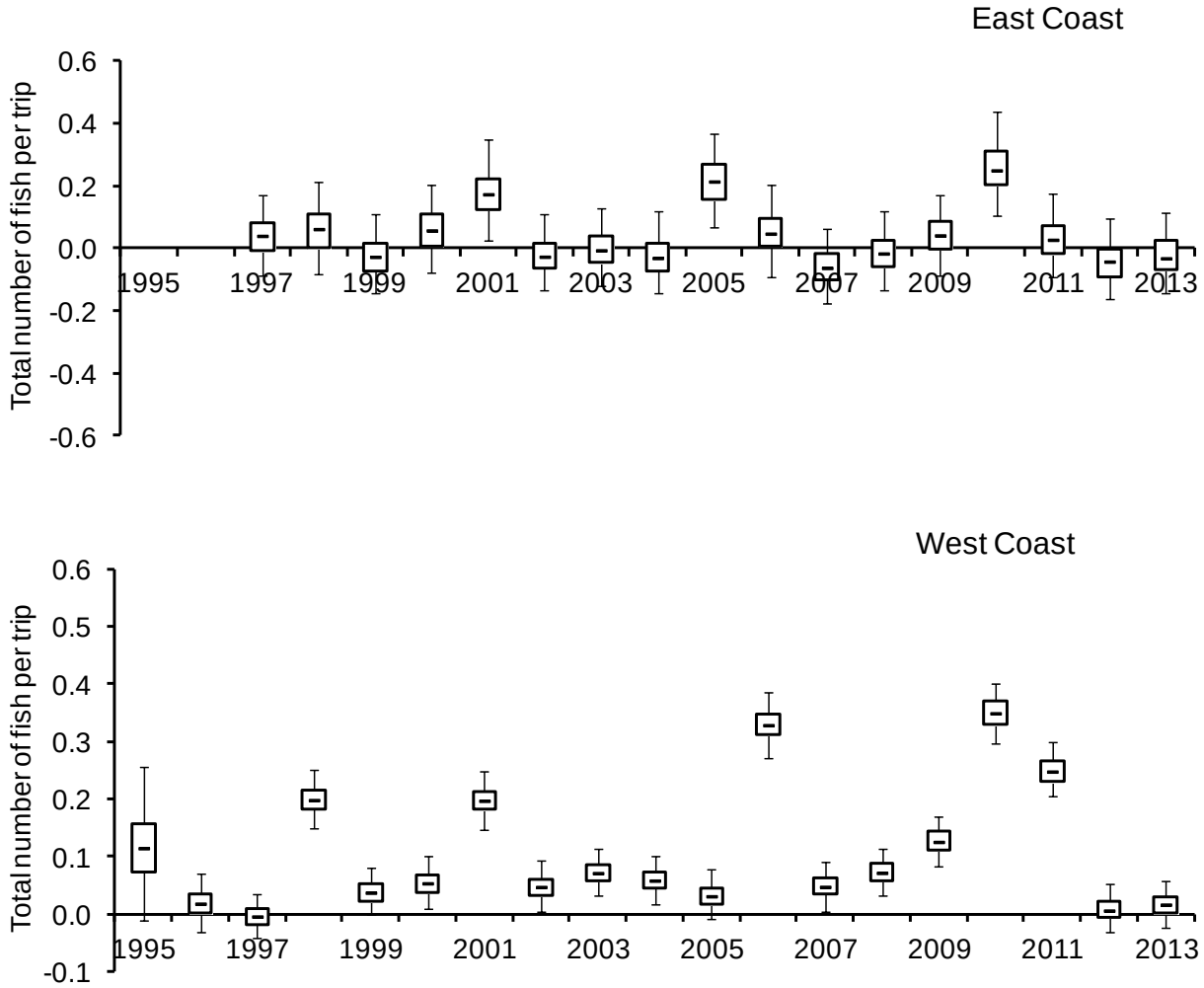


Figure 10. Box-and-whisker plots of standardized juvenile striped mullet FIM catch rates from the east and west coasts of Florida. The line within the box represents the median and the upper and lower edges define the 75th and 25th quartiles (box) with the 2.5th and 97.5th quantiles (whiskers).

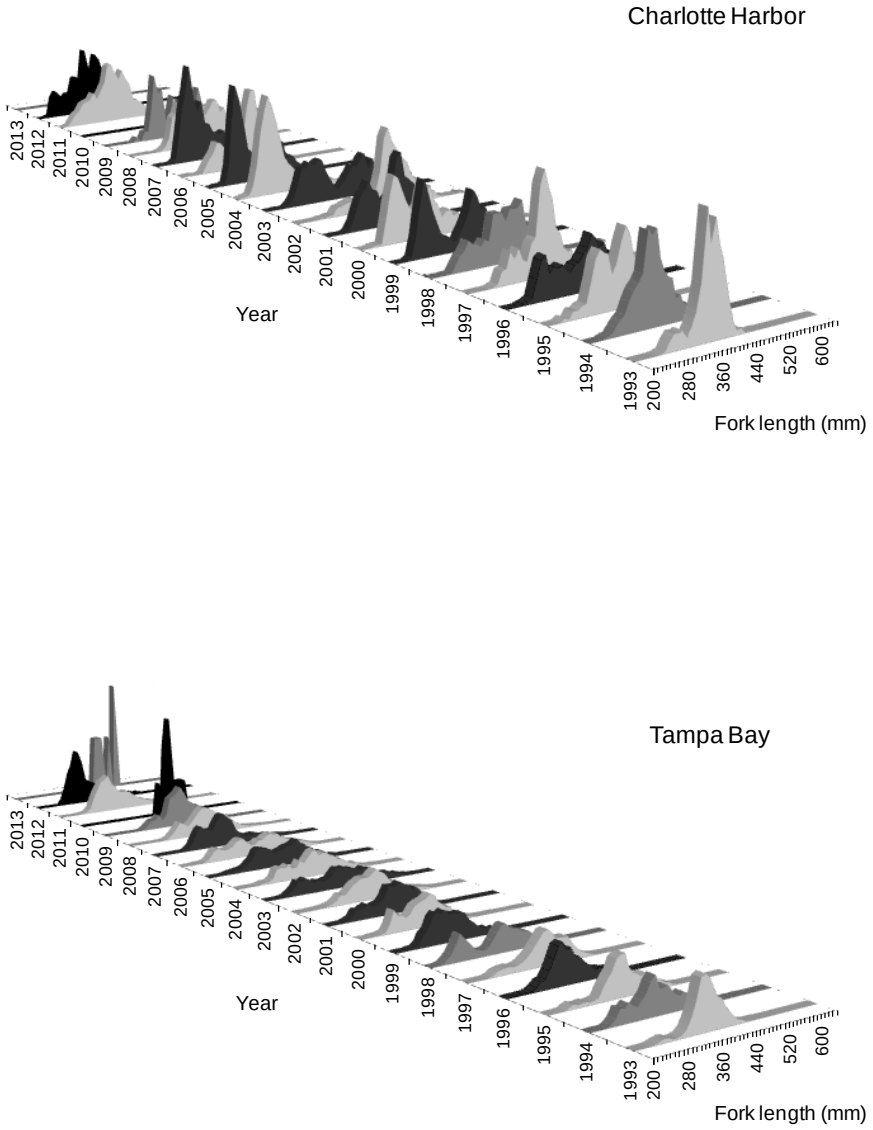


Figure 11. The length-frequency distributions of striped mullet, collected by the fishery-independent trammel net survey during September-January (spawning season) in Tampa Bay and Charlotte Harbor.

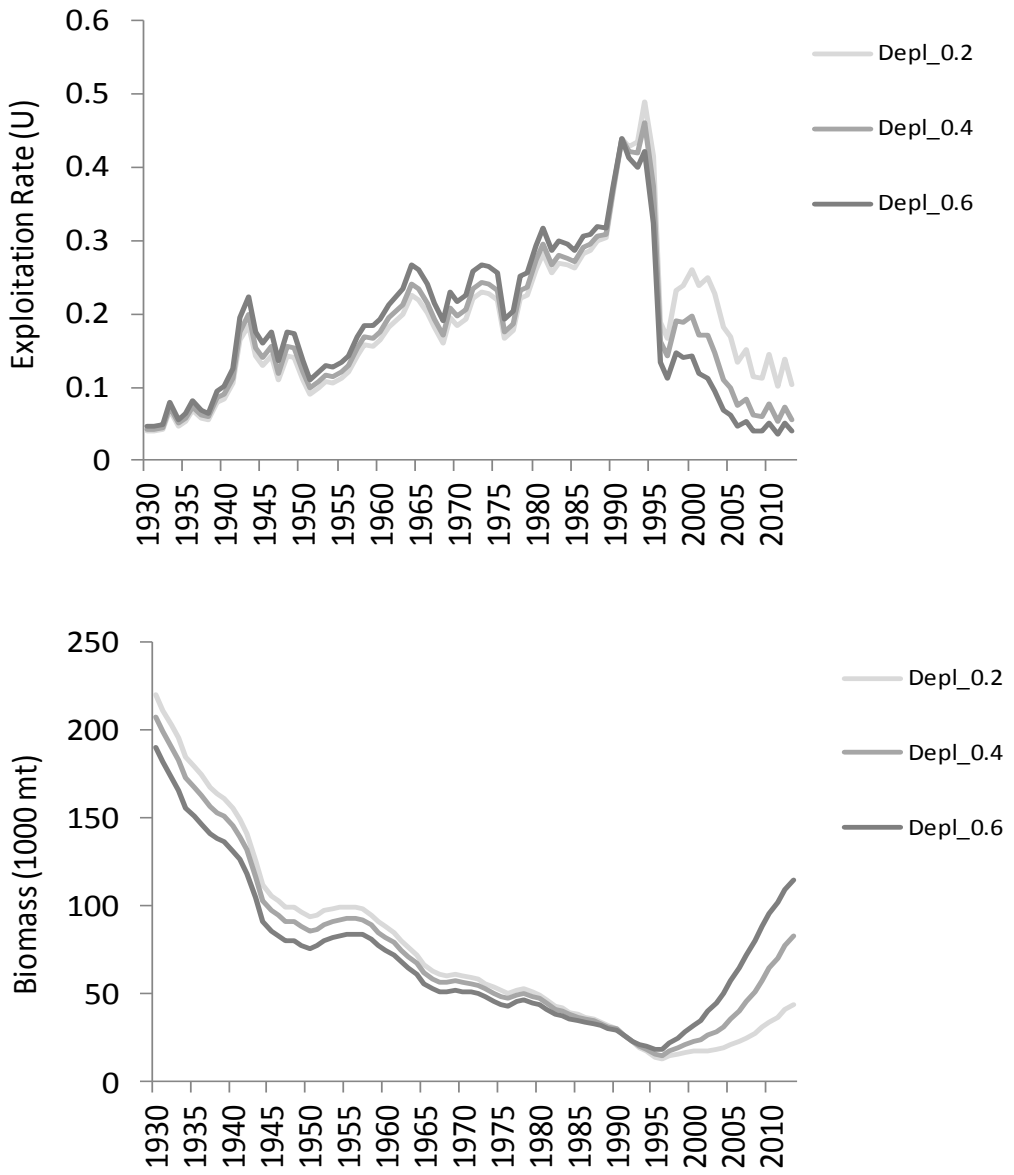


Figure 12. The exploitation rate and stock biomass trajectories estimated from the DBSRA model under various assumptions about the stock condition (poor, moderate, and good) of west coast striped mullet.

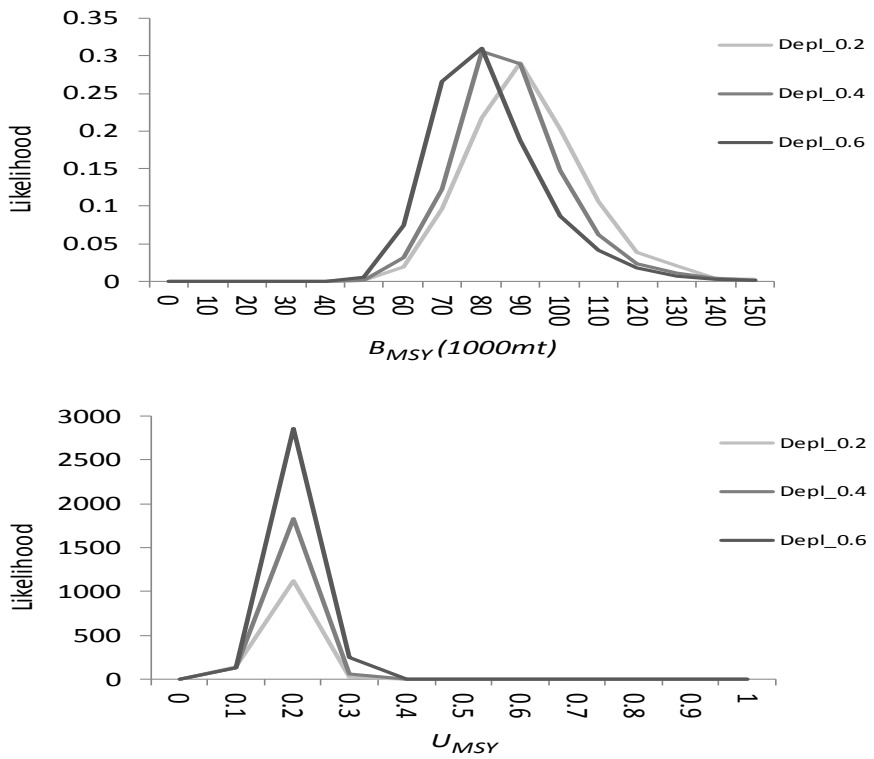


Figure 13. Probability distribution estimates of B_{MSY} and U_{MSY} from DBSRA model based on three assumed stock condition (poor, moderate, and good) of west coast striped mullet.

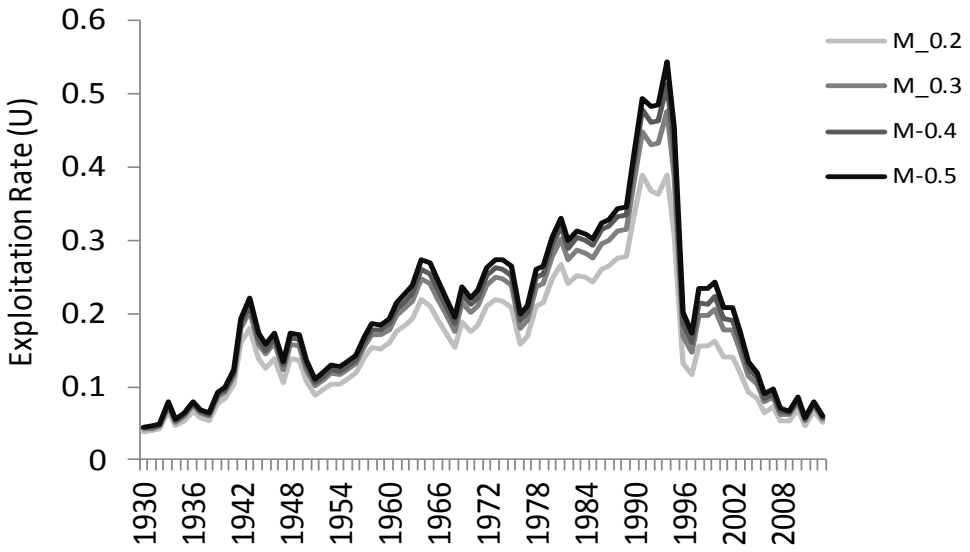


Figure 14. Exploitation rate trajectories generated from DBSRA based on four different input values of natural mortality (M) for west coast striped mullet.

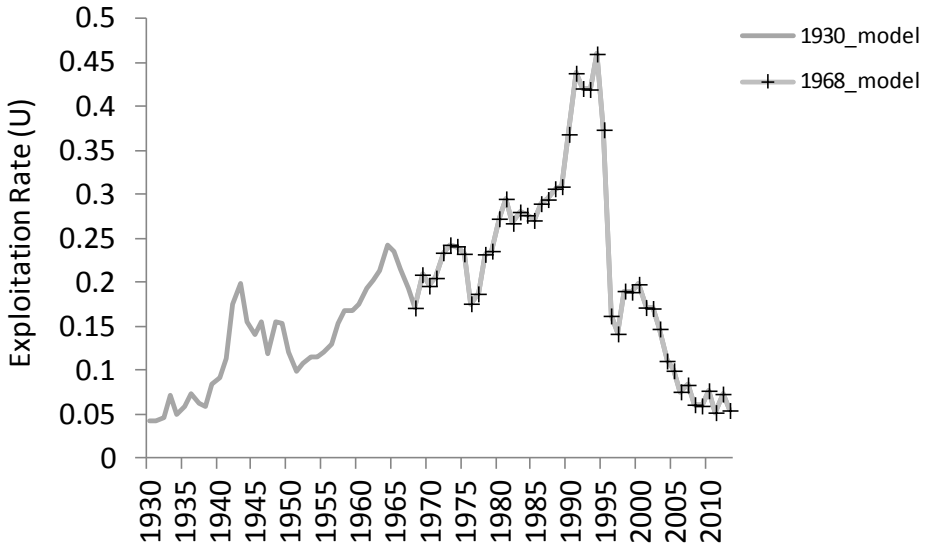


Figure 15. Exploitation rate trajectory generated from DBSRA based on two different landings time series, 1930-2013 and 1968-2013, for west coast striped mullet.

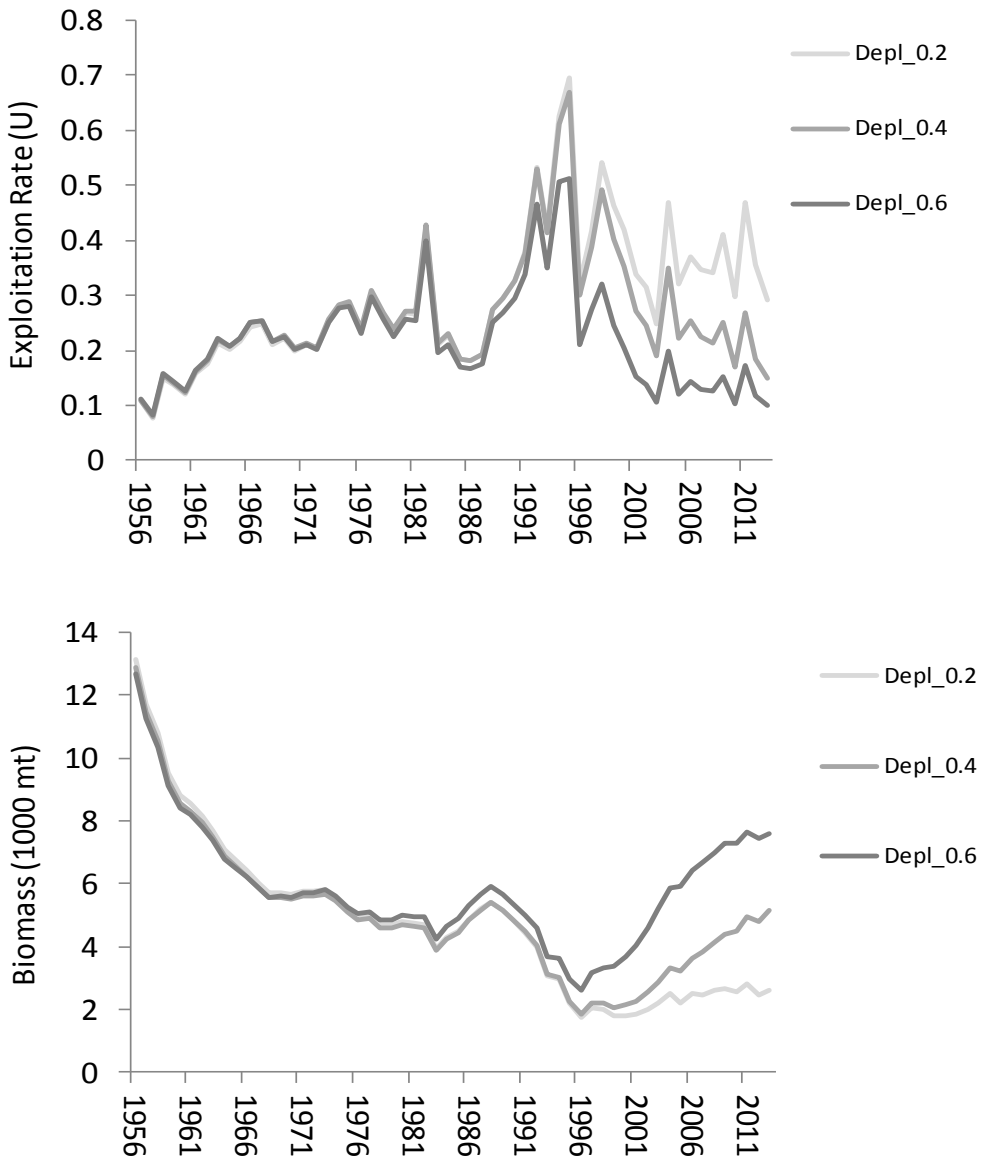


Figure 16. The exploitation rate and stock biomass trajectories estimated from the DBSRA model under various assumptions about the stock condition (poor, moderate, and good) of east coast striped mullet.

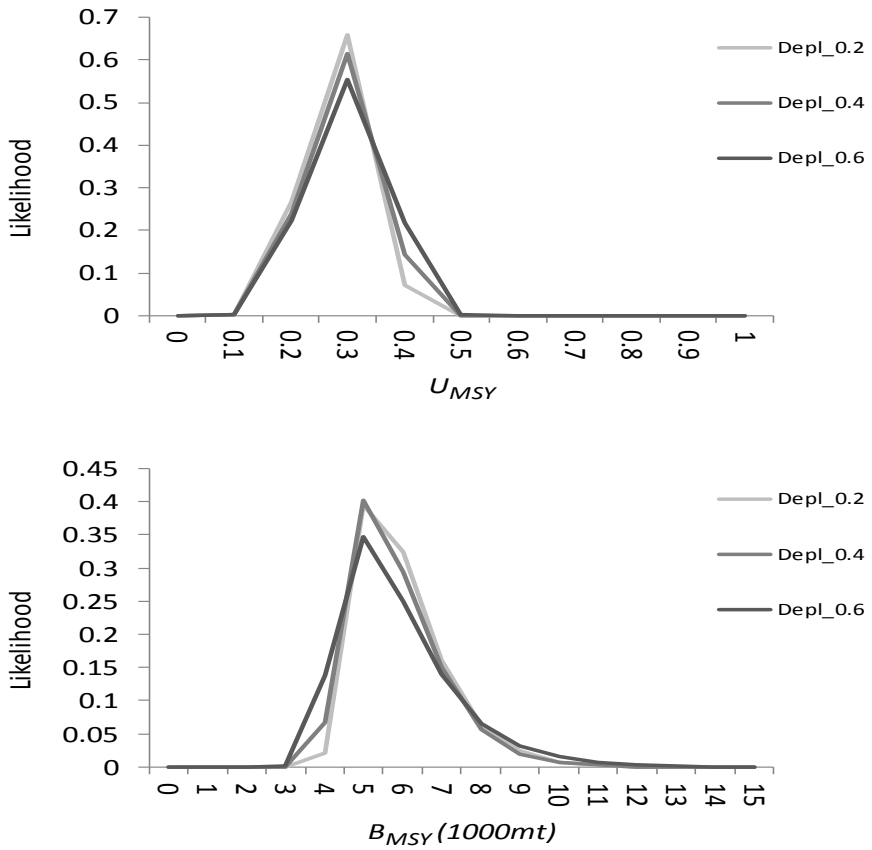


Figure 17. Probability distribution estimates of UMSY and BMSY from DBSRA model based on three assumed stock condition (poor, moderate, and good) of east coast striped mullet.

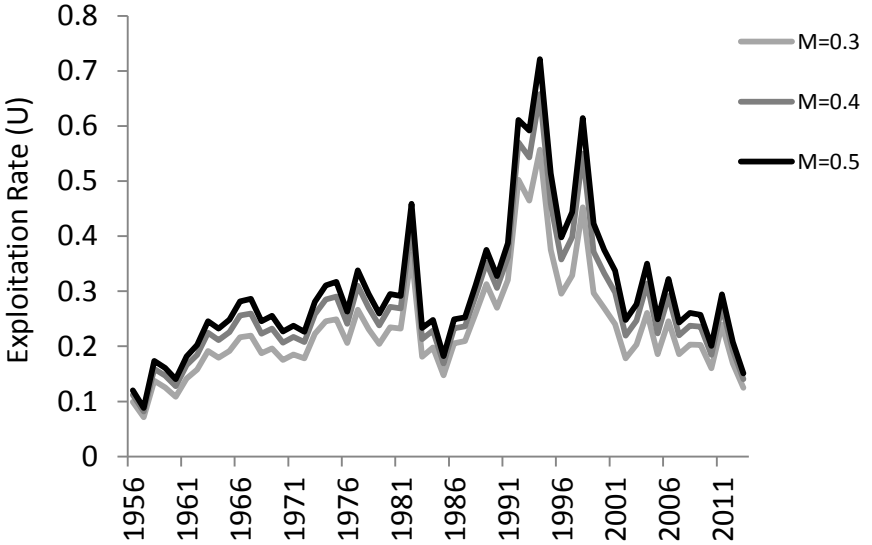


Figure 18. Exploitation rate trajectories generated from DBSRA based on four different input values of natural mortality (M) for east coast striped mullet.

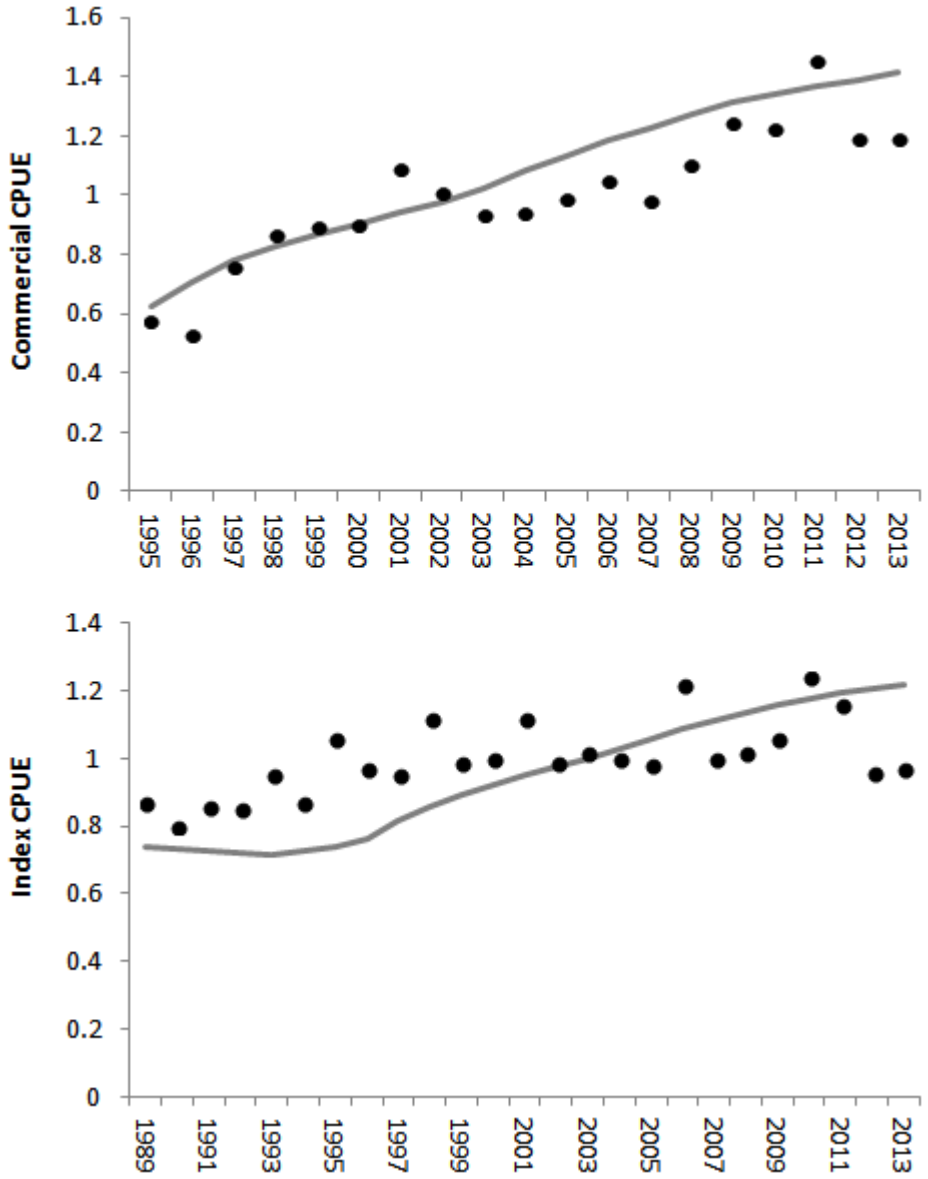


Figure 19. Predicted (line) and observed (dots) commercial cpue and juvenile index by SSRA model of striped mullet on the west coast.

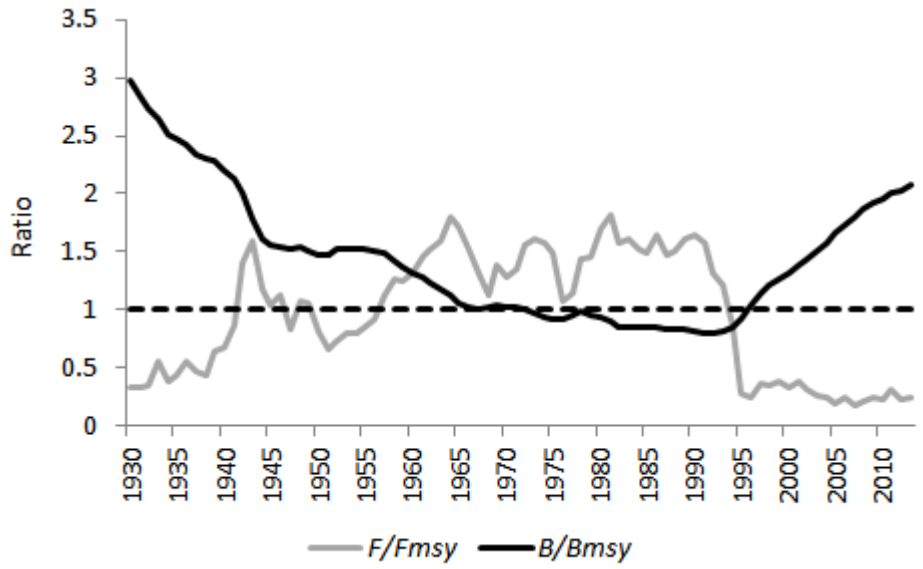


Figure 20. Biomass and fishing mortality rate ratios predicted by the SSRA model from 1930-2013 for striped mullet on the west coast.

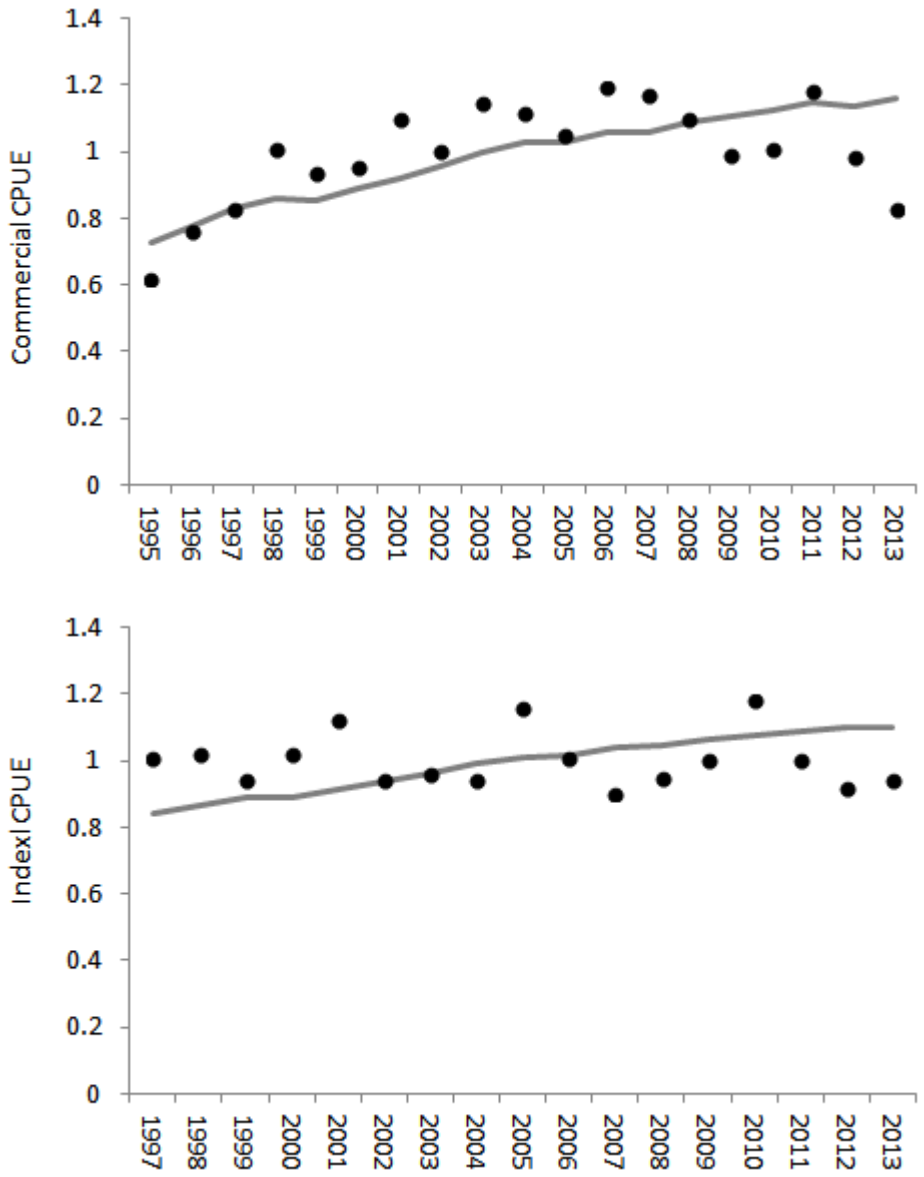


Figure 21. Predicted (line) and observed (dots) commercial cpue and juvenile index by SSRA model of striped mullet on the east coast.

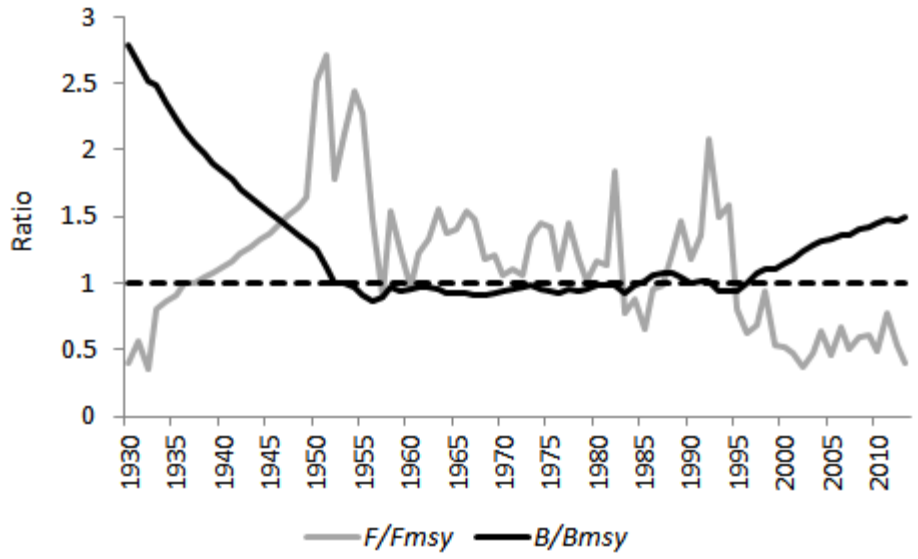


Figure 22. Biomass and fishing mortality rate ratios predicted by the SSRA model from 1930-2013 for striped mullet on the east coast.

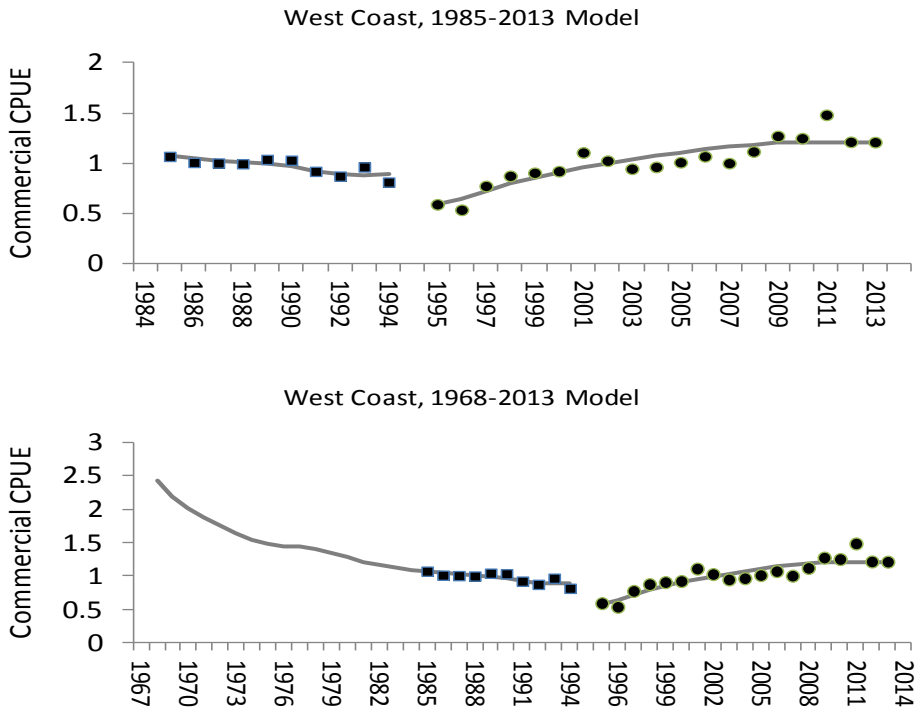
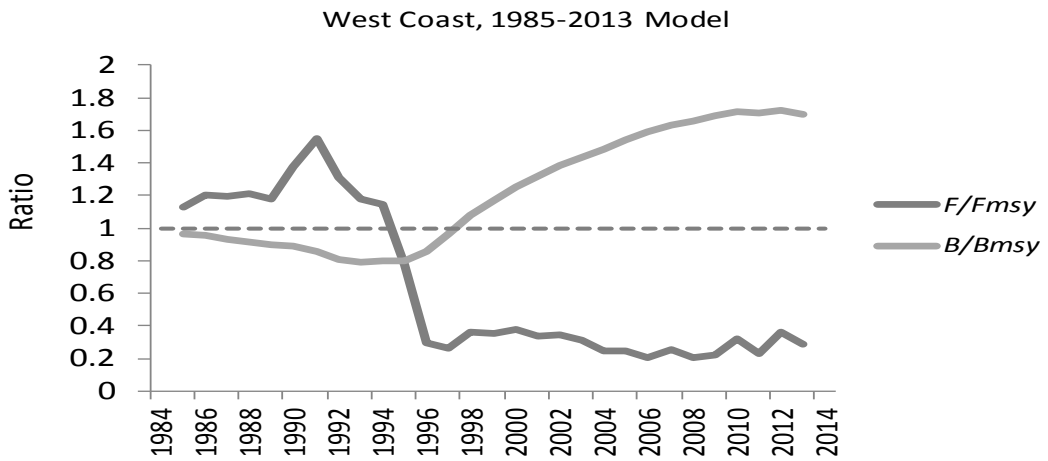


Figure 23. ASPIC model fits to the commercial catch rate (pre and post net-ban periods) based on two alternative model runs using short (1985-2013) and long (1968-2013) catch time series of striped mullet on the west coast of Florida.



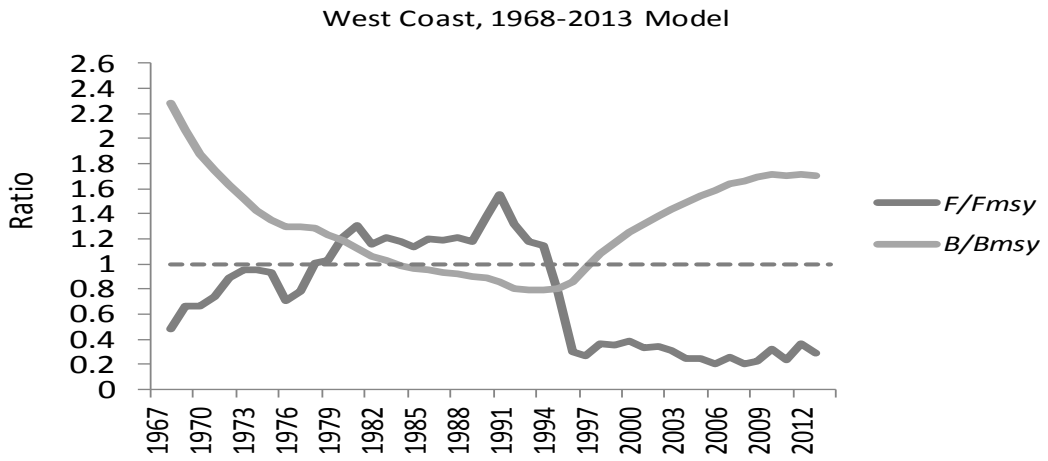
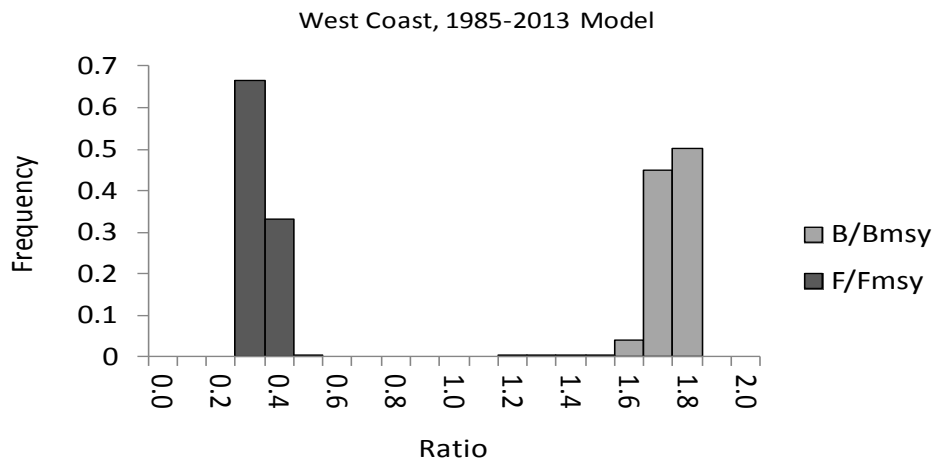


Figure 24. The ASPIC model estimates of *F/FMSY* and *B/BMSY* based on two alternative model runs using short (1985-2013) and long (1968-2013) catch time series of striped mullet on the west coast of Florida.



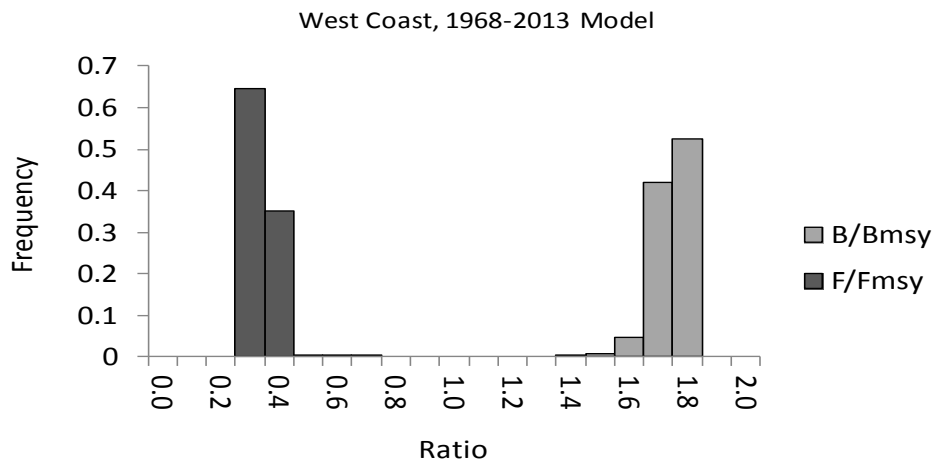


Figure 25. The ASPIC likelihood (bootstrap) estimates of *F/FMSY* and *B/BMSY* based on two alternative model runs using short (1985-2013) and long (1968-2013) catch time series of striped mullet on the west coast of Florida.

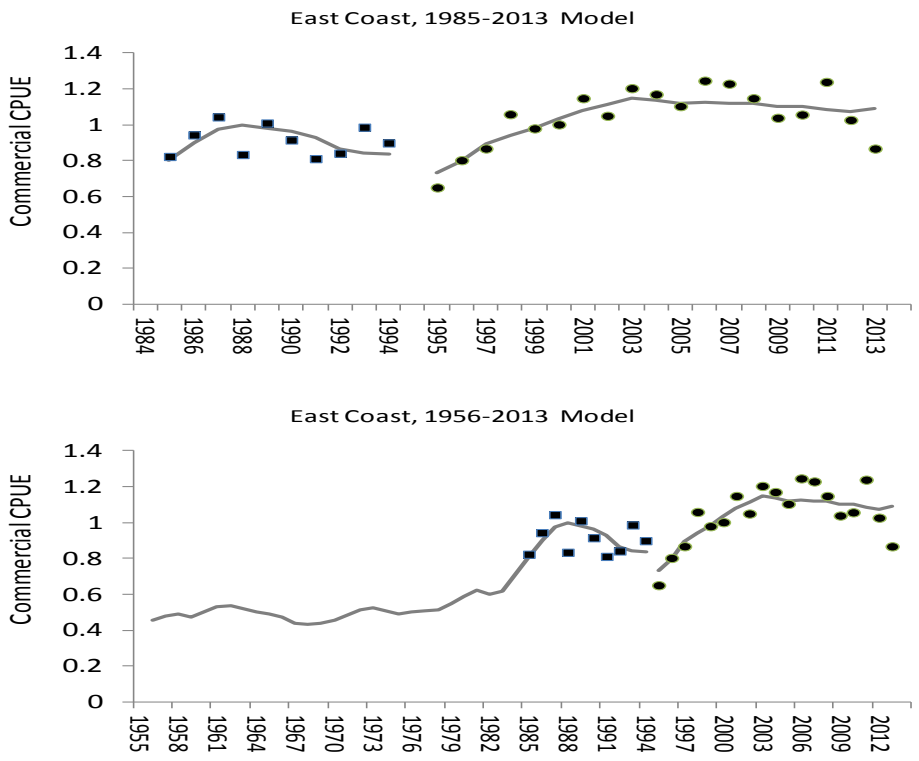


Figure 26. ASPIC model fits to the commercial catch rate (pre and post net-ban periods) based on two alternative model runs using short (1985-2013) and long (1956-2013) catch time series of striped mullet on the east coast of Florida.

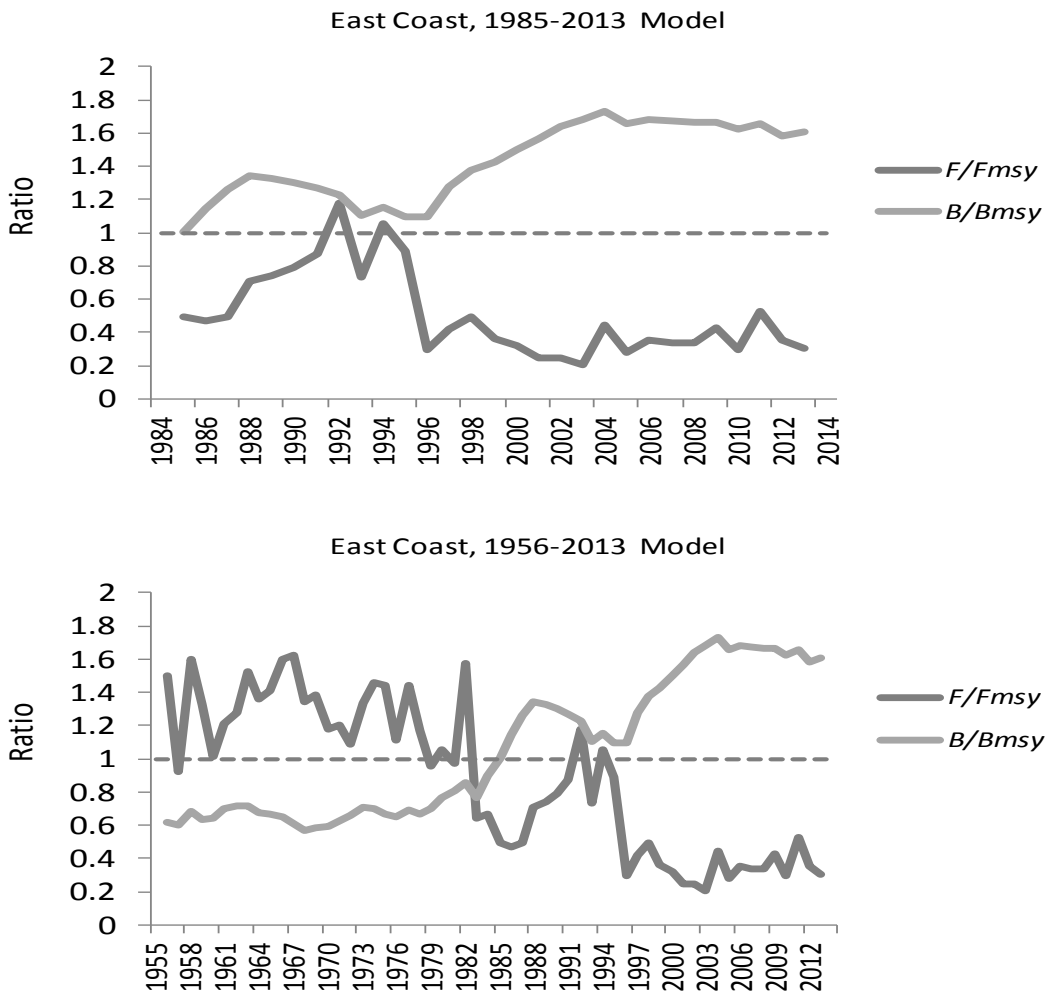
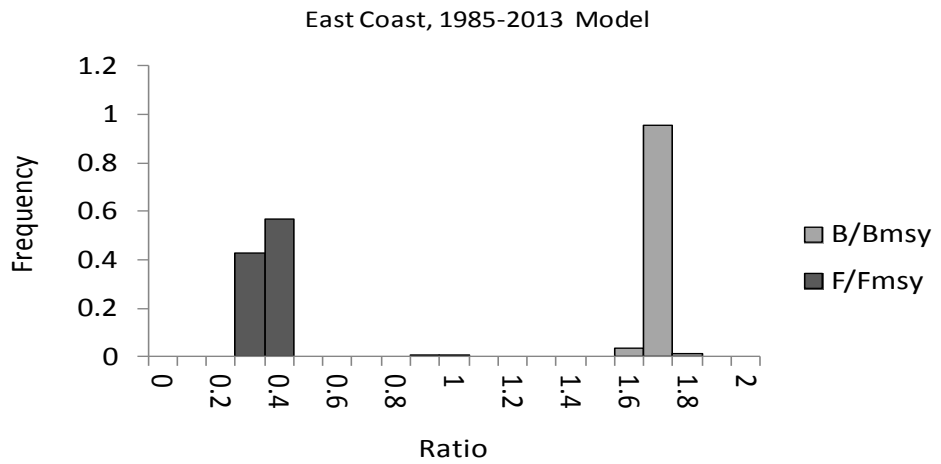


Figure 27. The ASPIC model estimates of F/FMSY and B/BMSY based on two alternative model runs using short (1985-2013) and long (1956-2013) catch time series of striped mullet on the east coast of Florida.



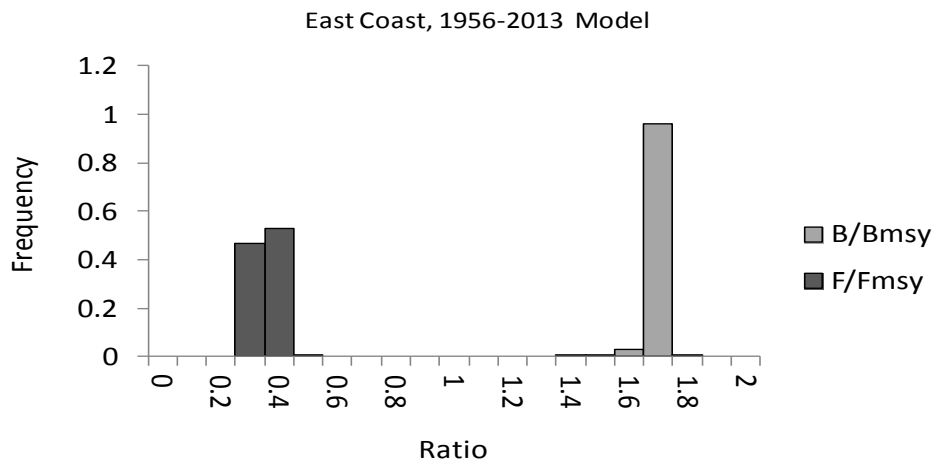


Figure 28. The ASPIC likelihood (bootstrap) estimates of F/FMSY and B/BMSY based on two alternative model runs using short (1985-2013) and long (1956-2013) catch time series of striped mullet on the east coast of Florida.

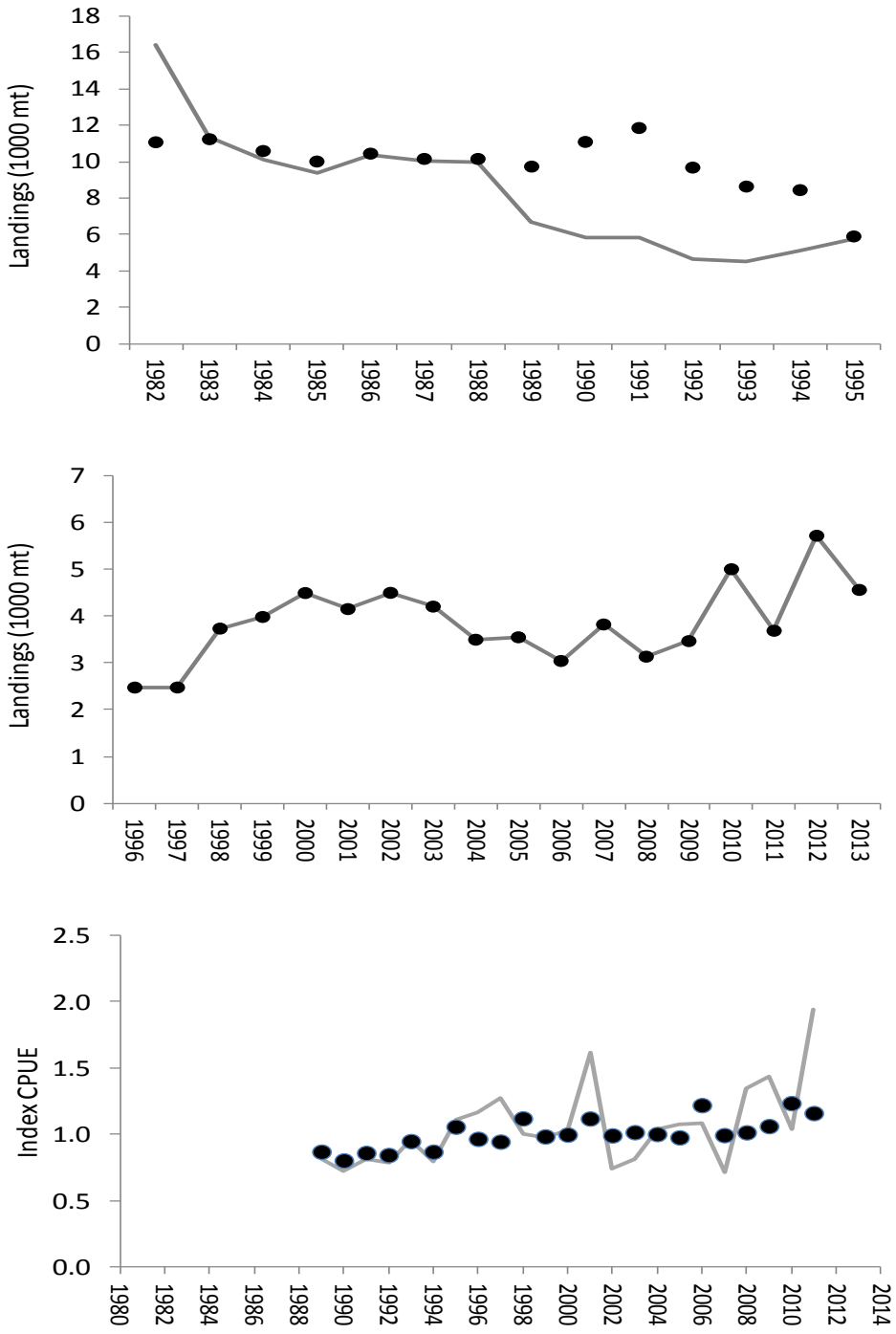


Figure 29. The Discrete Delay-difference model fits to the commercial landings (pre, 1982-95 and post net-ban periods, 1996-2013) and fishery-independent juvenile index series for striped mullet on the west coast of Florida.

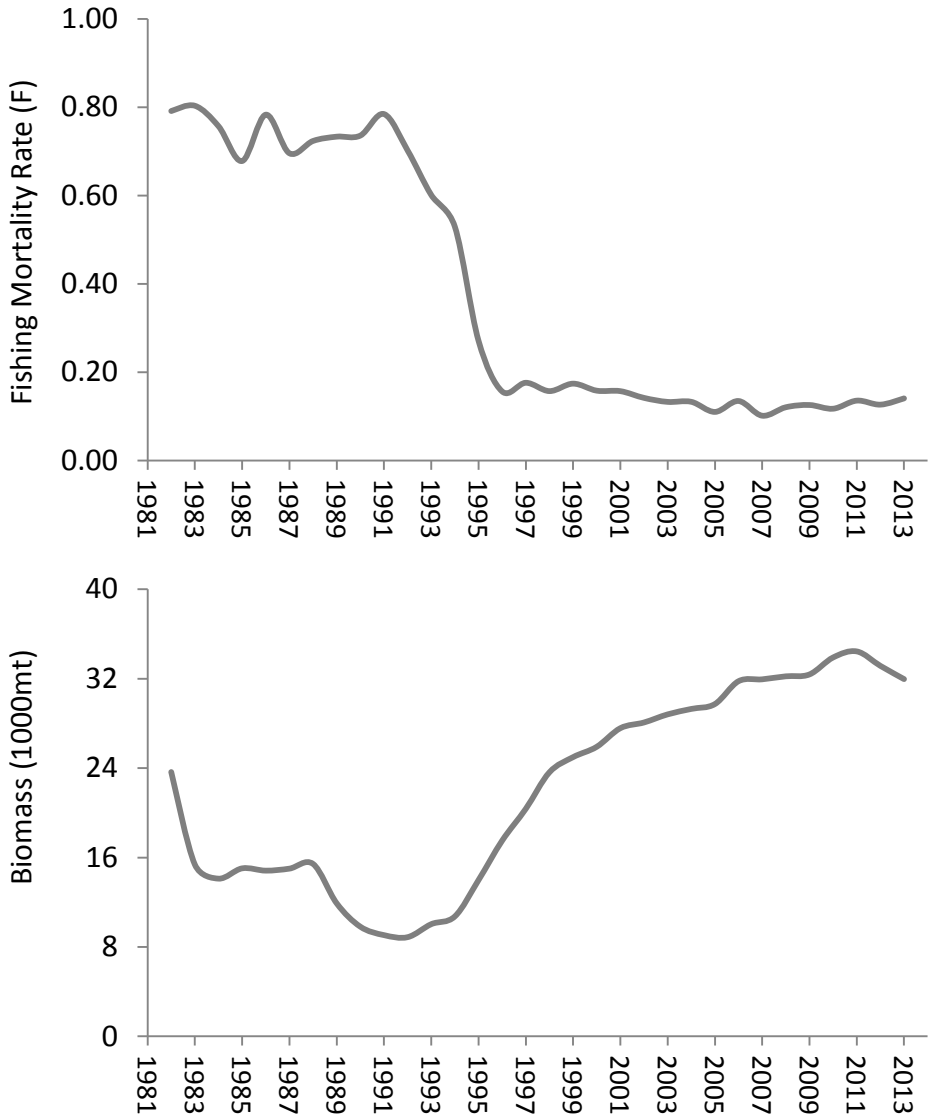


Figure 30. The Discrete Delay-difference model estimates of instantaneous fishing mortality rate (*F*) and biomass (mt) for striped mullet on the west coast of Florida.

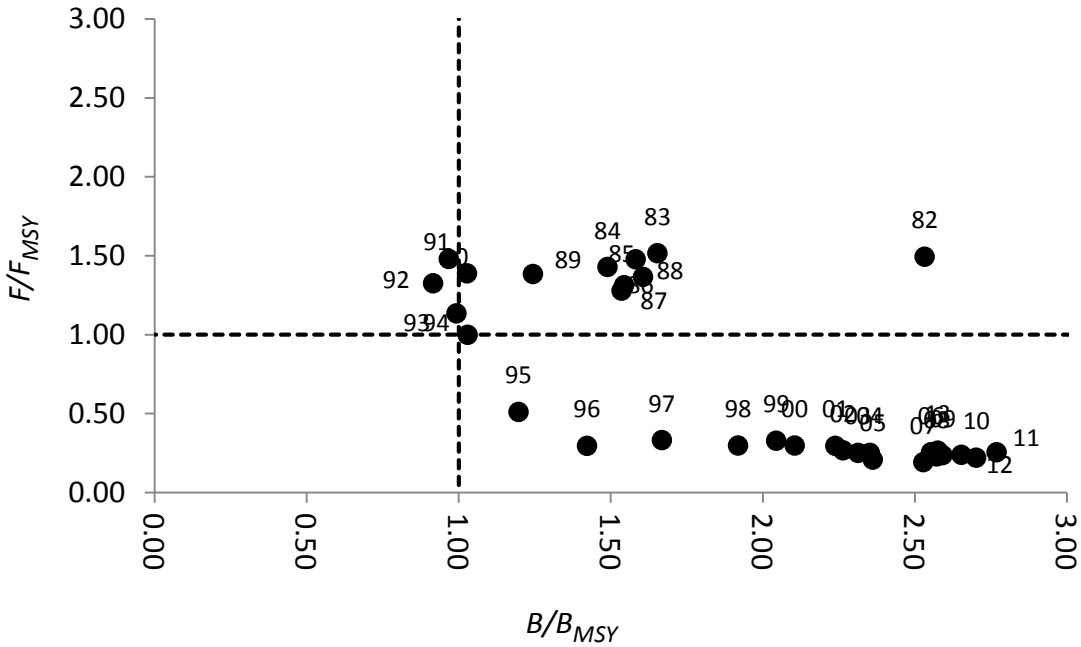


Figure 31. Phase plot of fishing mortality and stock status relative to F_{MSY} and B_{MSY} from the discrete delay-difference model for striped mullet on the west coast of Florida.

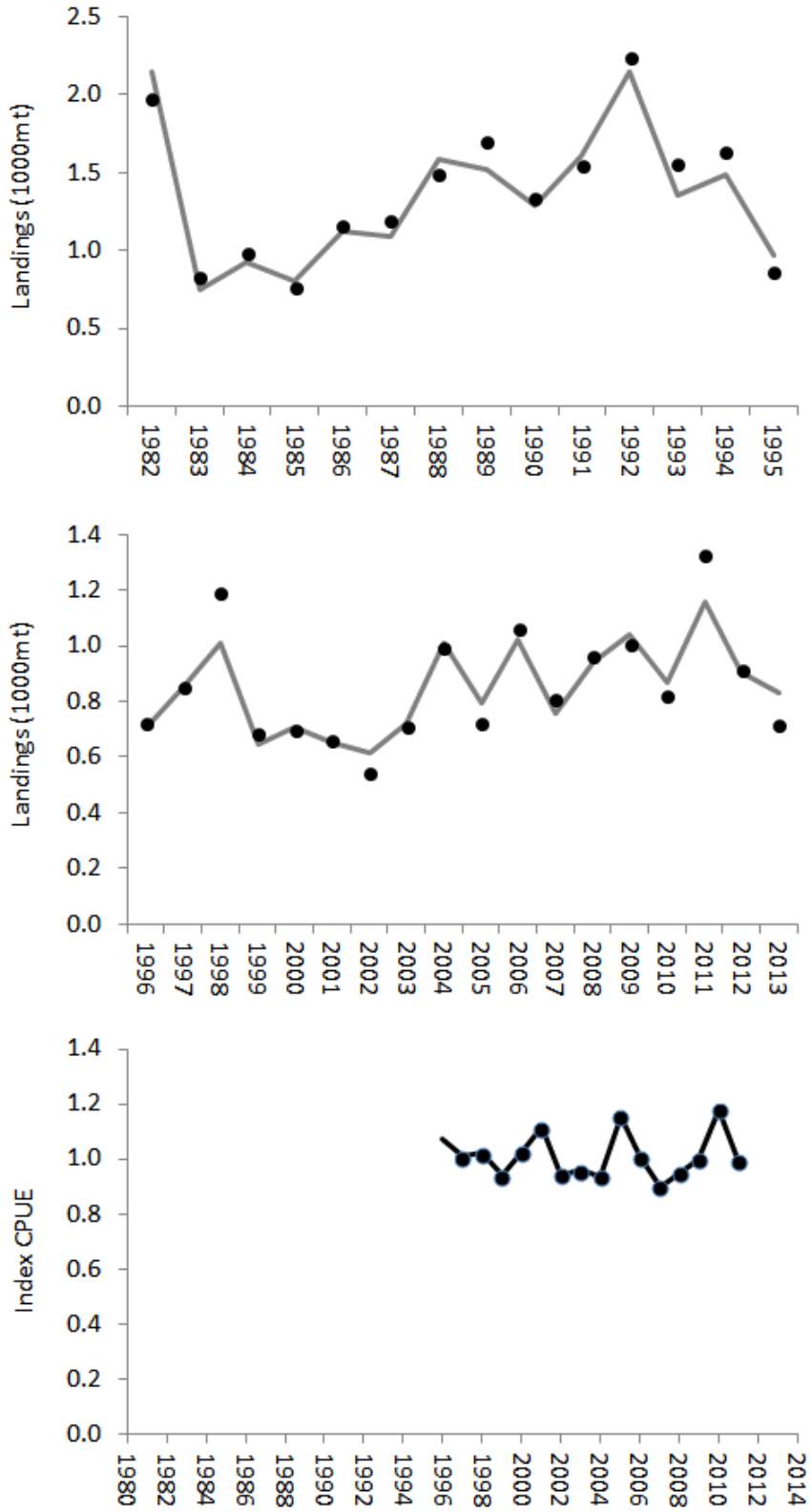


Figure 32. The Discrete Delay-difference model fits to the commercial landings (pre, 1982-95 and post net-ban periods, 1996-2013) and fishery-independent juvenile index series for striped mullet on the east coast of Florida.

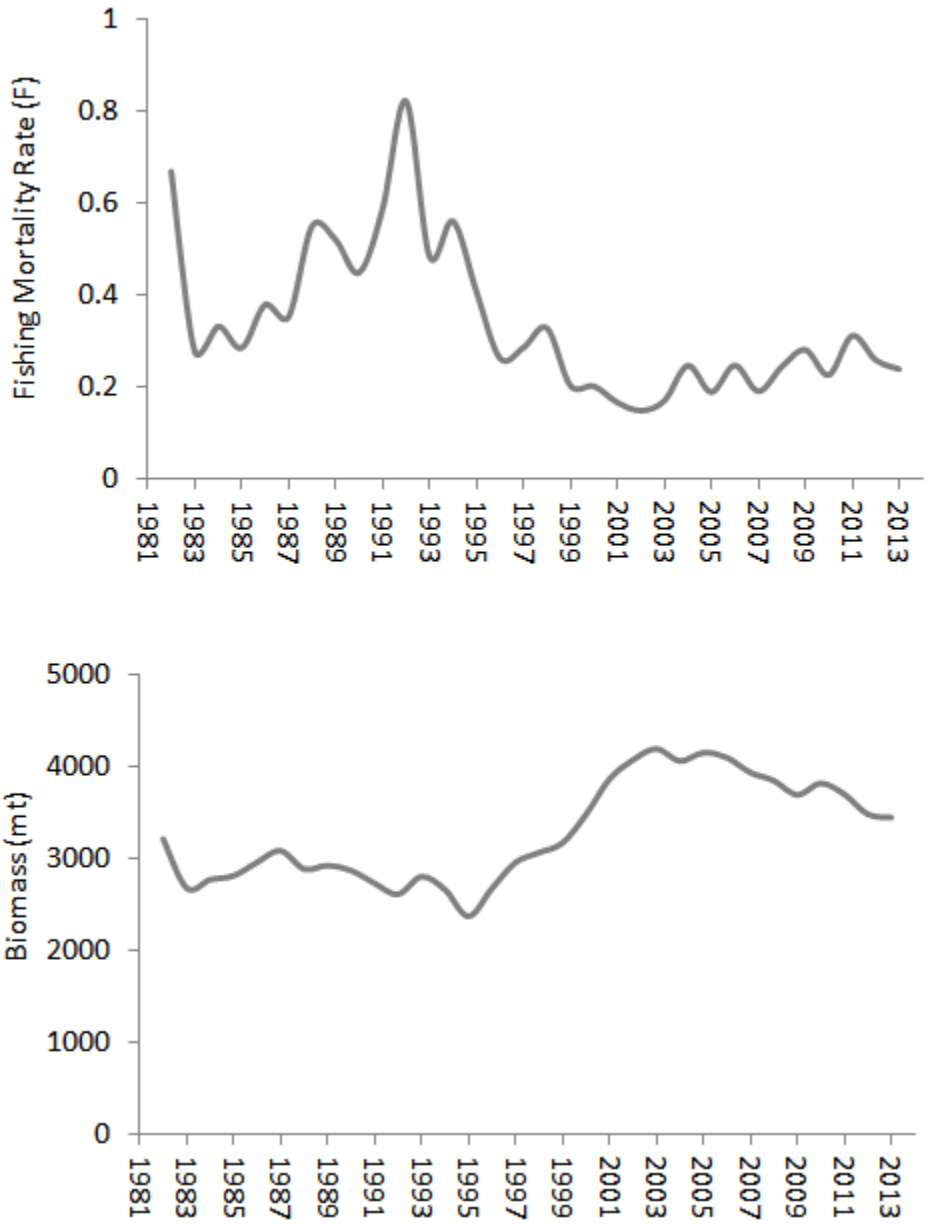


Figure 33. The Discrete Delay-difference model estimates of instantaneous fishing mortality rate (*F*) and Biomass (mt) for striped mullet on the east coast of Florida.

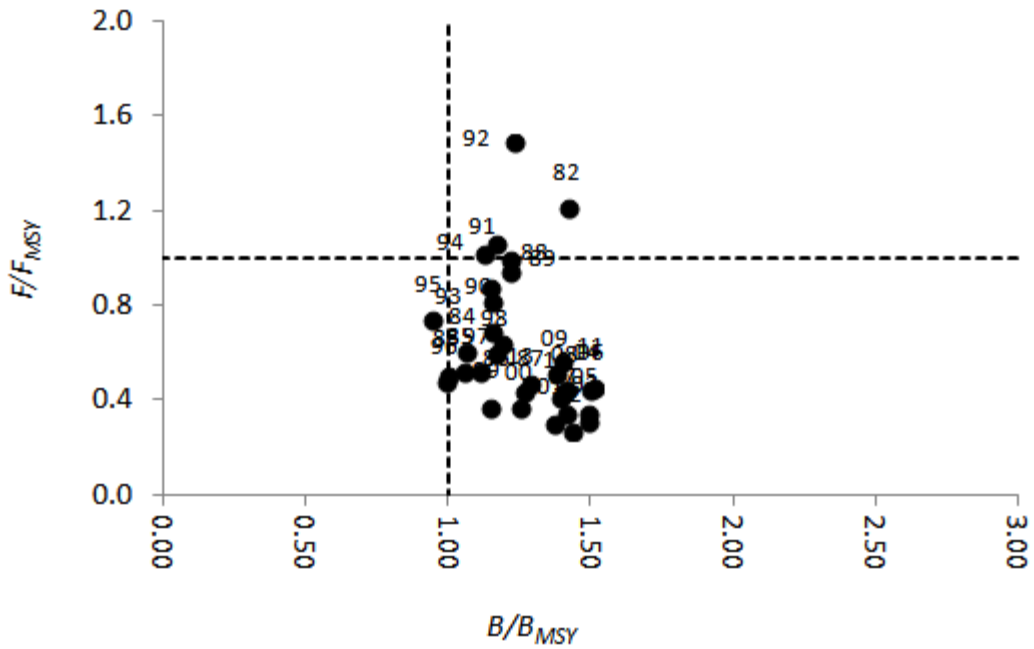


Figure 34. Phase plot of fishing mortality and stock status relative to F_{MSY} and B_{MSY} from the discrete delay-difference model for striped mullet on the east coast of Florida.

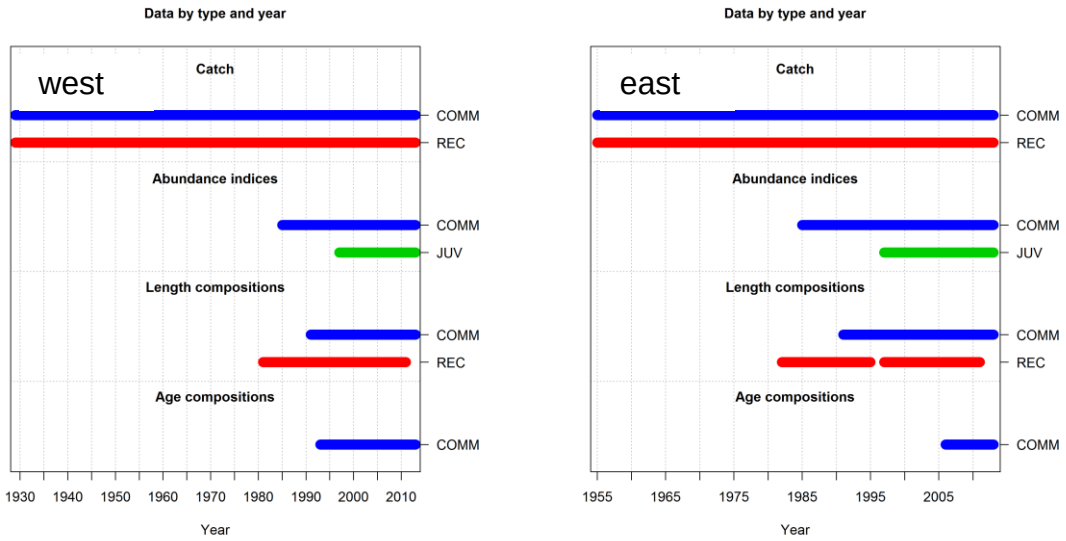


Figure 35. Data presence by year for each fleet for the SS3 models of striped mullet on the west and east coasts of Florida.

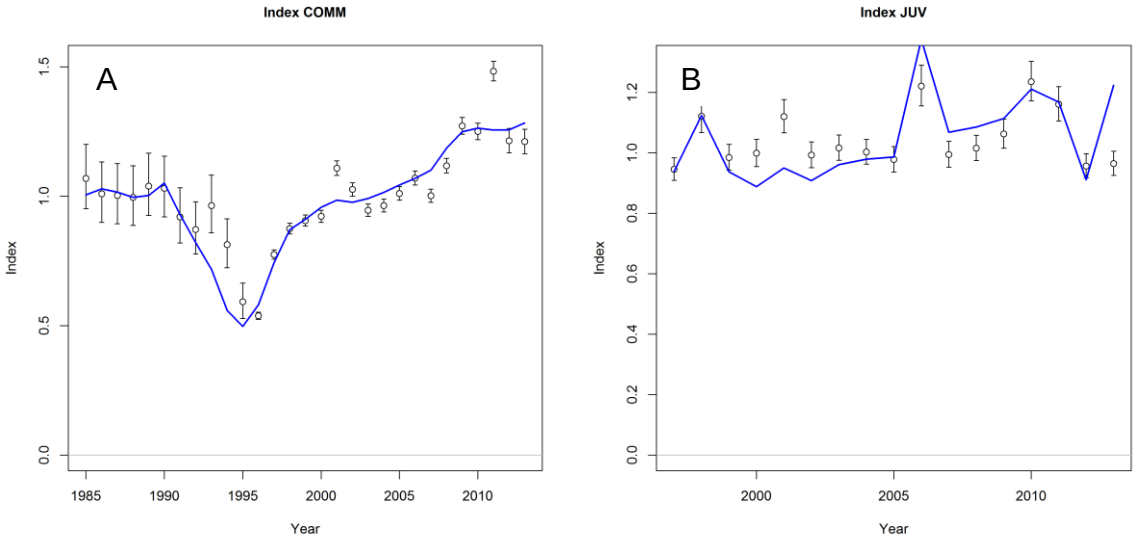


Figure 36. Fit to commercial CPUE (A) and FIM juvenile survey index (B) from the SS3 model of striped mullet on the west coast.

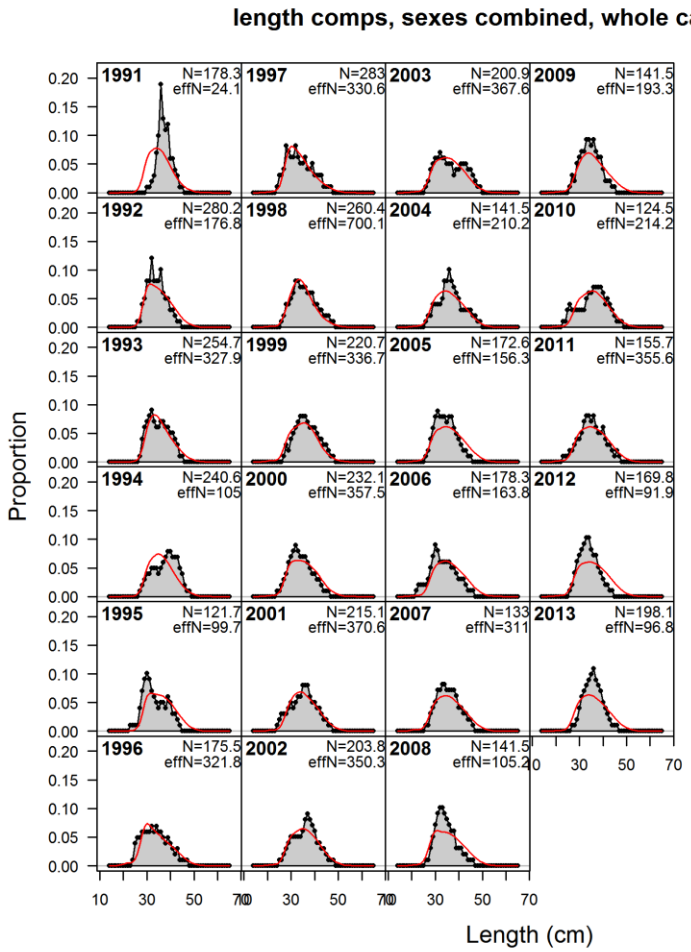


Figure 37. Fits to commercial length compositions by year from the SS3 model of striped mullet on the west coast.

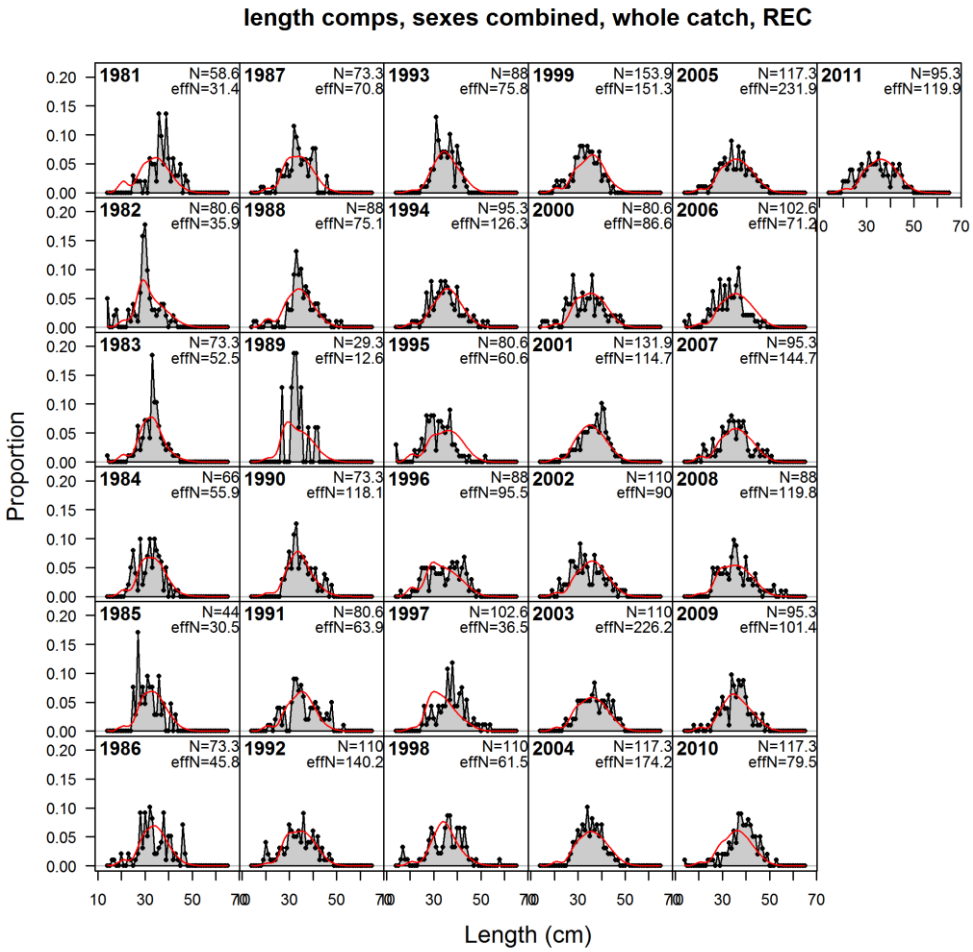


Figure 38. Fits to recreational length compositions by year from the SS3 model of striped mullet on the west coast.

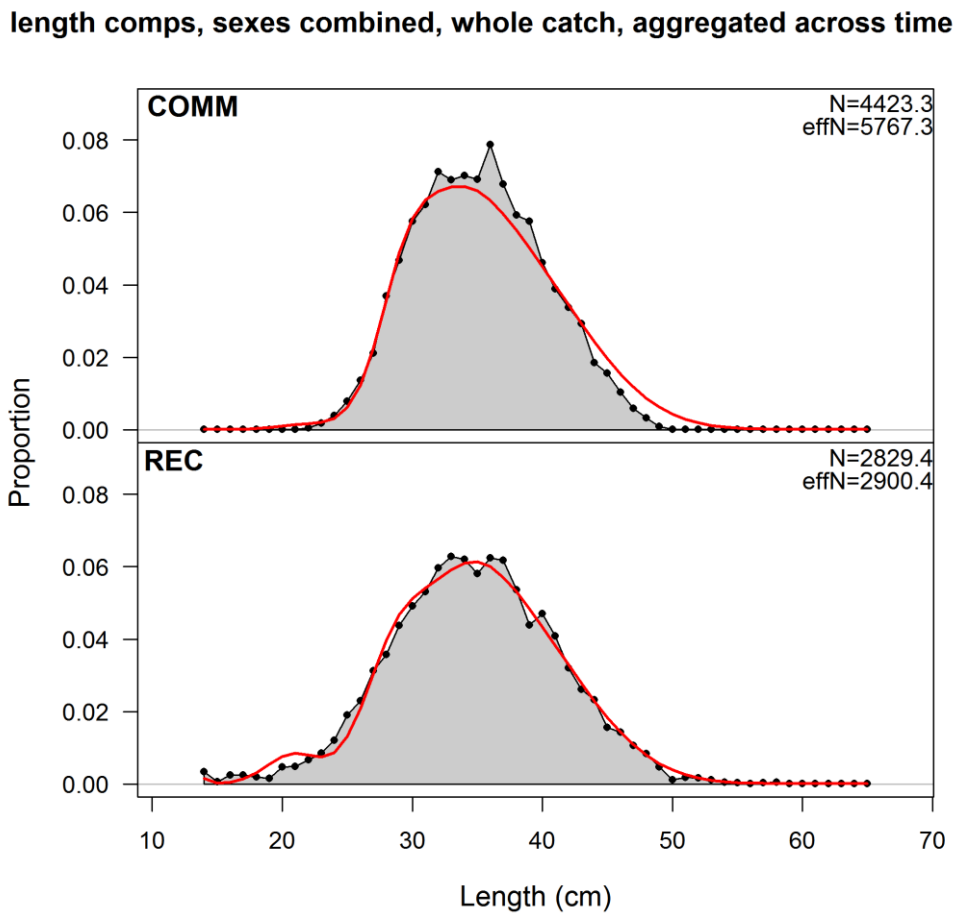


Figure 39. Fits to length compositions by fleet aggregated across time from the SS3 model of striped mullet on the west coast.

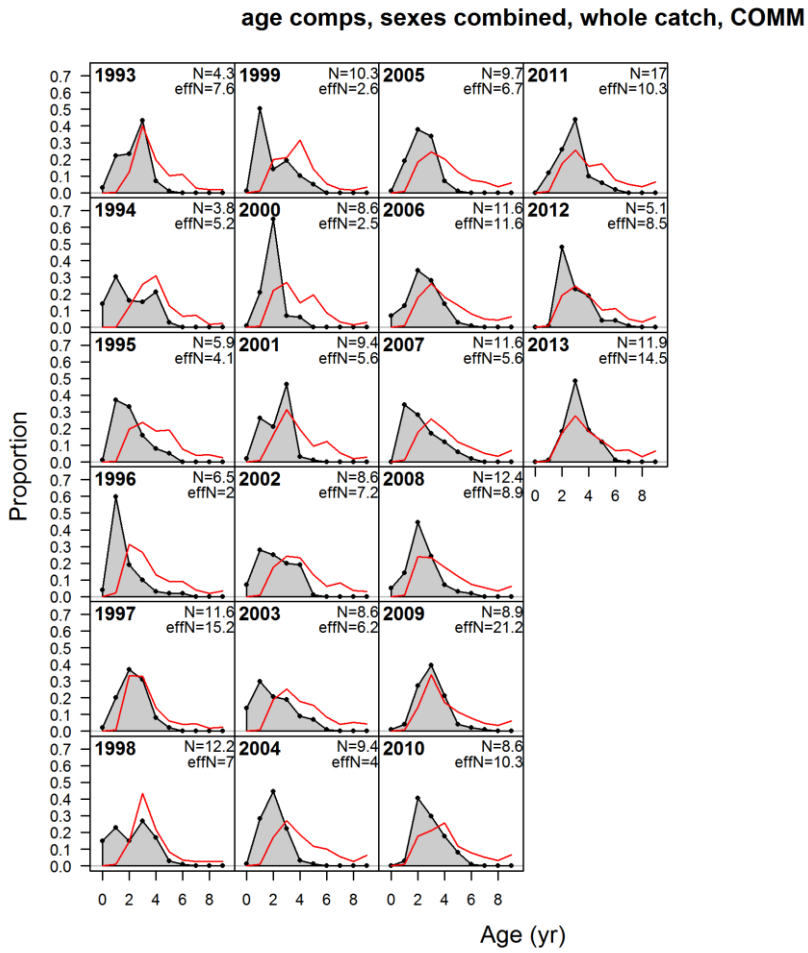


Figure 40. Fits to commercial age compositions by year from the SS3 model of striped mullet on the west coast.

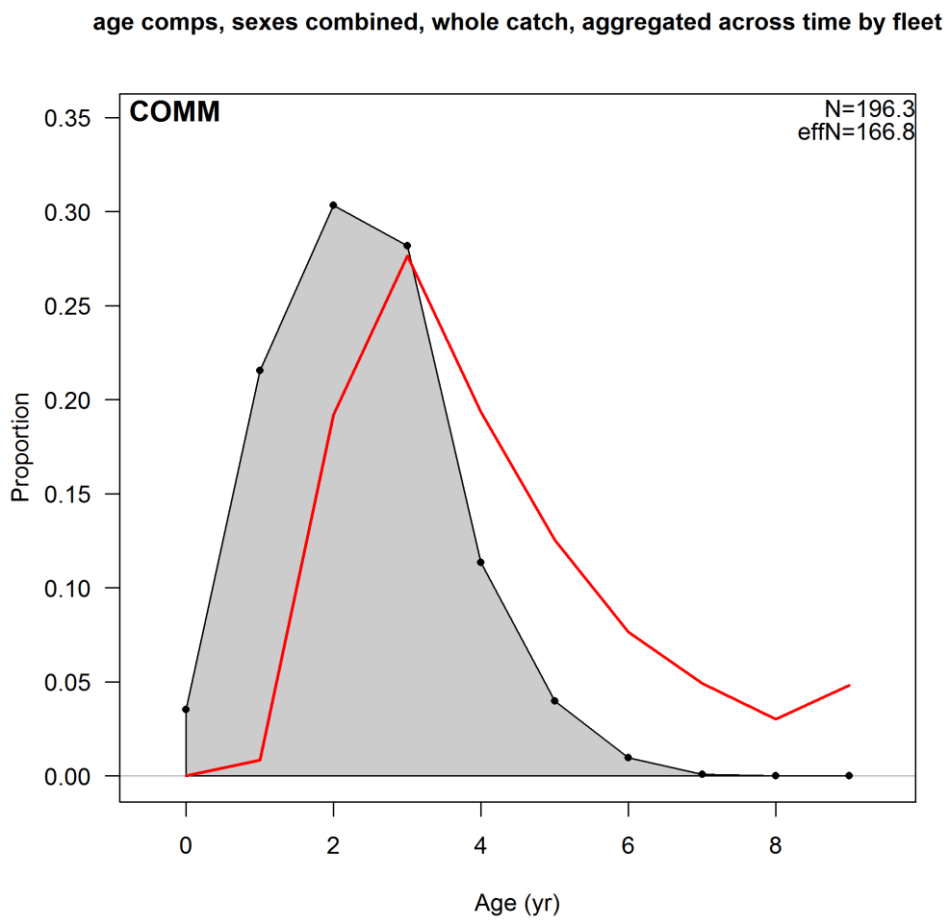


Figure 41. Fits to commercial age compositions aggregated across time from the SS3 model of striped mullet on the west coast.

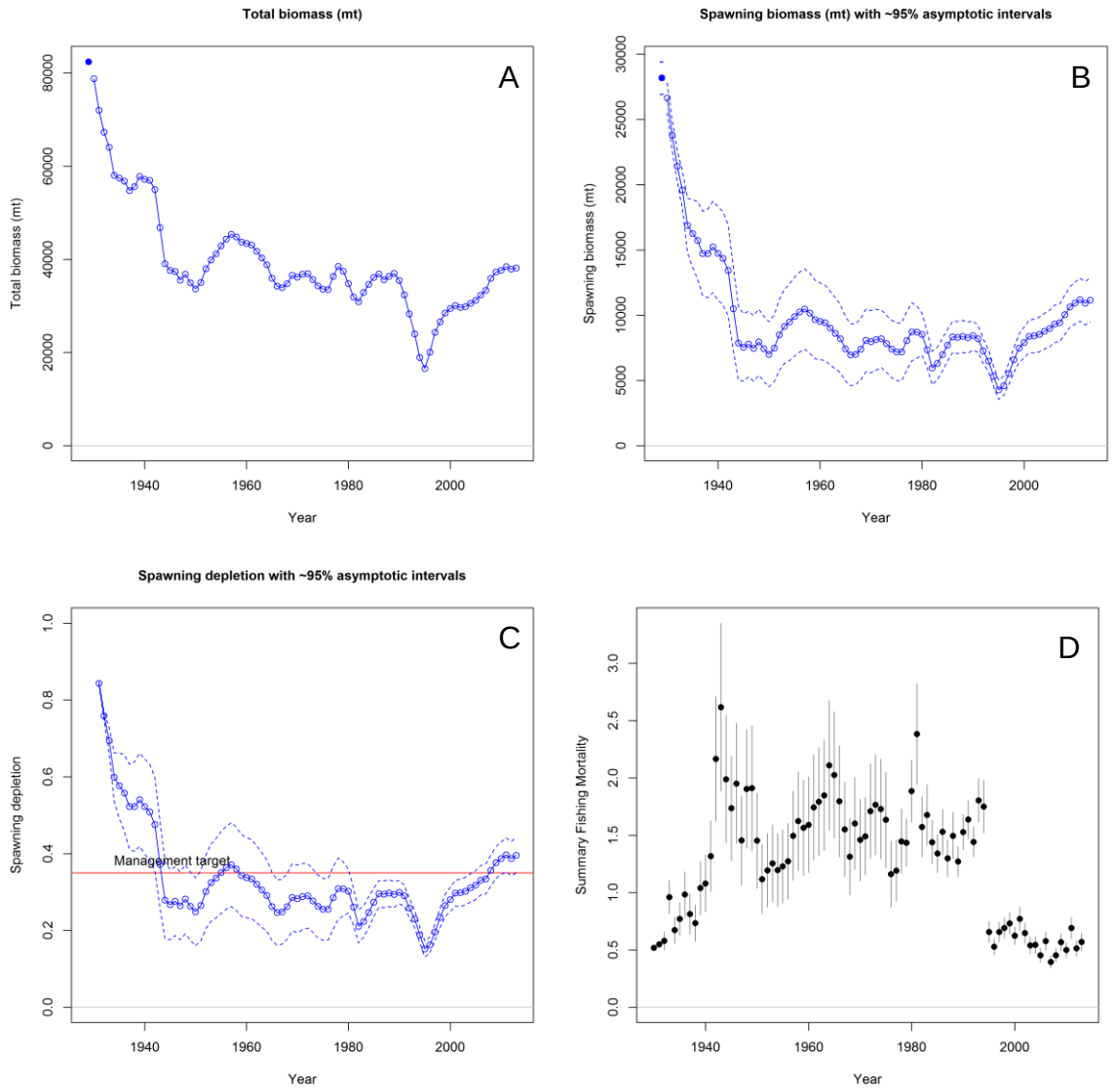


Figure 42. Total biomass (A), spawning biomass with ~95% asymptotic intervals (B), spawning depletion with ~95% confidence intervals (C), and fishing mortality ratio, $F/F_{SPR35\%}$, by year with ~95% confidence intervals (D) from the SS3 model of striped mullet on the west coast.

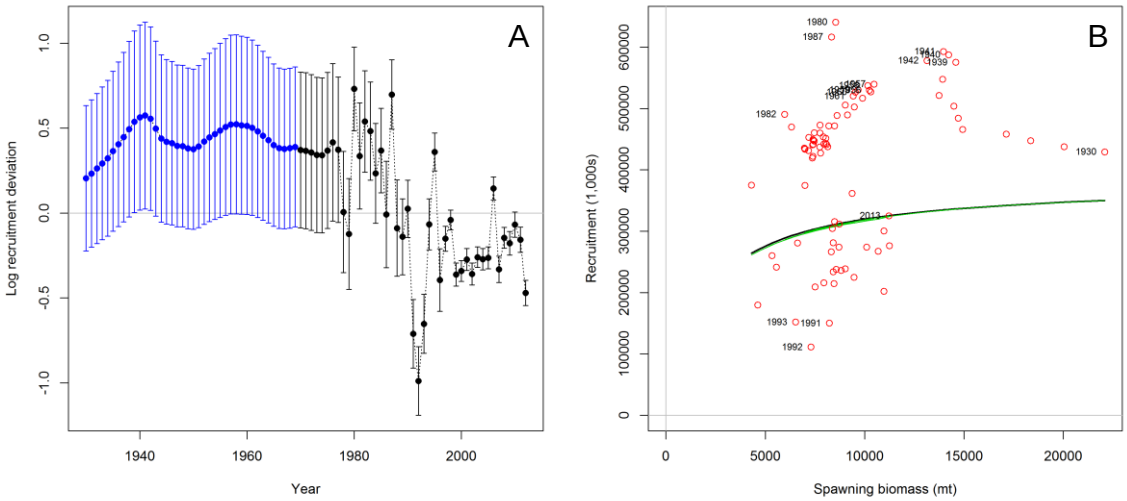


Figure 43. Recruitment deviations with uncertainty (A), and the spawner-recruit relationship (B) from the SS3 model of striped mullet on the west coast. Recruitment deviations are estimated for an early period (blue) and the main period with the majority of data available.

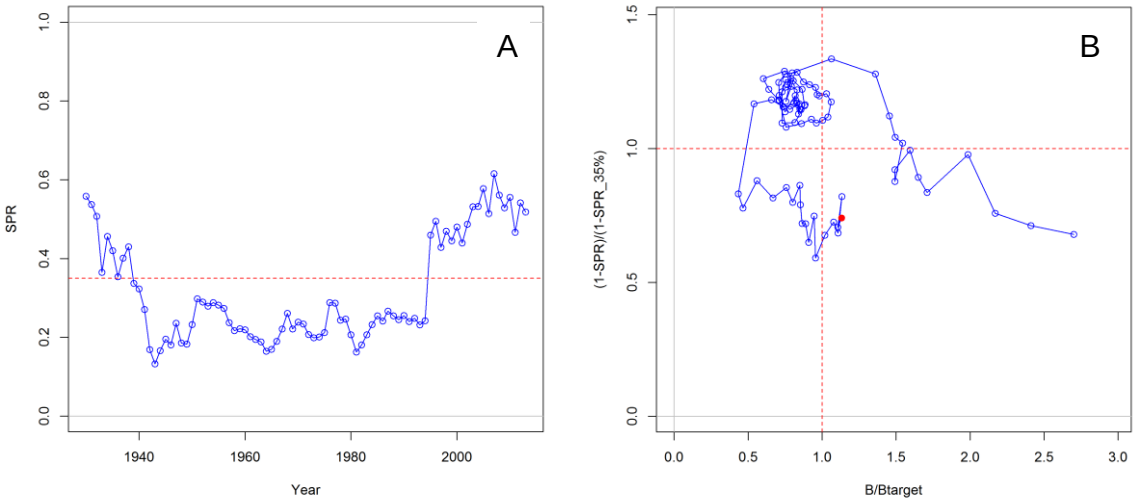


Figure 44. Timeseries of SPR ratio (A) and phase plot of biomass ratio vs. SPR ratio (B) from the SS3 model of striped mullet on the west coast.

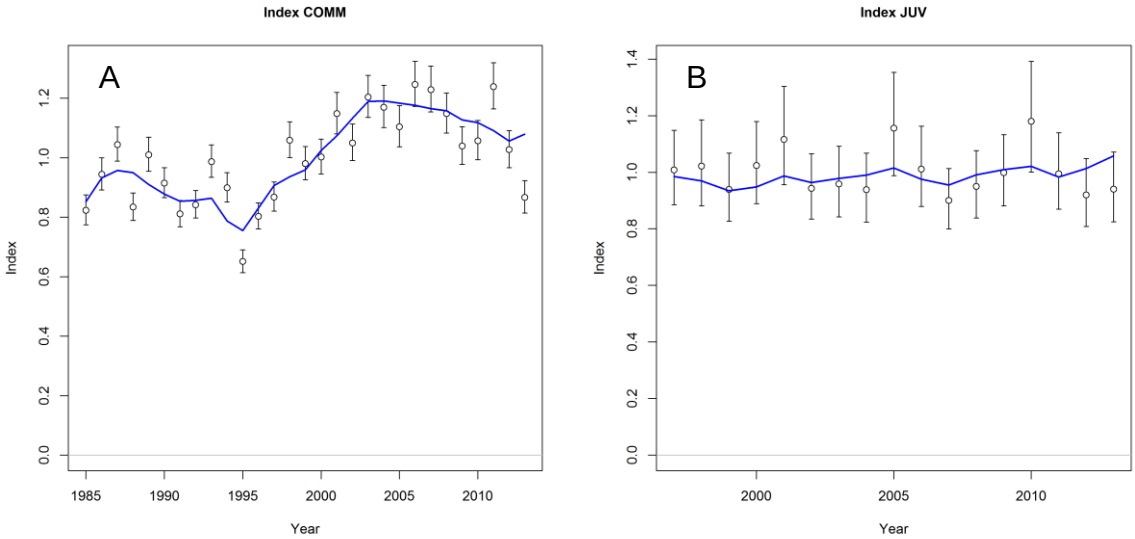


Figure 45. Fit to commercial CPUE (A) and FIM juvenile survey index (B) from the SS3 model of striped mullet on the east coast.

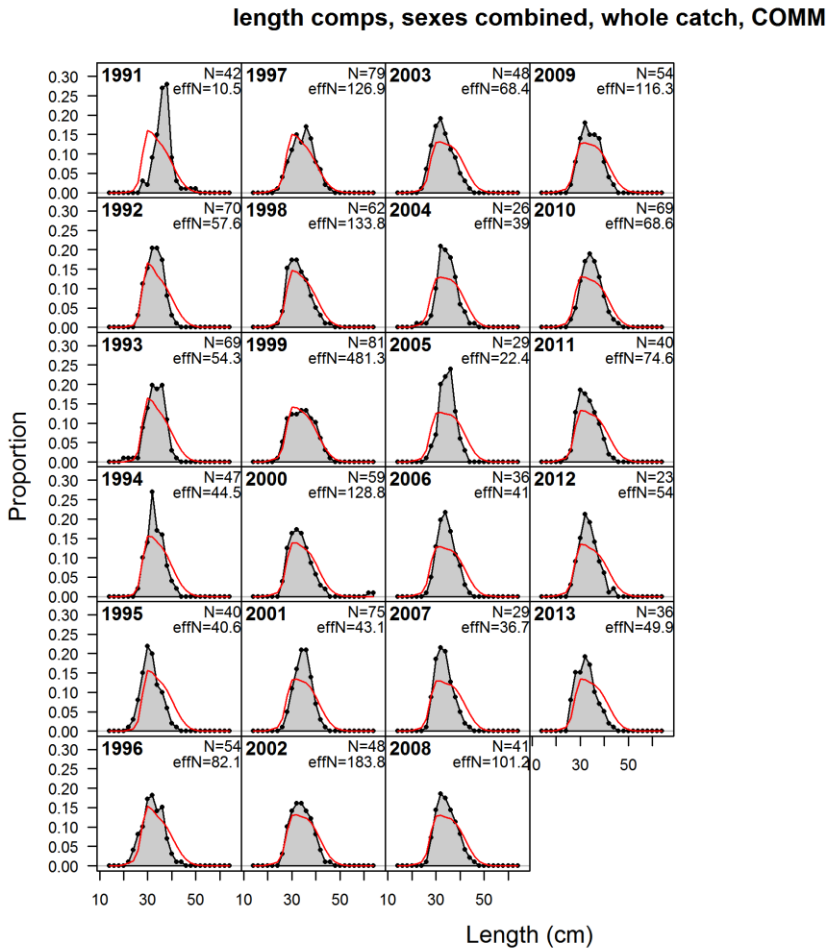


Figure 46. Fits to commercial length compositions by year from the SS3 model of striped mullet on the east coast.

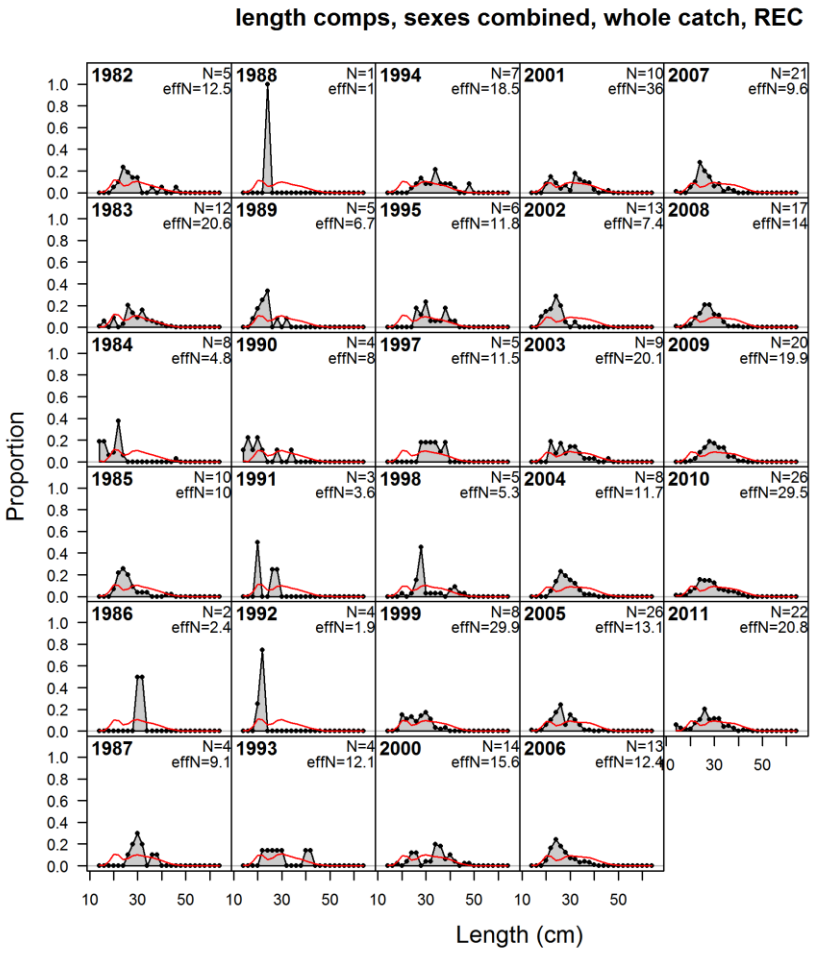


Figure 47. Fits to recreational length compositions by year from the SS3 model of striped mullet on the east coast.

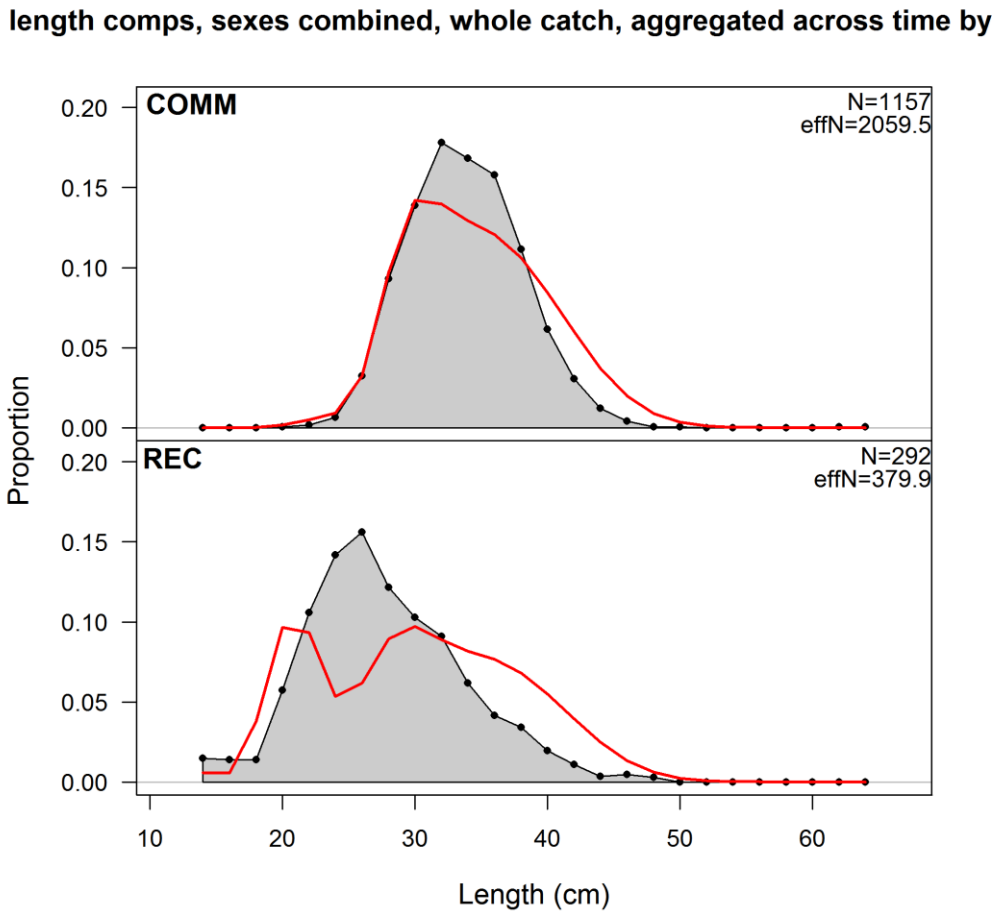


Figure 48. Fits to length compositions by fleet aggregated across time from the SS3 model of striped mullet on the east coast.

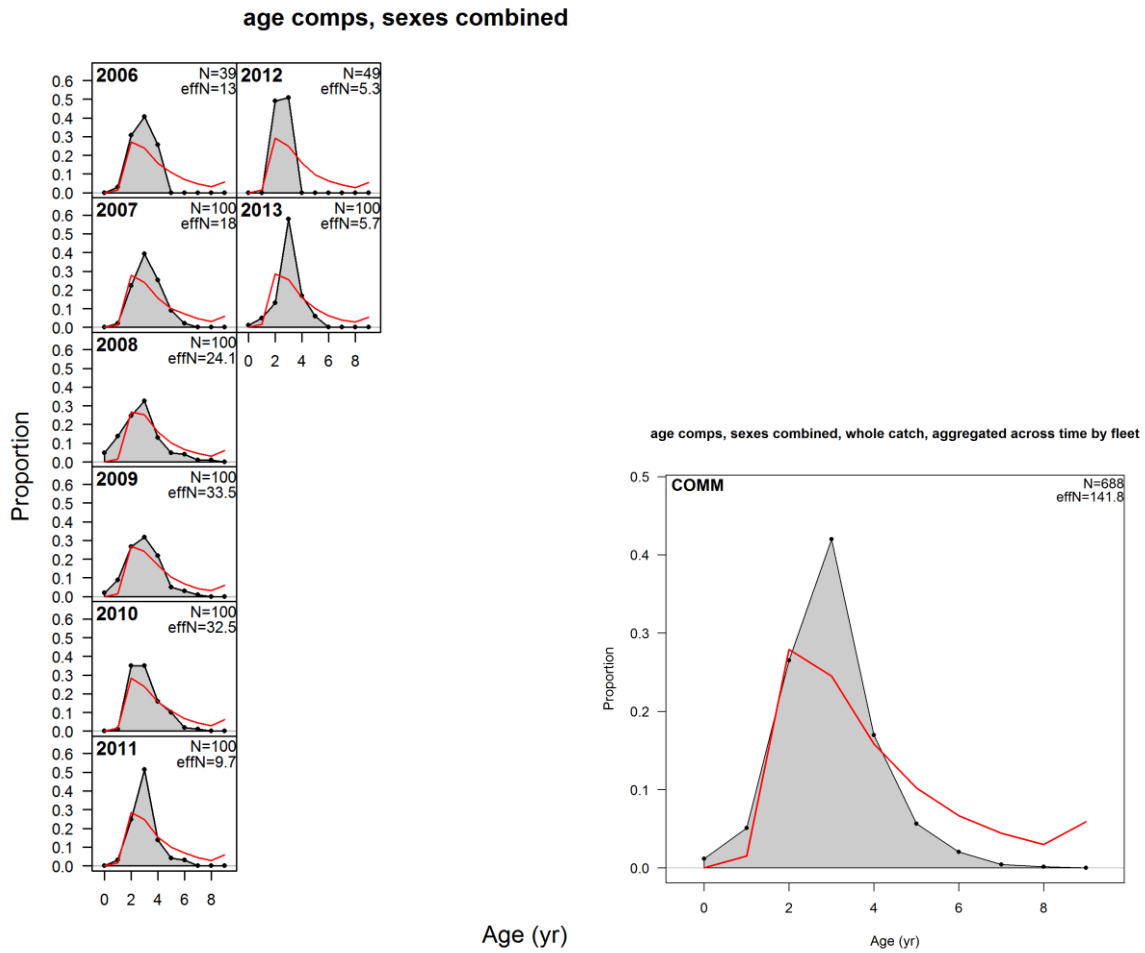


Figure 49. Fits to commercial age compositions by year and aggregated across years from the SS3 model of striped mullet on the east coast.

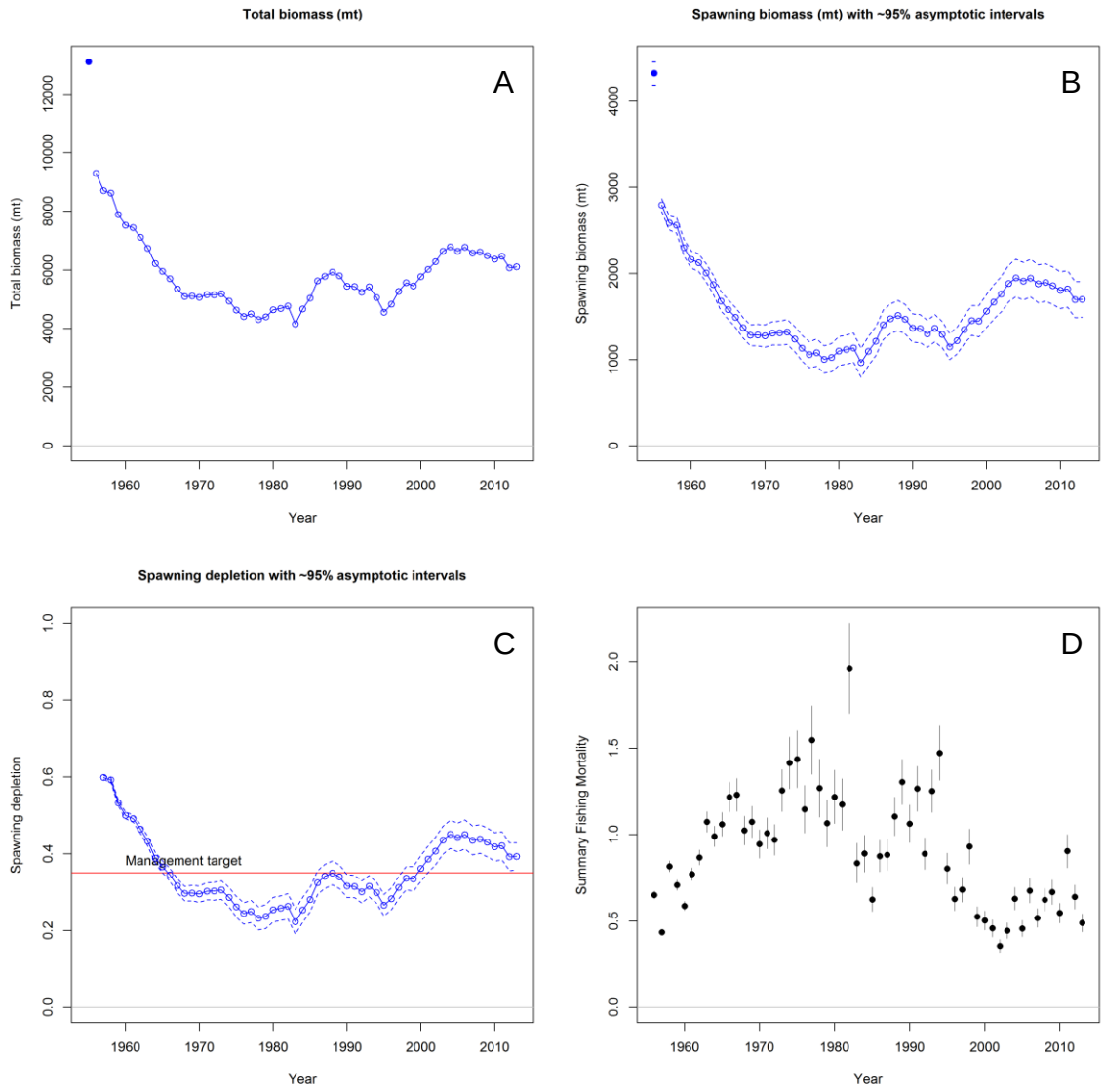


Figure 50. Total biomass (A), spawning biomass with ~95% asymptotic intervals (B), spawning depletion with ~95% confidence intervals (C), and fishing mortality ratio, $F/F_{SPR35\%}$, by year with ~95% confidence intervals (D) from the SS3 model of striped mullet on the east coast.

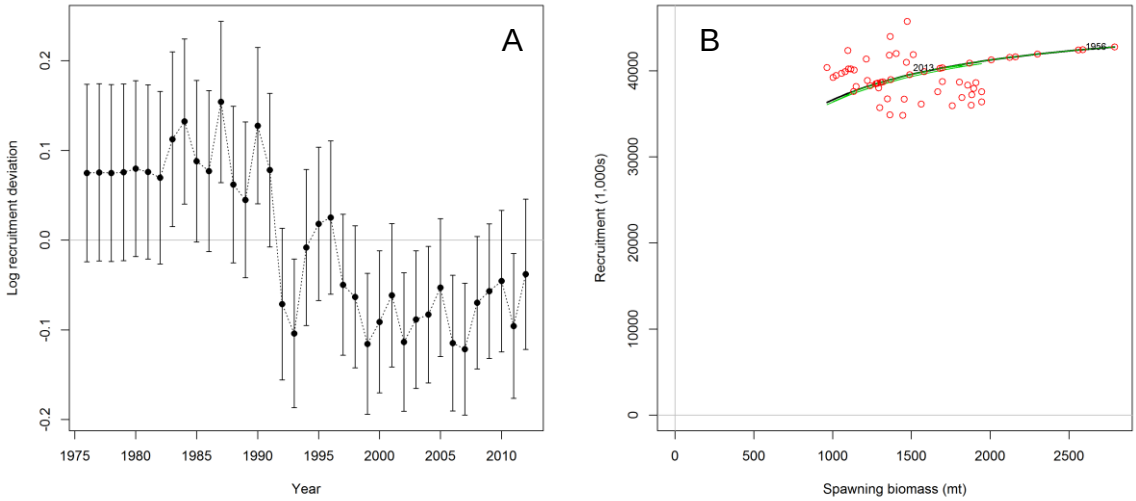


Figure 51. Recruitment deviations with uncertainty (A), and the spawner-recruit relationship (B) from the SS3 model of striped mullet on the east coast.

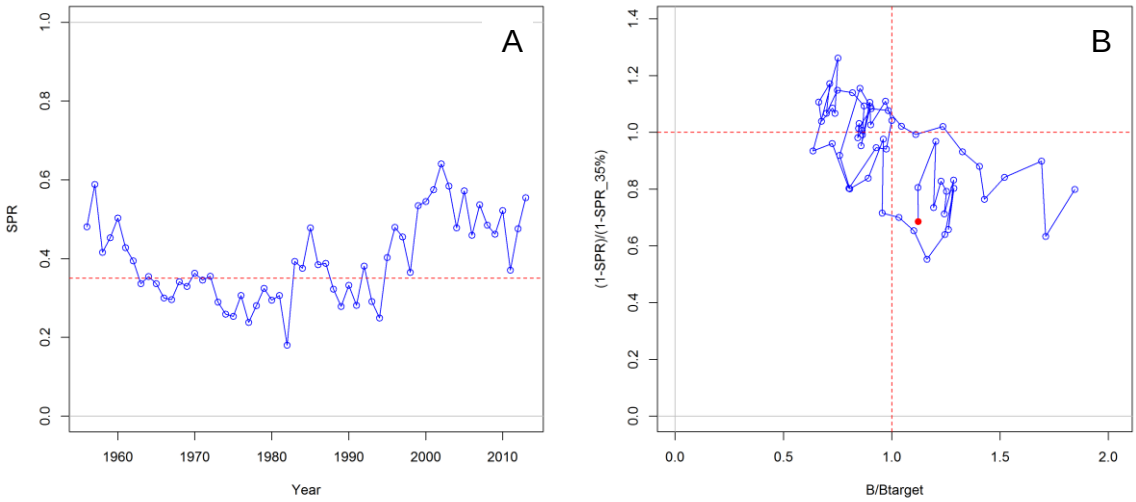


Figure 52. Timeseries of SPR ratio (A) and phase plot of biomass ratio vs. SPR ratio (B) from the SS3 model of striped mullet on the east coast.