Application of Data-Poor Harvest Control Rules to Atlantic Mackerel

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Executive Summary

The aim of this work was to provide the Statistical and Scientific Committee (SSC) of the Mid-Atlantic Fishery Management Council (MAFMC) options for setting the acceptable biological catch (ABC) for Atlantic mackerel using different approaches. First, a range of data-poor harvest control rules were applied to help identify potentially sustainable catch levels for mackerel. Second, catch curve analysis was used and a simulation model was developed to obtain additional insight into the population dynamics of mackerel. Catches estimated from the data-poor harvest control rules varied by two orders of magnitude, from 5,729 mt to 546,620 mt, but the majority predicted catches below the current ABC of 40,625 mt. Control rules that did not require assumptions about relative or absolute stock abundance estimated a catch, on average, of 16,567 mt. The simulation model revealed that an overfishing limit (OFL) in this range (below 40,000 mt) corresponded to an over-exploited stock, although for a very depleted stock the simulations predict an OFL below 20,000 mt and an ABC (calculated using the MAFMC P* control rule) below 10,000 mt. Catch curve analysis using landings data revealed a large decline in older fish in the landings starting in the early 2000s, although whether this decline resulted from an increase in total mortality (both fishing and natural) or the older fish being less susceptible to the fishery remains unclear. Although it is not possible with the available information to determine stock status, a more precautionary approach is favored in the face of uncertainty. The simulation model suggests that setting catches above the current ABC would likely result in a very high probability of overfishing if the stock is currently over-exploited.

Introduction

Fisheries management actions typically require estimates of stock status and management targets (biological reference points, BRP) produced from complex stock assessment models. For many stocks, however, estimates of stock status and BRPs are not available, posing a unique challenge to fisheries scientists and managers. Such stocks can be broadly classified as “data-poor”, although the reasons for this classification can vary greatly among stocks. For many stocks, insufficient data exist to conduct a traditional stock assessment model, and these stocks can be considered truly data-poor. For other stocks sufficient data exists to conduct an assessment, but the estimates from the assessment are considered unreliable. Such cases can be considered “information poor” because although the data exist, the understanding of stock is hampered due to the quality of the information some of the datasets are providing to the assessment model.

Atlantic mackerel, *Scomber scombrus*, in the northwest Atlantic represent an information-poor stock. The stock has been assessed multiple times, with the assessment output being used in the setting of catch limits for the stock (NEFSC 2006). The most recent assessment (Deroba et al. 2010), however, encountered a number of problems using both virtual population analysis (VPA) and statistical catch-at-age (SCAA) assessment models. Both models identified very strong retrospective patterns in the model estimates, with diverging trends in abundance based on the number of years used in the model (Figure 1). Attempts were made to reduce this retrospective pattern (i.e., splitting the survey time series in multiple “blocks”), but the pattern remained and the assessment did not pass the review process (Deroba et al. 2010). As a result, it is unclear what the current status of the stock is, and what catch limits should be. Atlantic mackerel landings in recent years have been the lowest in over 40 years (mean = 12,724 mt for 2011-2013; Figure 2), and were well below the specified acceptable biological catch (ABC; MAFMC 2014), raising concern over the status of the stock and current management targets.

Under the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act (MSFCMRA), ABCs must be set for all stocks under a fisheries management plan (including data-poor stocks). A number of harvest control rules have been developed to set catch limits in data-poor situations, and many of these approaches have been tested using simulation models (Wetzel and Punt 2011; Wiedenmann et al. 2013; Carruthers et al. 2014). The amount of information required by these data poor methods varies greatly, with some only requiring a catch time series, while others utilize life history, survey, and age-structure information. The ability of these approaches to limit overfishing in these studies depended on a variety of conditions, including the historical exploitation levels, the current population status, and biased control rule inputs. Certain data-poor methods tended to perform better in many of the scenarios explored in these studies, but no single control rule performed best in all situations, highlighting to need to consider a broad range of data poor methods in real world applications, such as Atlantic mackerel.

The recent decline in catches in the mackerel fishery could be the result of one or more factors. The most recent period of high catches in the mid 2000s could have resulted in overfishing. Increased natural mortality via increases in predation (Tyrell et al. 2008) may have also contributed to the decline. It is also possible that the stock is not overfished at all, and that shifts in the stock distribution may have resulted in the stock being less available to the fishery in recent years (Overholtz et al. 2011; Radlinski et al. 2013). Mackerel stocks in Europe have also seen substantial northward shifts in recent years, but in those cases fishing fleets have been able to track and find the mackerel (causing numerous political battles – see http://www1.american.edu/ted/ice/mackerel.html).

In this analysis, a number of data-poor harvest control rules were used to calculate potential catch limits for Atlantic mackerel under a range of assumptions about stock status. In addition to the data-poor harvest control rules, a simulation model was developed and catch curve analysis was used to provide additional information on the status of the stock to provide support or refute the hypotheses for the declining catches. The aim of this work was to provide the Statistical and Scientific Committee (SSC) of the Mid-Atlantic Fishery Management Council (MAFMC) with information to assist in the selection of a suitable ABC for Atlantic mackerel.

Methods

Work for this project utilized a variety of information on Atlantic mackerel, and can be grouped into 3 categories: 1) catch-curve analysis, 2) simulation modeling, and 3) application of data-poor harvest control rules. The approaches are described in detail below, along with the data sets and assumptions used in each analysis.

Catch curve analysis

Catch curve analysis (CCA) is a method of calculating the total mortality (Z) for a stock in a particular year using catch at age information. Many assumptions are made when doing a CCA, including constant recruitment and constant fishing effort, and these assumptions have most likely been violated for Atlantic mackerel. Nevertheless, CCA can be a useful tool in identifying changes in the age composition of the catches over time.

For the CCA, combined (U.S. and Canada) numerical catch at age values from 1962-2008 were used, and country-specific values were used from 1968-2008 (catches prior to 1968 were not attributed to each country). Catch at age values were log-transformed and a linear regression was fit to the catches in two ways to estimate the slope of the line, which is an estimate of Z. First, the linear regression was fit to catch at age values in each year using an assumed age at full recruitment to the fishery. Ages at full recruitment of 3,4, and 5 were explored to test the sensitivity of this assumption on estimates of Z. For this CCA, estimates of Z were produced for each year in the time series. However, multiple cohorts are present in the catch in a given year, such that this method is sensitive to trends in recruitment. Therefore another CCA approach was used that calculated Z using catch at age information aggregated for each cohort (not each year). For example, the catch at age for the cohort that recruited to the population (at age 1) in 1990 would use the catch of age 4 fish in 1993, age 5 fish in 1994, and so on up to the final age before the plus group (age 9). This method avoids the potential effects of trends in recruitment, but it is sensitive to changes in fishing effort over the life of the cohort. The cohort CCA estimated *Z* for all cohorts that had reached age 9 by 2008, resulting in a shorter time series of *Z* estimates (1968-2001).

Simulation model

The age-structured simulation model developed by Wiedenmann et al. (2013) was modified in a number of ways to explore the population dynamics of Atlantic mackerel over time. In the original model, population parameters were specified for different generic species life histories (slow, medium, and fast), and each population started in an unfished state and was subjected to different fishing intensities that resulted in a time series of catches that were then used in the analysis of different data poor control rules. Initial population size was specified, as were the fishing mortality rates (*F*) over time, and catches were determined based on the abundance and the *F* in a given year. For mackerel, however, a time series of catches is available (albeit not back to the start of the fishery), but it is not known what the population size was over time, and therefore what the *F* was. As a result, the simulation model was modified to account for this difference and for uncertainty in many of the input parameters. A brief description of the model dynamics is given first, followed by the specific modifications to the model for application to Atlantic mackerel.

The simulation model was an age-structured population model with the equations governing the population dynamics in Table 1 and variable definitions in Table 2. Equations used in the model are referenced by their number in Table 1, such that the numerical abundance at age is referred to as equation T1.1. Annual abundance of recruited ages was determined from the abundance of that cohort the previous year, decreased by continuous natural and fishing mortality (equation T1.1). Recruitment to the population followed the Beverton-Holt stock-recruit relationship, with bias-corrected lognormal stochasticity (equation T1.2). Parameters for the Beverton-Holt model were derived from the unfished spawning biomass, unfished recruitment, and the steepness parameter (equation T1.3), where steepness represents the fraction of unfished recruitment that results when the spawning biomass is reduced to 20% of the unfished level. The assumed level of recruitment variability ($\sigma_R = 0.77$) was based on the meta-analysis of Thorson et al. 2014. Total spawning biomass in a given year was calculated by summing the product of the proportion mature, weight at age and abundance at age over all recruited age classes (equation T1.4). Weight at age was an allometric function of length at age, which followed a von-Bertalanffy growth function (equations T1.5 and T1.6). The proportion mature at age was calculated using a logistic function (equation T1.7). Length, weight, and maturity at age were fixed for a given species life history. The model contained a single fishery, with selectivity at age calculated using a logistic function (equation T1.8). Although fishing for mackerel occurs primarily in the winter months, it was assumed that both natural (*M*) and fishing mortality (*F*) occurred continuously throughout the year, and the Baranov catch equation was used when estimating the F for an observed catch (Quinn and Deriso 1999; equation T1.9).

For mackerel the model was run from 1962 to 2014, spanning the period with estimates of total catch. Annual catches were assumed known in the simulation model (i.e., no uncertainty), as were length, weight and maturity at age (Table 2). All other inputs were assumed to be uncertain, and distributions were specified for each input (Table 2). For many of the input parameters, uniform distributions were assumed by specifying upper and lower bounds of the range, while in other cases a point estimate was specified as the median of a lognormal distribution with an assumed standard deviation.

For each model run, values of natural mortality (M), steepness (h), initial spawning biomass (S_{init}), and the ratio of S_{init} / S_0 were all drawn from uniform distributions, and age at 50% selectivity in the fishery (s_{50}) was drawn from a lognormal distribution (Table 2; Figures 4 and 5). Estimates of M, h, s50 were fixed over time for each run. With estimates of S_{init} and S_{init} / S_0, S_0 was calculated with S_{init} / (S_{init} / S_0). Equilibrium abundance at age was calculated using S_0 and the random value drawn for M, and the fixed weight and maturity at age. Abundance at age-1 was set as the value of R_0 for that run. With an initial estimate of abundance, F was calculated in the first year using observed catch in that year and the Baranov catch equation (equation T1.9). Recruitment in year 2 was calculated using equation T1.2 using the spawning biomass (S) in the previous year, and abundance at age in all other age classes was calculated using equation T1.1. This process was repeated each year to produce estimates of S and F for the entire time period.

In many instances, parameter combinations and recruitment deviations resulted in the exploitable population biomass in a given year being less than the observed catch. In such cases, the model run was halted and the results from that run were discarded. Only runs that did not result in population extinction were kept for further analysis. In addition, runs that resulted in $S > 3^x S_0$ were discarded.

For each of the kept runs, maximum sustainable yield (MSY)-based BRPs (S_{MSY}, F_{MSY}, and MSY) were calculated following NEFSC (2002) using the fixed weight and maturity at age, and the random M, S_0, R_0, h, and fishery selectivity. With BRPs and S and F estimates, the status of the population was classified over time (i.e., overfished, overfishing), and the overfishing limit (OFL) was calculated using the terminal estimate of biomass and the calculated F_{MSY} for that run. The mid Atlantic threshold P* control rule was then applied using the estimated OFL and the S / S_{MSY} to calculate the ABC. All kept runs were grouped based on the estimated status in the final year: over-exploited (S / S_{MSY} < 0.5), fully-exploited ($0.5 \leq S / S_{MSY} < 1.25$), and lightly-exploited ($S / S_{MSY} \geq 1.25$).

The age-structured simulation model was run 100,000 times, and each run provided estimates of catch at age over time for all of the kept runs. These estimates were compared with the observed catch at age to potentially provide additional information on the status of the mackerel stock. Annual observed and estimated proportions at age (p_{obs} and p_{est}, respectively) in the catch were used to calculate the negative log likelihood for each run *i* using a multinomial likelihood function with and assumed effective sample size (*ESS*) of 100. Total catch was not used in the likelihood calculation because catch was assumed known and the model was able to replicate the observed catch over time in the kept model runs.

$$NLL(i) = ESS \sum_t \sum_a (p_{obs}(i,a,t) \log(p_{obs}(i,a,t)))$$

The simulation model was also used to project mackerel biomass into the future under the harvests calculated from the different data-poor control rules explored (described below). For each kept run of the simulation, the population was projected 10 years into the future (2015 – 2024), using the final population size as the starting point for the projection and the median catch estimated from a control rule was fixed as the target catch in all years of the projection. The *F* that resulted from the catch was calculated using equation T1.9, and the probability of overfishing was calculated as the proportion of years that *F* exceeded the estimated F_{MSY} for that run. In cases where the target catch was greater than the exploitable biomass, *F* was set to $4 \text{x} F_{MSY}$ to prevent the removal of the entire population in a given year.

<u>Data-poor harvest control rules</u>

The analysis of Wiedenmann et al. (2013) considered a subset of the available data-poor control rules developed at the time. Many more control rules have been developed since that study, some of which were included in the work of Carruthers et al. (2014). Recently, an R package called the data-limited methods toolkit (DLMtool) was developed by Tom Carruthers (2014) that includes over 40 data-poor control rules. This package was designed to allow both for the application of these control rules to real world stocks, and to test the performance of different control rules using simulations. For this analysis, DLMtool was only used to calculate catches using various control rules for Atlantic mackerel.

The control rules available in DLMtool vary widely in complexity and in assumptions needed. For example, some methods require catch at age data, while others require assumptions about the current population size (either relative or absolute abundance). A comprehensive summary of all of the data-poor control rules available in DLMtool and of those used in this analysis is beyond the scope of this work, and more details about each approach can be found in Carruthers (2014). However, a brief description of the methods used in this analysis is provided in Table 3.

The DLMtool input parameters for Atlantic mackerel are presented in Appendix 1. Catch (both total by weight and numerical by age), survey abundance (by weight), length, weight, and maturity at age information were provided by Kiersten Curti, lead NMFS assessment scientist for Atlantic mackerel. Mean values for stock-recruit steepness, F_{MSY} / *M*, and B_{MSY} / B_0 were obtained from the meta-analyses of Myers et al. 1999, Zhou et al. 2012, and Thorson et al. 2013, respectively. There are problems associated with using estimates from such meta-analyses (see Brooks and Deroba 2015), but broad distributions were assumed for each input in this work (Appendix 1). The mean value assumed for *M* was the mean value for ages 1 and 2 mackerel from the previous assessment (0.4; TRAC 2010).

Many control rules available in DLMtool were omitted from this analysis, including a variety of length-based methods. In addition, DLMtool includes a few approaches that assume the population started in an unfished state, which was not the case for mackerel. One of these control rules was depletion-based stock reduction analysis (DB-SRA; Dick and MacCall 2011). It is possible, however, to relax the assumption about an unfished state in DB-SRA by assuming that the initial biomass is some fraction of the unfished biomass. This modification was not available in DLMtool, and therefore the DLMtool version of DB-SRA was excluded. However, a modified version of DB-SRA (descried below) was developed and used for this analysis.

ORCS and Restrepo Approaches

In addition to control rules in DLMtool, two average catch control rules were used; the ORCS (only reliable catch series) and Restrepo approaches (Berkson et al. 2011; Restrepo et al.1998). Both of these control rules require taking a summary catch statistic and adjusting it based on the perceived status of the stock (over-, fully-, or lightly-exploited). For these control rules two summary catch statistics were used, the median catch from 1980-2014, and the mean from 1992-2001. The latter period represents a time when catches were relatively stable for mackerel (Figure 2). Both the ORCS and Restrepo average catch methods were applied using these catch statistics for each assumed level of stock status.

Depletion-Based Stock Reduction Analysis (*DB-SRA*)

DB-SRA was developed by Dick and MacCall (2011), and is a combination of stock reduction analysis (Walters et al. 2006) and a data poor control rule called depletion corrected average catch (DCAC; MacCall 2009). DB-SRA is applied using a Monte Carlo simulation and requires specified distributions for M, F_{MSY} / M and B_{MSY} / B_0 (note that DB-SRA uses total biomass, B, and not spawning biomass, S). Given the catch time series, the specified distributions, and an assumed level of current depletion (B_{current} / B_0), DB-SRA estimates B_0 and the current OFL for each parameter combination. For this analysis, DB-SRA was modified by specifying an additional input parameter distribution for the ratio of B_{init} / B_0. In addition, a range of current depletion values were specified to explore the estimated OFL over a range of stock status. Because DB-SRA produces an estimate of the OFL, as well as estimates of current biomass and $\mathrm{B}_{\mathrm{MSY}}$, the Mid Atlantic control rule was applied to calculate the ABC for each run. A total of 20,000 runs were conducted using DB-SRA using input distributions specified in Figure 6.

Results

Catch curve

Estimates of the total mortality (Z) from the catch curve analysis are shown in Figure 7. The assumed age at full recruitment had little effect on the mortality trends. The catch curve analysis revealed variable but consistent trends in mortality over most of the time series, but an abrupt increase in mortality occurred between approximately 2002 and 2003, and high mortality was estimated for the remainder of the time series (through 2008). Similar trends in mortality were observed when the catch curve was calculated using separated landings (U.S. and Canada; Figure 8), and when it was calculated using catch for each cohort across years (Figure 9).

Simulation model

The simulation model was initially run starting in 1962 through 2014 assuming the random natural mortality for a given run was fixed across the entire time period (called the base model run). Additional simulations were run using 1) a truncated time series starting in 1978 (called the truncated run), and 2) assuming an increase in M occurred starting in 2003 (called the M-ramp run). The rationale for 1) was that the very large catches in the 1970s might affect predictions from the model. For 2), the rationale was based on the large increase in total mortality seen in the catch curve analysis (Figures 7 and 8) combined with the MSVPA results from Tyrell et al. (2008). Input parameters for the truncated model are shown in Figure 5, while the M-ramp model used the same inputs as the base model (Figure 4). Inputs for M and h were the same for the truncated and base / M-ramp runs, but differed for S_{init} and S_{init} / S_0. Because of the low catches in the 1960s, it was assumed that the biomass in 1962 was high and closer to S_0 compared to 1978, right after the period of very high catches. The M-ramp model with an increase in M spanned the entire time period (1962-2014), and M from 1962 to 2002 was fixed at the randomly selected value for the run, and M for 2003-2014 was fixed at twice the drawn M.

For each simulation model (base, truncated, and M-ramp), accepted parameter combinations (Figures 10 - 12) produced a wide range of trajectories for spawning biomass (S) and fishing mortality rates (F; Figures 13 - 15). Runs were grouped according to the estimated status in the final year, and were either over-exploited ($S / S_{MSY} < 0.5$), fully-exploited ($0.5 \leq S / S_{MSY} < 1.25$) and lightly-exploited ($S / S_{MSY} > 1.25$). Acceptance rates (percentage of runs that were kept) ranged between 30-50%, depending in part on the range of input parameters. Trajectories of S and F, reference points, and the kept parameters across status categories are shown in Figures 10 - 15. Of all the parameters, steepness (h) varied the most by status category, with lower values kept for the more heavily depleted runs. For the over-exploited runs from the base model, only very low values of steepness were kept (most between 0.2 and 0.5), below the range estimated by Myers et al. (1999) for Atlantic mackerel (0.62 - 0.9), but within the range estimated for the Family *Scombridae* (0.3 - 0.72). Across status categories a greater proportion of high M and high S_{init} values were kept. Across models, initial biomass had little effect on the final predicted biomass (i.e., large starting biomass did not necessarily result in large final biomass; Figure 16). Across models and status categories, F / F_{MSY} in the final year was typically well below 1, indicating that the current catches (mean for 2012-2014 = 12,724 mt) did not result in overfishing in most model runs (Tables 4 - 6). The exception to this was for the over-exploited runs for M-ramp model, which resulted in a median F / F_{MSY} of 1.33 (Table 5).

Estimates of the OFL and ABC (calculated using the Mid Atlantic control rule) are shown Table 7 across models and status categories. Although the different models resulted in large differences in biomass for a given status category, the estimated OFLs and ABC did not vary as much for the over-exploited runs. For the over-exploited runs, biomass in the base model was nearly 3x larger than the biomass from the truncated time series model, but the OFL and ABC for the truncated model were approximately 50% higher than the base model. The difference in biomass and OFL estimates results from the differences in the kept parameters, with the truncated time series model run having much higher steepness and F_{MSY} compared to the base model for a given status category (Figure 10 and 12). Thus, inclusion of the large catches in the 1970s in the simulation model did have an effect on the model predictions.

For each run, the fit of the estimated catch-at-age proportions was compared to the observed proportions using a multinomial likelihood function, and the negative log-likelihood (NLL) was calculated. In general, fits were better for the over- and fully-exploited runs compared to the lightly-exploited runs. The difference between the over- and fully-exploited NLL estimates varied across model runs, with the over-exploited runs having better, similar, and worse fits for the base, truncated, and *M*-ramp models, respectively. In addition, the *M*-ramp model resulted in by far the worst fit to the age-structured data (Tables 4 - 6).

Control rules

A total of 22 control rules in the DLMtool package were applied to Atlantic mackerel. Control rules that did not require assumptions about current relative or absolute abundance were only run once to produce a single distribution of catch estimates for each control rule (Table 8). Control rules that required abundance estimates were run multiple times over a range of possible values to produce a range of catch estimates for each assumed level of abundance (Tables 9 and 10). Many of the control rules do not explicitly estimate the OFL but the catch estimates from these control rules could be considered as an approximation of the OFL, and herein the catches are referred to as the OFL. If one wanted an estimate of the ABC, the OFL could be used in the Mid Atlantic P* control rule for an assumed S / S_{MSY}. In this analysis the ABC was not calculated for the control rules in DLMtool because the vast majority of the ones included (20 / 22) in this analysis made no assumptions about relative depletion.

For control rules that did not require assumptions of abundance, OFL estimates varied widely. Median OFL estimates for most (11 of 14) were within 5,729 and 38,564 mt (Table 8). One control, DD, and its variant DD_4010 estimated catches above 500,000 mt. Because these estimates were higher than any catch in the mackerel time series, they were not considered realistic. The DCAC_40 control rule estimated a catch of 77,383 mt, and although this estimate is within the range of recent catches, some caveats of DCAC must be highlighted. First, DCAC is not recommended for species with an *M* above 0.2. Second, DCAC has the tendency to overestimate catches for low population sizes and for long time series of catch data (Wiedenmann et al. 2013, Carruthers et al. 2014). Because of these factors, estimates from DCAC_40 and the additional DCAC permutations run in DLMtool (Table 9) are likely unreliable. Excluding DD, DD_4010, and DCAC_40, the mean across control rules that do not require abundance estimates is 16,567 mt. (Table 8).

The remaining control rules used in DLMtool required assumption about relative or absolute abundance. Those requiring relative abundance estimates were variations on DCAC, and estimates of catch are shown in Table 9 across a range of depletion assumptions, but the same caveats mentioned above apply to DCAC with an assumed depletion. All other control rules required an assumed level of current biomass. For these control rules, a range of biomass values (from 50,000 to 500,000 mt) were assumed for each control rule. This range of assumed biomass was selected because it spanned the range of terminal estimates from the many assessment models run in the previous assessment (Deroba et al. 2010). For a given assumed biomass, catch estimates were generally consistent across the control rules, and increase proportionally with increased biomass (Figure 20). For example, the average catch across control rules was approximately 25,168, 51,394, and 76,604 mt for and assumed biomass of 100,00, 200,000, and 300,000 mt, respectively (Table 10).

The modified DB-SRA control rule was run for 20,000 iterations, and similar to the age-structure simulation models, the runs were grouped according to the predicted status in the final year. Trends in total biomass and harvest rates are shown in Figure 18, and kept parameters are shown in Figure 17. Estimates of current biomass, the OFL and ABC are presented in Table 11. Median estimates of the OFL were 28,186 mt, 95006 mt, and 168027 mt for the over-, fully, and lightly-exploited runs, respectively. Estimates of the ABC were 8,949 mt, 70165 mt, and 136,074 mt, for the over-, fully, and lightly-exploited runs, respectively.

Estimates from the ORCS and Restropo average catch control rules are presented in Table 7. The ORCS method produces both estimates for the OFL and the AB , while the Restrepo approach only produces a single estimate, treated as the ABC here. The mean OFL estimates from the two ORCS approaches were 18,324 mt, 36,649 mt, and 73,827 mt, for the over-, fully, and lightly-exploited runs, respectively. ABC estimates averaged across both the ORCS and Restrepo approaches were 11,911 mt, 23,822 mt, and 43,062 mt, for the over-, fully, and lightly-exploited runs, respectively.

Projections

Median estimates from most of the control rules explored in this analysis (Tables 8, 10,11, and 12) were used in the simulation model projection to determine the frequency of overfishing associated with each control rule over a 10 year period. Projections were done using the truncated and *M*-ramp simulation models for the runs that resulted in the population being over- and fully-exploited. For the truncated model runs that were fully-exploited, all of the control rules resulted in the a median probability of overfishing (P_{OF}) below the 0.5 threshold (Figure 21). For the runs where the population was over-exploited, the majority of the control rules resulted in $P_{OF} < 0.5$.

Control rules that resulted in P_{OF} > 0.5 included all control rules that required an estimate of current biomass, with an assumed biomass above 200,000 mt, as well as DCAC, and DB-SRA assuming the population was fully-exploited. Of the three ABC options considered by the MAFMC for 2015, the chosen ABC (option B; 40,165 mt) resulted in a median P_{OF} of 0.5, while option C (ABC = 33,400 mt) resulted in a median POF of 0.3, although the range of estimates for both options B and C was between 0 and 1. For the over-exploited population runs, control rules that resulted in target catches below 20,0000 were estimated to have a very small risk of overfishing (median P_{OF} = 0).

Across control rules, P_{OF} using the *M*-ramp model for a fully-exploited population was in between estimates from the fully- and over-exploited runs from the truncated simulation model (Figure 22). For example, the current ABC was predicted to have a median P_{OF} = 0.3 for the full-exploited M-ramp simulation. For the over-exploited *M*-ramp runs, however, median P_{OF} was above 0.5 for nearly all control rules explored. Only the most conservative controls rules with target catches < 11,000 mt resulted in a median P_{OF} below the 0.5 threshold for the over-exploited population in the *M*-ramp simulation runs.

Conclusions

In the absence of a stock assessment, the SSC develops ABCs on a case-by-case basis. The aim of this work was to provide options for the setting of the ABC for Atlantic mackerel using different approaches. First, a range of data-poor harvest control rules were applied to help identify potentially sustainable catch levels for mackerel. Catches estimated from these control rules were tested using a simulation model to explore the risk of overfishing associated with each control rule. The simulation model was also utilized, in conjunction with catch curve analysis, to obtain additional insight into mackerel population dynamics.

The catch curve analysis identified an abrupt and large change in the age structure of the catch in early 2000s, with very few older individuals being caught. One possible explanation for this pattern is an increase in natural (*M*) or fishing (*F*) mortality (or both). Using a multispecies VPA Tyrell et al. (2008) estimated the mortality for both herring and mackerel, and noted a large increase in predation mortality for mackerel in the early 2000s. This study period ended in 2002, however, so it is unclear if the trend continued. Interestingly, the temporal pattern in *M* estimated for the previous assessment using consumption estimates (Deroba et al. 2010) does not seem to show a similar increase in *M*.

While increased mortality (both natural and fishing), could be the cause of this change, other factors could be involved. For example, a shift in the habitat of older fish away from the fishing grounds could result in such a pattern in the catch curve. Based on the NEFSC trawl survey, mackerel have been moving to the north and east over the past few decades (Deroba et al. 2010; Overholtz et al. 2011; Radlinkski et al. 2013), and it is possible that older mackerel have moved farther to the northeast than younger mackerel. However, given that the same pattern was observed in both the U.S. and Canadian fisheries, a simple northeast movement of adults is unlikely. Older mackerel may have moved off the shelf in recent years, but Radlinksi et al. (2013) found that the across shelf distribution of mackerel in the NEFSC survey from 1985-1999 was affected by temperature but not the size of the mackerel. It is interesting to note, however, that at the same time of the change in age-structure in the catch, there was a large change in distribution of mackerel in NEFSC survey, although the shift was to the southwest (Figure 23). The catch curve analysis was only done through 2008 due to the availability of the catch data, so it is unclear if older fish have returned to the fishery catches in recent years, although length truncation in the survey has been observed in recent years (K. Cuerti, *personal communication*).

The primary purpose of the simulation model was to provide a range of OFL and ABC estimates for mackerel at different levels of depletion, and for these estimates to be compared to those produced by the different data-poor harvest control rules.
If mackerel are lightly-exploited, simulation models and harvest control rules that categorize stock status (DB-SRA, ORCS, and Restrepo) predict the OFL and ABC to be, on average, 298,904 and 188,238 mt, respectively (Table 7). Because these catches are in the range of the largest catches ever for mackerel, it is unlikely that mackerel are a lightly-exploited stock. Furthermore, the age-structure observed in the catch does not support the notion of a lightly exploited stock (Tables 4-6).

Arguments could be made, however, that the mackerel stock is in good shape (i.e., fully-exploited) but that due to migrations many of the fish are unavailable to fishery. For a fully-exploited stock, the approaches estimate the OFL and ABC at 87,016 and 52,921 mt, respectively (Table 7). If the older fish have become unavailable to the fishery, these catches (if achieved) could result in high fishing mortality rates for the younger fish, potentially having long-term impacts on stock abundance. Furthermore, if the population is over-exploited but assumed fully-exploited, these catches (if achieved) would likely result in $F >> F_{MSY}$, further impacting the stock (Figures 21 and 22).

If the stock is over-exploited, the simulation models and control rules predict the OFL and ABC to be, on average, 23,893 and 10,179 mt, respectively (Table 7). The majority of the control rules explored here that did not consider stock status (Table 8) produced catch estimates within this range, with a mean catch of 16,567, adding support to the notion of an over-exploited stock. Control rules that estimated a catch target below 20,000 mt were predicted to have a very low risk of overfishing for the over-exploited population runs from the truncated time series simulation model (Figure 21). In contrast, the current ABC of 40,165 mt was estimated to have a median probability of overfishing of 0.5. Some of the control rules explored use a catch-curve in the final year of catch-at-age data, so bias in the age-structure of the catch will impact these estimates. Furthermore, the final year available for catch at age data was 2008, so more recent changes in the catch age structure would change the estimates from these catch curve-based control rules.

Although it is not possible with the available information to determine if the stock is over- or fully-exploited, a more precautionary approach is favored favored in the face of uncertainty. The simulation study of Wiedenmann et al. (2013) highlighted the impact of bias in perception of stock status on control rule performance. When data-poor stocks were incorrectly classified as fully-exploited when they were actually over-exploited, the catches estimated from the harvest control rules resulted in high rates of overfishing and further decreases in stock biomass.

References

Beddington, J.R., Kirkwood, G.P., 2005. The estimation of potential yield and stock status using life history parameters. Philos. Trans. R. Soc. Lond. B Biol. Sci. 360, 163-170.

Berkson, J., L. Barbieri, S. X. Cadrin, S. L. Cass-Calay, P. Crone, M. Dorn, C. Friess, D. Kobayashi, T. J. Miller, W. S. Patrick, S. Pautzke, S. Ralston, M. Trianni. 2011. Calculating acceptable biological catch for stocks that have reliable catch data only (only reliable catch stocks – ORCS). NOAA (National Oceanic and Atmospheric Administration) Technical Memorandum. NMFS-SEFSC-616, 56 p. Available: http://www.pifsc.noaa.gov/tech/NOAA_Tech_Memo_SEFSC_616. pdf. (February 2011).

Brook, E. N. and J. J. Deroba. 2015. When "data" are not data: the pitfalls of post hoc analyses that use stock assessment model output. Canadian Journal of Fisheries and Aquatic Sciences. 72(4): 634-641.

Carruthers, T.R. 2014. Data-limited methods toolkit. R package manual. Available from http://cran.r-project.org/web/packages/DLMtool/DLMtool.pdf

Carruthers, T.R., A. E. Punt, C. J. Walters, A. MacCall, M. K. McAllister, E. J. Dick, and J. Cope 2014. Evaluating methods for setting catch limits in data-limited fisheries. Fisheries Research. 153: 48-68.

Deroba, J., Shepherd, G., Gregoire, F., Nieland, J., and Rago, P. 2010.Stock assessment of Atlantic mackerel in the Northwest Atlantic for 2010. Transboundary Resources Assessment Committee, Reference Document 2010/01. 59 pp.

Geromont, H.F. and Butterworth, D.S. 2014. Complex assessment or simple management procedures for efficient fisheries management: a comparative study. ICES J. Mar. Sci. doi:10.1093/icesjms/fsu017

Gulland, J.A., 1971. The fish resources of the ocean. Fishing News Books, West Byfleet, UK.

MacCall, A.D., 2009. Depletion-corrected average catch: a simple formula for estimating sustainable yields in data-poor situations. ICES J. Mar. Sci. 66, 2267-2271.

Martell, S., Froese, R., 2012. A simple method for estimating MSY from catch and resilience. Fish Fish. doi: 10.1111/j.1467-2979.2012.00485.x.

McAllister, M.K., Pikitch, E.K., and Babcock, E.A. 2001. Using demographic methods to construct Bayesian priors for the intrinsic rate of increase in the Schaefer model and implications for stock rebuilding. Can. J. Fish. Aquat. Sci. 58: 1871-1890.

Mid-Atlantic Fishery Management Council (MAFMC) 2014. Specifications and Management Measures For: Atlantic Mackerel (2015, Including River Herring and Shad Cap),Illex Squid (2015-2017), Butterfish (2015-2017), and Longfin Squid (2015-2017). Available from: http://www.greateratlantic.fisheries.noaa.gov/regs/2014/November /14msb2015174specsea.pdf

Myers, R. A., K. G. Bowen, and N. J. Barrowman. 1999. Maximum reproductive rates of fish at low population sizes. Canadian Journal of Fisheries and Aquatic Sciences 56:2404-2419.

Northeast Fisheries Science Center (NEFSC). 2002. Final Report of the Working Group on Re-Evaluation of Biological Reference Points for New England Groundfish. U.S. Department of Commerce, Northeast Fisheries Science Center Reference Document. 02-04; 254 p. Available: http://www.nefsc.noaa.gov/nefsc/ publications/. (July 2010).

NEFSC (Northeast Fisheries Science Center). 2006. 42nd Northeast Regional Stock Assessment Workshop (42nd SAW) stock assessment report, part A: silver hake, Atlantic mackerel, and northern shortfin squid (CRD 06-09a). U.S. Department ofCommerce Northeast Fisheries Science Center Reference Document 06-09a; 284 p.

Overholtz, W.J., J.A. Hare, and C.M. Keith. 2011. Impacts of Inter-Annual Environmental Forcing and Long-Term Climate Change on the Distribution of Atlantic Mackerel on the U.S. Northeast Continental Shelf. Marine and Coastal Fisheries: Dynamics,Management, and Ecosystem Science.

Quinn, T. and R Deriso. 1999. Quantitative fish dynamics, Oxford University Press, New York.

Radlinksi, M., M.A. Sundermeyer, J.J. Bisagni, and S.X. Cadrin. 2013. Spatial and temporal distribution of mackerel along the northeast coast of the United States, 1985-1999. ICES Journal of Marine Science; doi:10.1093/icesjms/fst029

Restrepo, V. R., G. G. Thompson, P. M. Mace, W. L. Gabriel, L. L. Low, A. D. MacCall, R. D. Methot, J. E. Powers, B. L. Taylor, P. R. Wade, and J. F. Witzig. 1998. Technical guidance on the use of precautionary approaches to implementing National Standard 1 of the Magnuson–Stevens Fishery Conservation and Management Act. NOAA Tech. Memo. NMFS-F/SPO-31, 54 p.

Thorson, J. T., J. M. Cope, T. A. Branch, and O. P Jensen. 2012. Spawning biomass reference points for exploited marine fished, incorporating taxonomic and body size information. Canadian Journal of Fisheries and Aquatic Sciences 69:1556-1568.

Thorson, J.T., O.P. Jensen, and E. Zipkin. 2014. How variable is recruitment for exploited marine fishes? A hierarchical model for testing life history theory. Canadian Journal of Fisheries and Aquatic Sciences. 71: 973 - 983

Tyrell, M.C., J.S. Link, H. Moustahfid, and W.J. Overholtz. 2008. Evaluating the effects of predation mortality on forage species population dynamics in the Northeast US continental shelf ecosystem using multispecies virtual population analysis. ICES Journal of Marine Science, 65: 1689-1700..

Walters, C. J., S. J. D. Martell, and J. Korman. 2006. A stochastic approach to stock reduction analysis. Canadian Journal of Fisheries and Aquatic Sciences 63:212-223.

Wetzel, C. R., and A. E. Punt. 2011. Model performance for the determination of appropriate harvest levels in the case of data-poor stocks. Fisheries Research 110: 342-355.

Wiedenmann, J., Wilberg, M., and T. Miller. Evaluation of harvest control rules for data poor fisheries. 2013. North American Journal of Fisheries Management. 33: 845-860.

Zhou, S., S. Yin, J. T. Thorson, A .D. M. Smith, and M. Fuller. 2012. Linking fishing mortality reference points to life history traits: and empirical study. Canadian Journal of Fisheries and Aquatic Sciences 69:1292-1301.

Table 1. Equations governing the mackerel population dynamics in the simulation model.

	Equation	Description
	Population dynamics	
1	$N(a,t)=\begin{cases} R(t) & a=a_R \\ N(a-1,t-1)e^{[-M-s(a-1)F(t-1)]} & a_R<a\le a_{\max} \end{cases}$	Numerical abundance at age
2	$R(t)=\dfrac{S(t-a_R)}{\alpha+\beta S(t-a_R)}e^{\theta_R-0.5\sigma_R^2}$	Stock-recruit relationship
3	$\alpha=\dfrac{S_0(1-h)}{4hR_0}$ $\beta=\dfrac{5h-1}{4hR_0}$	Stock-recruit parameters
4	$S(t)=\sum_{a=a_R}^{a_{\max}} m(a)w(a)N(a,t)$	Spawning biomass
	Life history	
5	$L(a)=L_\infty\left(1-e^{-k(a-a_0)}\right)$	Length at age
6	$w(a)=bL(a)^c$	Weight at length
7	$m(a)=\dfrac{1}{1+e^{-\left(\frac{a-m_{50\%}}{m_{slope}}\right)}}$	Maturity at age
	Fishing dynamics	
8	$s(a)=\dfrac{1}{1+e^{-\left(\frac{a-s_{50\%}}{s_{slope}}\right)}}$	Selectivity at age in the fishery
9	$C(t)=\sum_a \dfrac{s(a)F(t)}{M+s(a)F(t)}w(a)N(a,t)\left(1-e^{-M-s(a)F(t)}\right)$	Total catch

Table 2. Parameters governing the dynamics in the mackerel simulation model.

Parameter	Description	Value	
a_R	Age at recruitment (to population)	1	
a_{max}	Maximum age	10	
a_0	Age at length=0	-2.42	
L_∞	Maximum length	44.59	
k	Growth rate	0.2	
b_1	L-W scalar	3.25×10^{-6}	
b_2	L-W exponent	3.3	
m_{50}	Age at 50% maturity	1.9	
s_{50}	mean age at 50% selectivity in fishery	~lognorm (log(1.9),σ_s)	
m_{slope}	Slope of maturity function	0.4	
s_{slope}	Slope of selectivity function	0.4	
M	Mean natural mortality rate	~Unif (0.2,0.8)	
h	Steepness	~Unif (0.21,1.0)	
σ_R	standard deviation of stock-recruit relationship	0.77	
σ_s	standard deviation of age at 50% selectivity	0.1	
		base	truncated
S_{init}	Initial biomass	~Unif ($1\text{x}10^6$, $3\text{x}10^6$)	~Unif ($1\text{x}10^6$, $3\text{x}10^6$)
S_{init} / S_0	Initial depletion	~Unif (0.5,1.0)	~Unif (0.1,0.5)

Table 3. A list of data-poor control rules used in this analysis.

Control rule abbreviation	Description	Source
BK_CC	Beddington and Kirwood life history method combined with catch curve analysis. Calculates the OFL using a catch curve estimate of current F and an approximation of FMSY based on length at first capture.	Beddington and Kirkwood 2005
DCAC	Depletion-corrected average catch. A method for adjusting average catches based on an assumed change in biomass over the time period.	MacCall 2009
DCAC4010	A variation of DCAC that uses the 40:10 control rule to reduce the catch estimate based on the assumed depletion level (as biomass falls below B_{MSY}).	MacCall 2009
DBSRA	Depletion-based stock reduction analysis. A method that calculates the OFL by calculating unfished biomass given the catch history and assumed distributions for depletion, M, F_{MSY} / M and B_{MSY} / B_0.	Dick and MacCall 2011
DD	A delay difference method that estimates the OFL based on the catch and index time series.	Carruthers 2014
DD4010	A combination of the DD method and the 40:10 control rule.	Carruthers 2014
DepF	The Fratio method with a controller that reduces F according to the production curve given an estimate of current stock depletion.	Carruthers 2014
DynF	The Fratio method with a controller that changes the level of F according to the relationship between surplus production and biomass (i.e. lower F when dSP/dB is positive and higher F when dSP/dB is negative.	Carruthers 2014
Fdem	FMSY is calculated as r/2 where r is calculated from a demographic approach. Coupled with an estimate of current abundance that gives you the OFL.	McCallister et al. 2001; Carruthers 2014
Fdem_CC	Demographic MSY method using catch-curve analysis to estimate recent Z	McCallister et al. 2001; Carruthers 2014
Fratio	Calculates the OFL based on a fixed F_{MSY} / M ratio and an assumed current stock size	Gulland 1971; Martell and Froese 2012; Carruthers 2014
Fratio_CC	Calculates the OFL based on a fixed F_{MSY} / M ratio and a catch curve estimate of current stock size	Gulland 1971; Martell and Froese 2012; Carruthers 2014
GB_slope	A harvest control rule similar to SBT1 that modifies a time-series of catch recommendations aims for a stable catch rates.	Geromont and Butterworth (2014)
Gcontrol	A harvest control rule proposed by Carl Walters that uses trajectory in inferred surplus production to make upward/downward adjustments to quota recommendations	Carruthers 2014 (based on mthod proposed by Carl Walters)

MMHCR	A harvest control rule that makes incremental adjustments to quota recommendations based on the apparent trend in surplus production	http://www.iattc.org/Meetings/Meetings2014/MAYSAC/PDFs/SAC-05-10b-Management-Strategy-Evaluation.pdf
ORCS	Only reliable catch series method that estimates the OFL by adjusting a catch statistic (e.g., the median) based on an assumed stock status. Additional buffers can be applied to estimate the ABC based on the perceived risk or sensitivity to overfishing.	Berkson et al. 2011
Rcontrol	A harvest control rule that modifies quotas according to trends in apparent surplus production that includes information from a demographically derived prior for intrinsic rate of increase	Carruthers 2014 (but proposed by Carl Walters)
Rcontrol2	Similar to Rcontrol, but this method includes a quadratic approximation of recent trends in surplus production given biomass.	Carruthers 2014 (but proposed by Carl Walters)
Restrepo	A method that adjusts a summary catch statistic based on an assumed stock status.	Restrepo 1998
SBT1	A harvest control rule that makes incremental adjustments to quota recommendations based on the apparent trend in surplus production.	http://www.ccsbt.org/site/recent_assessment.php
SPMSY	A method for estimating MSY to determine the OFL. Since their approach estimates stock trajectories based on catches and a rule for intrinsic rate of increase it also returns depletion. Given their surplus production model predicts K, r and depletion it is straightforward to calculate the OFL based on the Schaefer productivity curve.	Martell and Froese (2012).
YPR	A simple yield per recruit approximation to F_{MSY} ($F_{0.1}$) which is the position of the ascending YPR curve for which dYPR/dF = 0.1(dYPR/d0). The OFL is calculated using an assumed abundance.	Carruthers 2014
YPR_CC	A simple yield per recruit approximation to F_{MSY} ($F_{0.1}$) which is the position of the ascending YPR curve for which dYPR/dF = 0.1(dYPR/d0) A naive catch-curve analysis is used to determine recent Z which given M gives F and thus abundance = $C_t/(1-\exp(-F))$	Carruthers 2014

Table 4. Percentiles and summary statistics the distribution of estimates from the age-structured simulation model for the base model run.

Exploitation status	Summary statistic	S	S/S_{MSY}	F/F_{MSY}	OFL	ABC	NLL all years	NLL 2002-2008
	10%	85,108	0.09	0.17	5,058	0	27,685	2,306
	25%	166,043	0.16	0.26	12,641	2,542	27,857	2,350
Over-exploited	40%	249,064	0.24	0.37	20,056	5,282	27,981	2,388
	50%	291,301	0.29	0.45	27,556	8,065	28,072	2,407
	75%	444,212	0.40	1.01	47,214	17,339	28,335	2,476
	mean	316,937	0.28	1.66	33,353	11,761	28,129	2,425
	s.d.	190,867	0.14	6.70	27,016	12,062	395	108
	10%	576,699	0.62	0.03	60,458	36,390	27,753	2,311
	25%	758,798	0.79	0.04	101,434	66,925	27,915	2,356
Fully-exploited	40%	905,740	0.92	0.06	141,329	99,210	28,042	2,390
	50%	1,006,961	0.99	0.07	168,840	124,556	28,123	2,417
	75%	1,310,059	1.13	0.12	253,088	199,834	28,370	2,488
	mean	1,052,459	0.95	0.31	188,006	143,086	28,168	2,433
	s.d.	395,009	0.21	8.16	114,790	96,756	361	111
	10%	1,307,497	1.62	0.00	287,224	232,604	27,802	2,328
	25%	1,677,104	2.05	0.01	460,626	373,031	27,983	2,379
Under-exploited	40%	1,984,686	2.43	0.01	626,541	507,395	28,121	2,421
	50%	2,189,539	2.68	0.01	753,466	610,183	28,212	2,450
	75%	2,854,055	3.53	0.02	1,240,323	1,004,457	28,492	2,556
	mean	2,338,654	2.98	0.03	958,964	776,602	28,281	2,485
	s.d.	918,454	1.80	0.57	725,265	587,344	438	152

Table 5. Percentiles and summary statistics the distribution of estimates from the age-structured simulation model for the M-ramp model where M is doubled abruptly in 2002 for the remainder of the model run.

Exploitation status	Summary statistic	S	S/S_{MSY}	F/F_{MSY}	OFL	ABC	NLL all years	NLL 2002-2008
	10%	25,111	0.18	0.37	2,340	552	27,808	2,380
	25%	37,118	0.25	0.63	5,193	1,585	27,991	2,434
Over-exploited	40%	50,293	0.31	0.99	8,640	2,780	28,137	2,480
	50%	58,581	0.35	1.33	11,708	3,919	28,231	2,513
	75%	80,176	0.43	3.27	22,755	8,685	28,476	2,594
	mean	60,995	0.33	3.79	16,393	6,211	28,253	2,524
	s.d.	28,918	0.11	8.26	15,411	6,638	360	122
	10%	94,583	0.61	0.07	10,475	6,829	27,803	2,380
	25%	133,084	0.74	0.13	26,040	16,968	27,987	2,435
Fully-exploited	40%	163,530	0.86	0.19	42,451	28,626	28,130	2,481
	50%	184,092	0.93	0.25	54,420	37,901	28,222	2,510
	75%	246,081	1.10	0.54	97,715	73,588	28,492	2,594
	mean	193,912	0.91	1.06	71,593	53,553	28,259	2,523
	s.d.	83,103	0.21	6.29	65,403	52,982	382	122
	10%	265,329	1.46	0.01	40,609	32,887	27,836	2,394
	25%	364,017	1.76	0.01	123,964	100,390	28,036	2,454
Under-exploited	40%	448,106	2.08	0.03	212,577	172,152	28,187	2,502
	50%	507,103	2.32	0.04	281,437	227,917	28,287	2,534
	75%	702,937	3.12	0.10	529,812	429,060	28,588	2,630
	mean	560,234	3.26	1.74	372,676	301,806	28,345	2,550
	s.d.	277,769	31.52	50.71	334,408	270,815	444	131

Table 6. Percentiles and summary statistics from the distributions of estimates from the age-structured simulation model using the truncated time series (1978-2014).

Exploitation status	Summary statistic	S	S/S_{MSY}	F/F_{MSY}	OFL	ABC	NLL all years	NLL 2002-2008
Over-exploited	10%	23,270	0.07	0.13	10,268	0	22,685	2,326
	25%	51,824	0.16	0.19	22,656	4,694	22,857	2,370
	40%	84,396	0.24	0.27	32,710	9,353	22,981	2,402
	50%	107,990	0.29	0.31	39,260	12,856	23,072	2,417
	75%	193,853	0.40	0.56	63,807	23,460	23,335	2,488
	mean	144,194	0.28	1.02	49,576	17,299	23,129	2,451
	s.d.	130,938	0.14	5.18	40,984	18,103	395	108
Fully-exploited	10%	145,105	0.61	0.04	66,227	39,833	22,753	2,328
	25%	220,007	0.75	0.06	90,198	60,767	22,915	2,376
	40%	291,413	0.86	0.08	114,406	81,064	23,042	2,408
	50%	343,447	0.93	0.09	130,536	95,456	23,123	2,432
	75%	536,282	1.10	0.13	197,555	149,318	23,370	2,510
	mean	415,404	0.92	0.10	161,032	118,908	23,168	2,454
	s.d.	272,543	0.21	0.06	107,211	87,648	361	131
Under-exploited	10%	270,683	1.52	0.00	177,463	143,715	22,802	2,353
	25%	417,239	1.94	0.01	264,930	214,549	22,983	2,394
	40%	561,694	2.42	0.02	363,603	294,458	23,121	2,436
	50%	668,199	2.83	0.02	443,898	359,484	23,212	2,464
	75%	1,063,939	4.90	0.04	787,109	637,428	23,492	2,572
	mean	814,852	4.40	0.03	644,006	521,539	23,281	2,496
	s.d.	555,427	4.39	0.02	621,570	503,369	438	176

Table 7. Estimates of median biomass, OFL and ABC across simulation model runs and across control rules that could be categories according to population status. For the ORCS and Restrepo control rules, each method was applied using the median catch from 1980-2014, and the mean catch from 1992-2001 (representing a period of "stable" catches). For the ORCS method the ABC was calculated as 80% of the OFL. Estimates produced from the Restrepo method were treated as the ABC.

	Over-exploited			Fully-exploited			Lightly-exploited		
	Biomass	OFL	ABC	Biomass	OFL	ABC	Biomass	OFL	ABC
Simulation (base)	291,301	27,556	8,065	1,006,961	168,840	124,556	2,189,539	753,466	610,183
Simulation (M-ramp)	58,581	11,708	3,919	184,092	54,420	37,901	507,103	281,437	227,917
Simulation (truncated)	107,990	39,260	12,856	343,447	130,536	95,456	668,199	443,898	359,484
DB-SRA	304,538	28,186	8,949	896,789	95,006	70,166	1,355,847	168,028	136,075
ORCS (median)	-	20,109	16,087	-	40,217	32,174	-	80,434	64,347
ORCS (stable)	-	16,540	13,232	-	33,080	26,464	-	66,160	52,928
Restrepo (median)	-	-	10,054	-	-	20,109	-	-	30,163
Restrepo (stable)	-	-	8,270	-	-	16,540	-	-	24,810
Mean		23,893	10,179		87,016	52,921		298,904	188,238

Table 8. Summary values for the distributions of the catches estimated by the different data-poor control rules in the DLMtool package. Control rules shown do not require estimates of relative of absolute abundance (see Table 3 for summary descriptions of each method)

Control rule	Median	Mean	CV
BK_CC	13,764	21,895	1.23
DCAC_40	77,383	76,717	0.05
Fdem_CC	16,651	25,462	1.15
Fratio_CC	14,876	23,530	1.16
SPMSY	38,564	38,061	0.53
YPR_CC	26,048	32,492	0.89
DD	506,064	994,653	1.34
DD4010	546,620	1,038,325	1.29
GB_slope	11,809	11,809	0.00
MMHCR	11,674	11,936	0.20
SBT1	14,472	14,688	0.20
Gcontrol	5,729	5,732	0.01
Rcontrol	5,729	5,729	0.00
Rcontrol2	22,918	22,918	0.00
Mean	16,567		
Median	14,472		

Table 9. Summary values for the distributions of the catches estimated by the different data-poor control rules in the DLMtool package. Control rules shown require estimates of relative abundance (depletion = B / B_0) and relative change over the time period available (Δ_t; see Table 3 for summary descriptions of each method).

	Δ_t= 0.15				Δ_t= 0.25		Δ_t= 0.50		
	Depletion = 0.07				Depletion = 0.125		Depletion = 0.125		
Control rule	Median	Mean	CV	Median	Mean	CV	Median	Mean	CV
DCAC	74,472	72,975	0.09	75,849	74,850	0.06	78,525	78,103	0.07
DCAC4010	9,426	13,230	1.06	31,559	34,834	0.71	77,847	69,497	0.27
Mean	41,949			53,704			78,186		

Table 10. Summary values for the distributions of the catches estimated by the different data-poor control rules in the DLMtool package. Control rules require estimates of absolute abundance (see Table 3 for summary descriptions of each method).

		B (mt) 100,000			B (mt) 200,000			B (mt) 300,000	
	Median	Mean	CV	Median	Mean	CV	Median	Mean	CV
BK	20,232	41,256	3.49	39,346	77,895	3.46	58,821	100,602	1.53
DepF	32,227	35,858	0.49	64,503	72,305	0.50	96,159	107,720	0.50
DynF	19,548	27,206	0.49	43,552	56,358	0.48	68,054	85,580	0.48
Fdem	25,581	35,567	0.90	50,545	71,526	0.93	74,811	107,492	0.95
Fratio	22,512	33,631	0.99	45,848	69,584	1.06	67,864	104,074	1.01
YPR	30,908	55,122	1.29	64,571	110,408	1.25	93,914	167,327	1.30
Mean	25,168			51,394			76,604		
Median	24,046			48,197			71,433		

Table 11. Estimated total biomass (*B*), biomass ratio (B / B_{MSY}), OFL and ABC using DBSRA. DBSRA produces a distribution of estimates, so values are shown for the 25th and 50th percentiles, the mean, standard deviation, and CV of the distribution. Runs are grouped according to the value of B / B_{MSY} in the final year, with over exploited referring to runs with the final B / B_{MSY} < 0.5, fully-exploited referring to runs with 0.5 ≤ B / B_{MSY} < 1.25, and lightly-exploited referring to runs with B / B_{MSY} ≥ 1.25.

Variable	Exploitation status	25th percentile	50th percentile	Mean	Standard deviation	CV
B	over-exploited	178,840	304,538	315,790	175,964	0.56
B / B_{MSY}	over-exploited	0.17	0.30	0.29	0.13	0.46
OFL	over-exploited	17,671	28,186	30,160	16,889	0.56
ABC	over-exploited	3,836	8,949	10,507	8,350	0.79
B	fully-exploited	689,647	896,789	948,915	365,707	0.39
B / B_{MSY}	fully-exploited	1.39	1.55	1.61	0.27	0.17
OFL	fully-exploited	72,949	95,006	99,937	35,948	0.36
ABC	fully-exploited	44,184	70,166	72,872	34,000	0.47
B	lightly-exploited	1,134,110	1,355,847	1,488,041	585,912	0.39
B / B_{MSY}	lightly-exploited	0.70	0.91	0.90	0.22	0.25
OFL	lightly-exploited	143,206	168,028	173,699	44,842	0.26
ABC	lightly-exploited	115,973	136,075	140,668	36,315	0.26

Figures

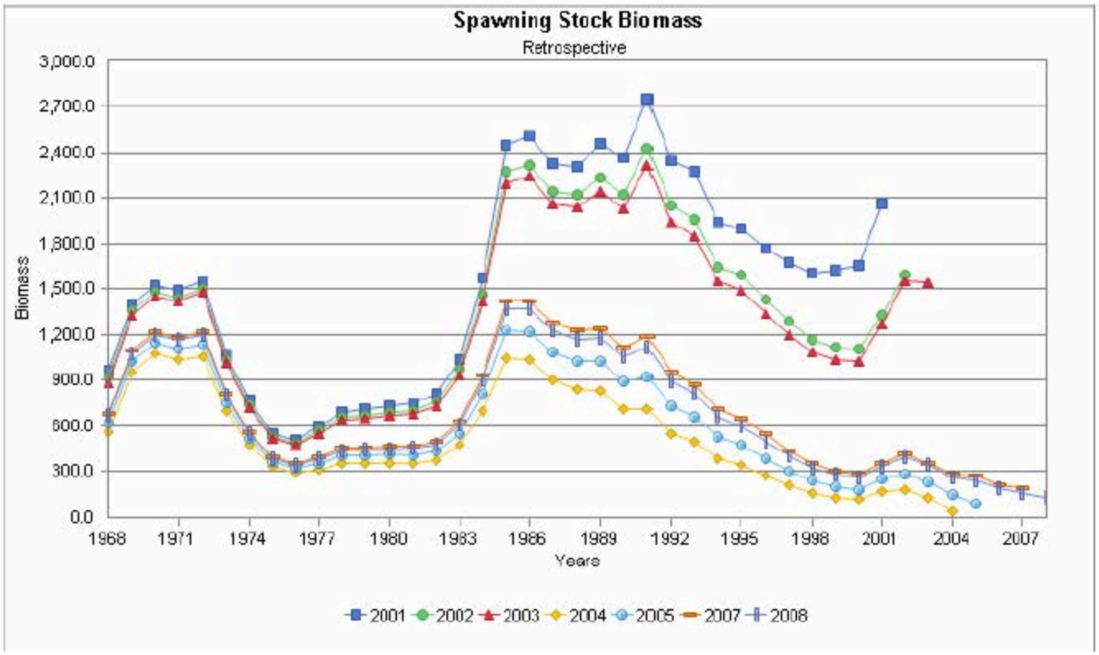

Figure 1. Retrospective estimates of mackerel biomass the previous assessment (TRAC 2010). Estimates of biomass diverged greatly when new data were added after 2003.

Figures

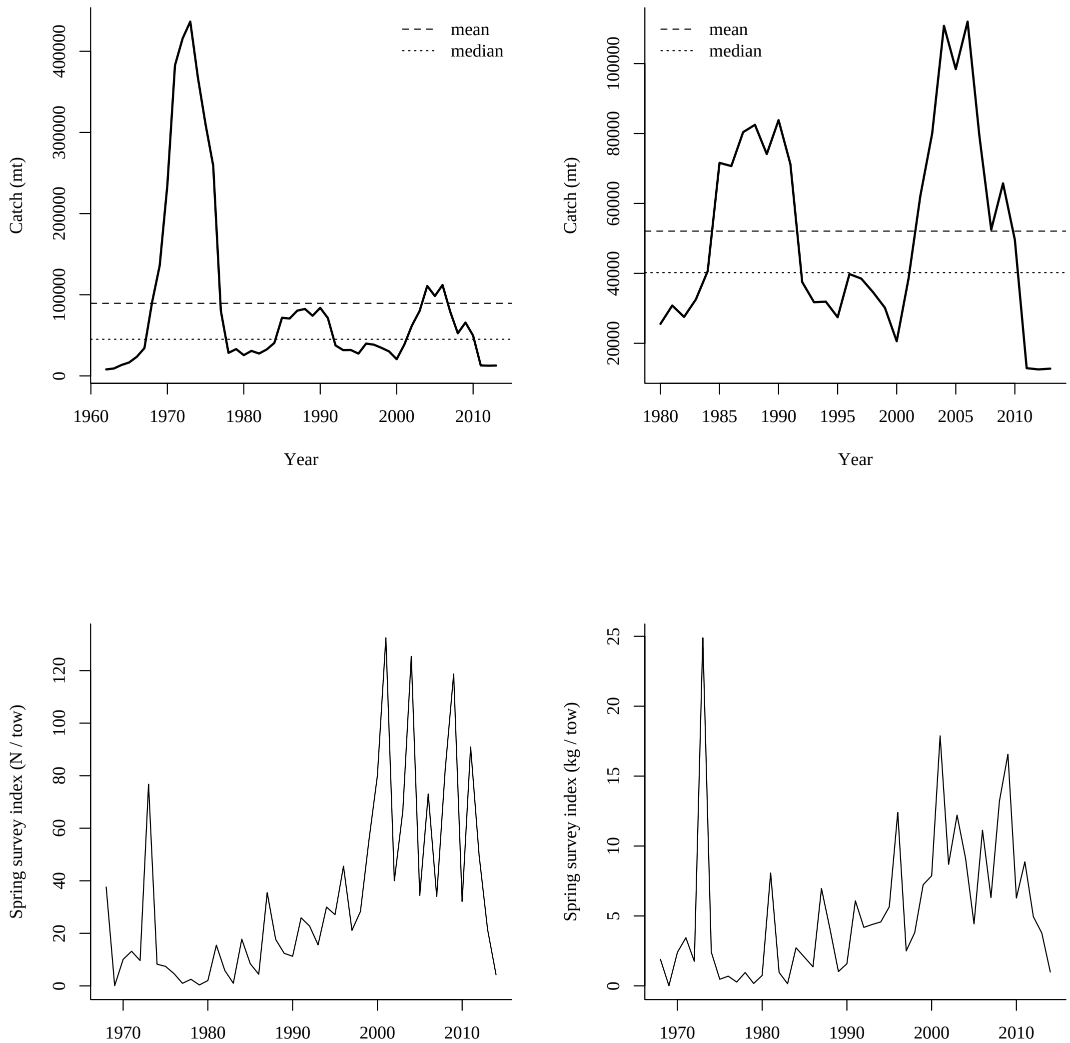

Figure 2. Top: Annual catch of Atlantic mackerel (mt) over two time periods: 1962-2014 (left) and 1980-2014 (right), along with the mean and median catches for each period. Bottom: Numerical (left) and weight-based (right) index of abundance from the NEFSC Spring bottom trawl survey from 1968 to 2014.

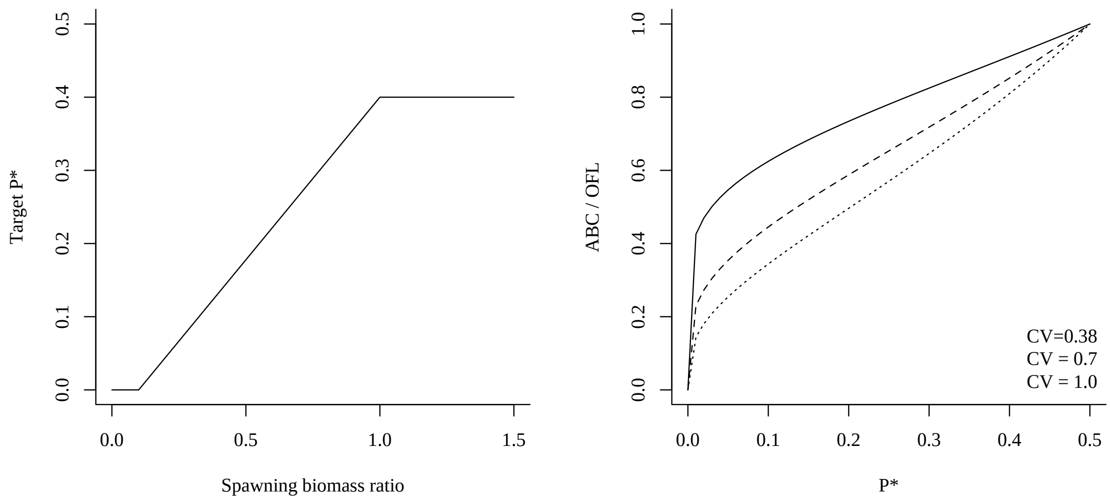

Figure 3. Mid Atlantic threshold-based P* control rule, where the target P* declines linearly as the estimated spawning biomass falls below the S_{MSY} level. Right: Buffer size (ABC / OFL) as a function of the target P* and the assumed CV of the distribution for the OFL. The Mid Atlantic assumes of CV of 1.0 for their stocks.

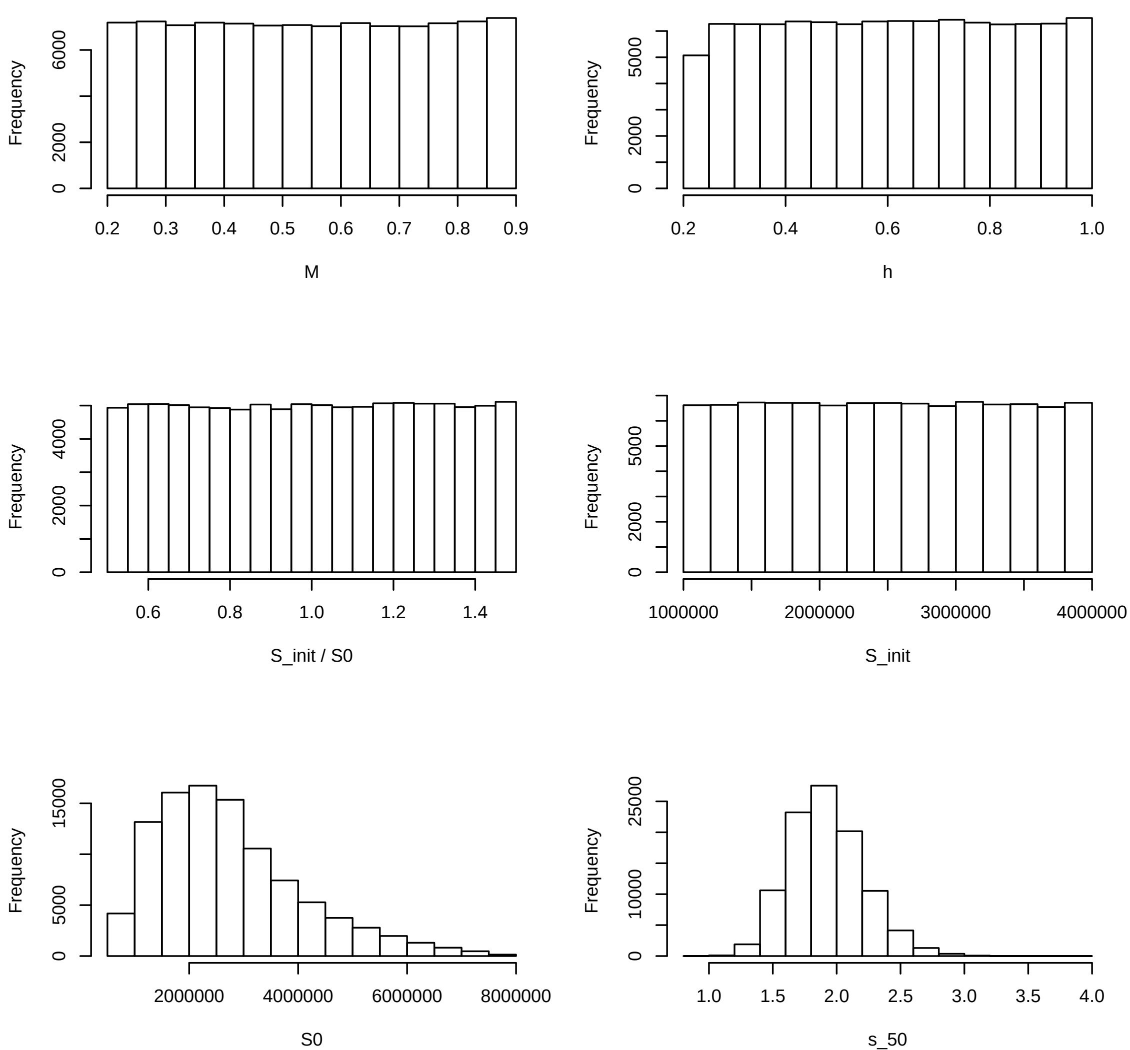

Figure 4. Distribution for input parameters for M, steepness (h), initial depletion (S_{init} / S_0), initial biomass (S_{init}), unfished biomass (S0) and age at 50% selectivity in the fishery (s_{50}) for the base and M-ramp simulation models.

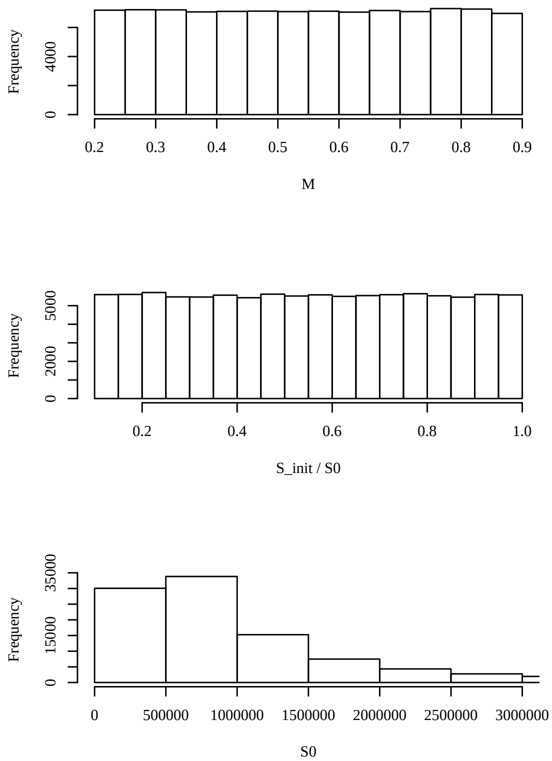

Figure 5. Distribution for input parameters for M, steepness (h), initial depletion (S_{init} / S_0), initial biomass (S_{init}), unfished biomass (S0) and age at 50% selectivity in the fishery (s_{50}) for the truncated simulation model.

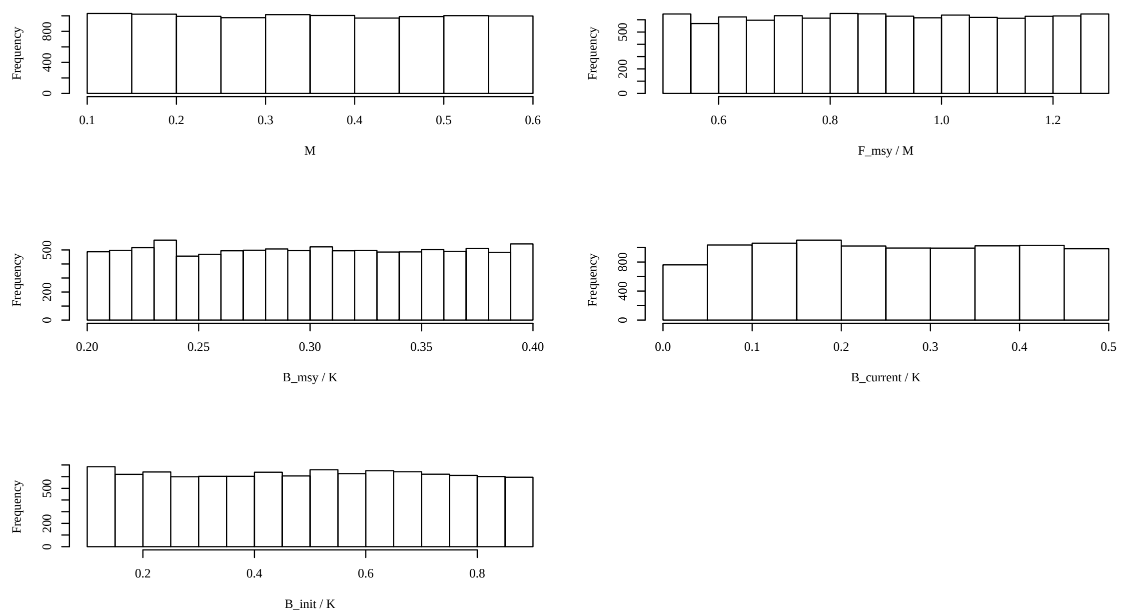

Figure 6. Distributions for input parameters for to the DB-SRA control rule for M, F_{MSY} / M, B_{MSY} / K, $B_{current}$ / K, B_{init} / K. For DB-SRA K is equivalent to B_0. In DB-SRA, production is influenced by the estimate of F_{MSY} (which is calculated based on values for *M* and F_{MSY} / *M*), with higher production resulting from higher estimates of F_{MSY}. Initial runs indicated that higher *M* values were rarely kept (see Figure 17), so the upper bound for *M* was reduced (compared to Figures 4 and 5) to allow for more kept runs.

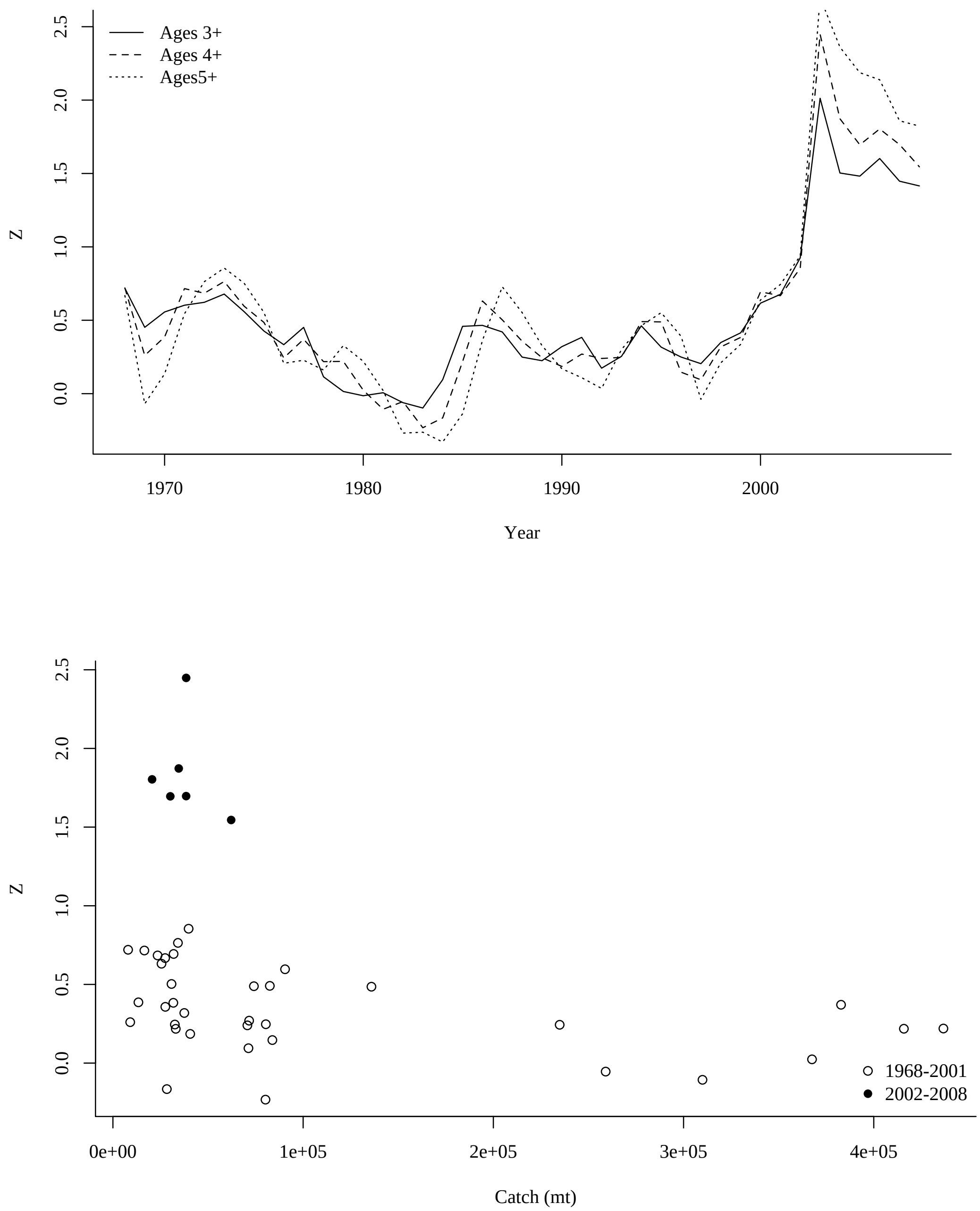

Figure 7. Top: Estimates of Z (the inverse of the slope from the catch curve analysis) each year assuming full recruitment to the fishery at ages 3, 4, and 5. The more negative values indicate higher mortality. Bottom: relationship between Z and the catch in that year. Estimates are split prior to 2002, and from 2002 – 2008.

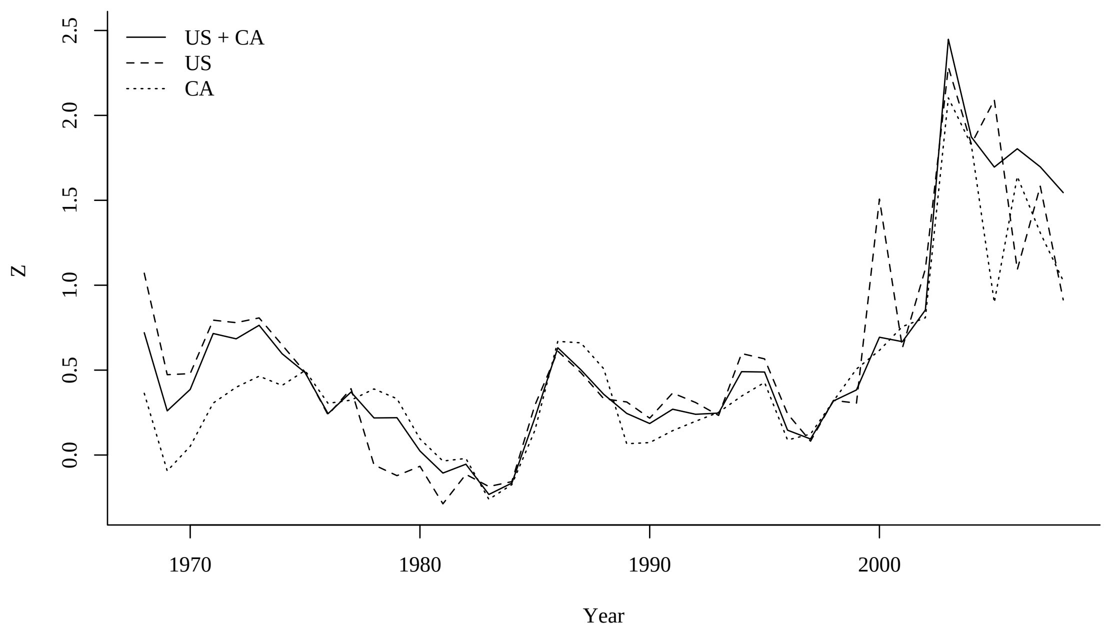

Figure 8. Estimated Z by year from U.S., Canadian (CA), and combined landings, assuming full recruitment to the fishery by age 4.

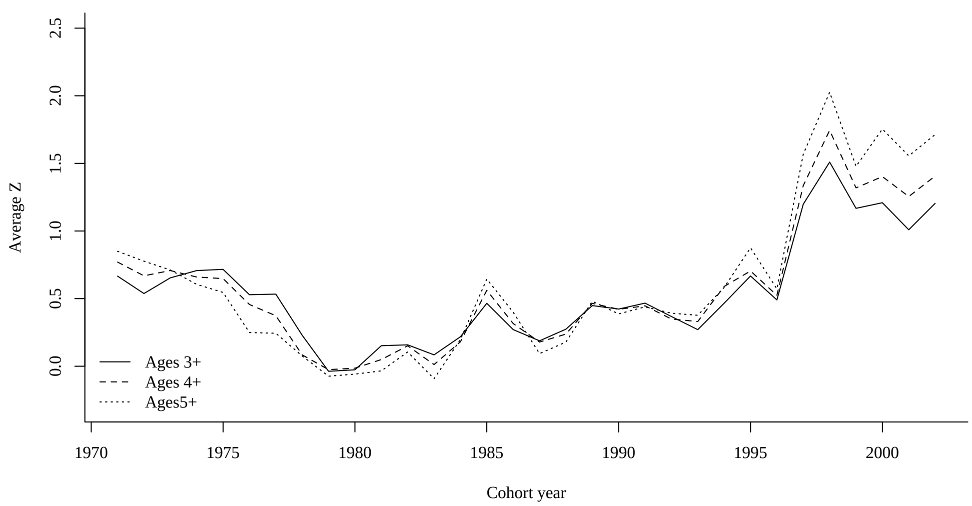

Figure 9. Estimated Z for each cohort, using combined US and Canadian landings assuming full recruitment to the fishery at ages 3, 4, and 5. Cohort year represents the year each cohort recruited to the population at age-1.

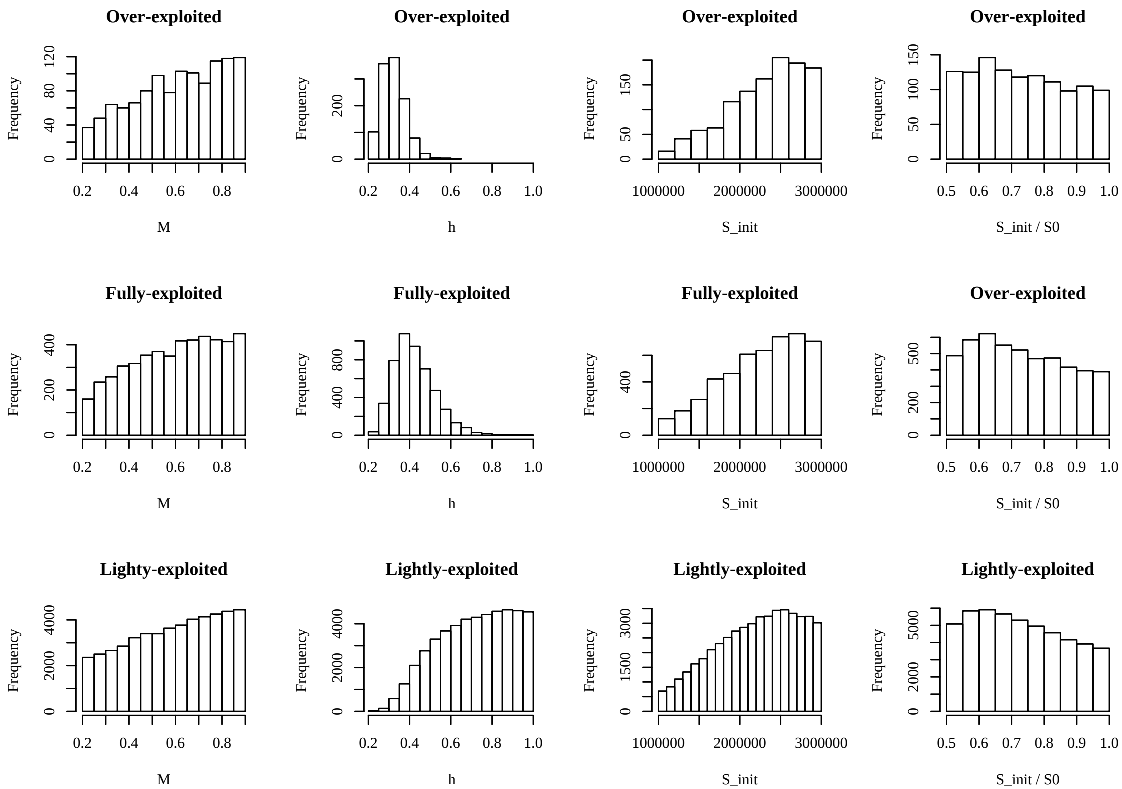

Figure 10. Kept values for M, steepness (h), initial spawning biomass (S_{init}) and the initial depletion (S_{init} / S_0) for the base simulation model using the entire time series of catch data (1962-2014). The dashed and solid vertical lines represent the values of steepned from Myers et al. (1999) for Atlantic mackerel and all members of the family *Scombridae*, respectively.

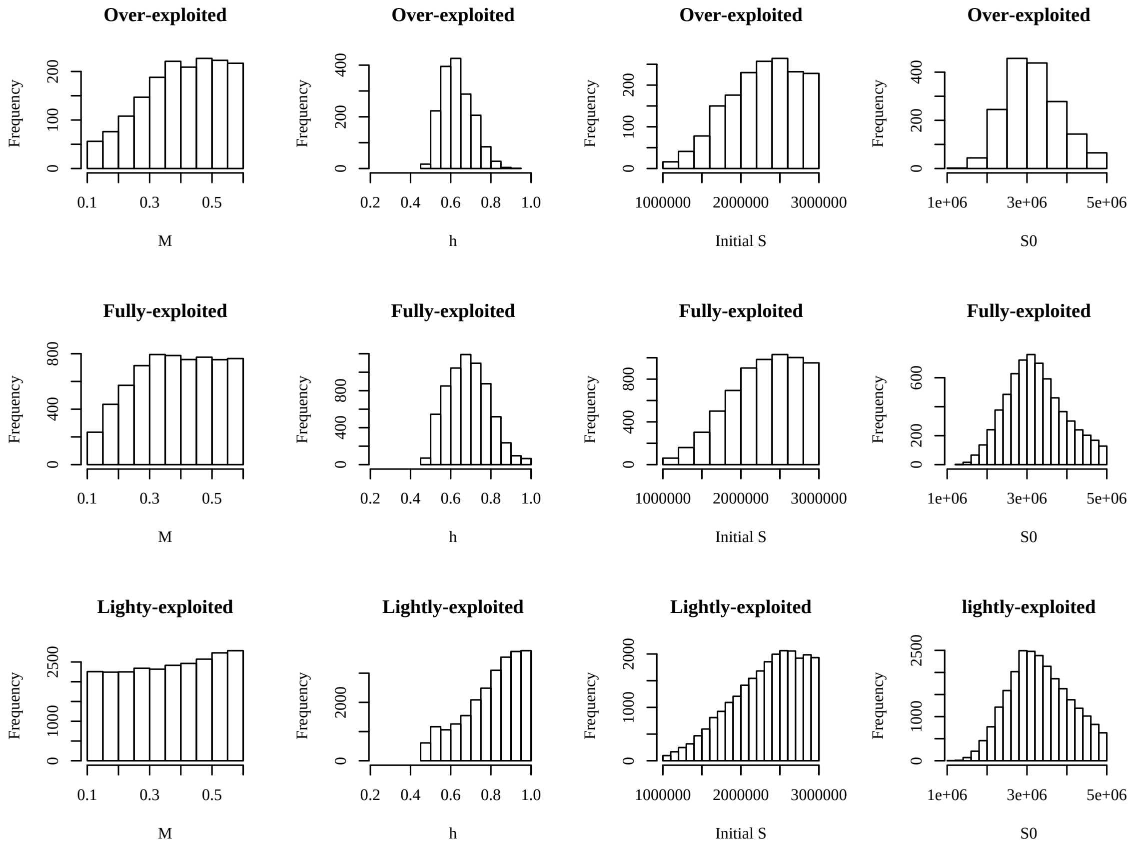

Figure 11. Kept values for M, steepness (h), initial spawning biomass (S_{init}) and the initial depletion (S_{init} / S_0) for the simulation model where M is doubled staring in year 2002. The dashed and solid vertical lines represent the values of steepned from Myers et al. (1999) for Atlantic mackerel and all members of the family *Scombridae*, respectively.

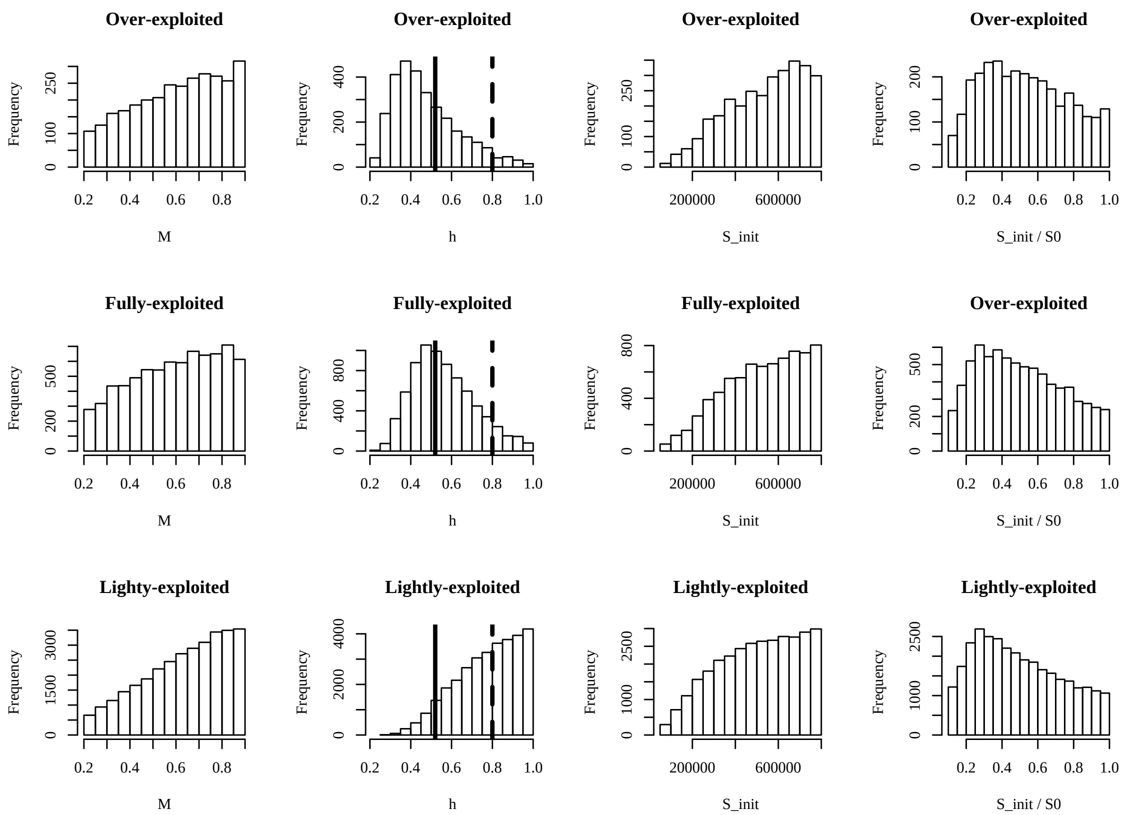

Figure 12. Kept values for M, steepness (h), initial spawning biomass (S_{init}) and the initial depletion (S_{init} / S_0) for the simulation model using the truncated time series of catch data (1978-2014). The dashed and solid vertical lines represent the values of steepness from Myers et al. (1999) for Atlantic mackerel and all members of the family *Scombridae*, respectively.

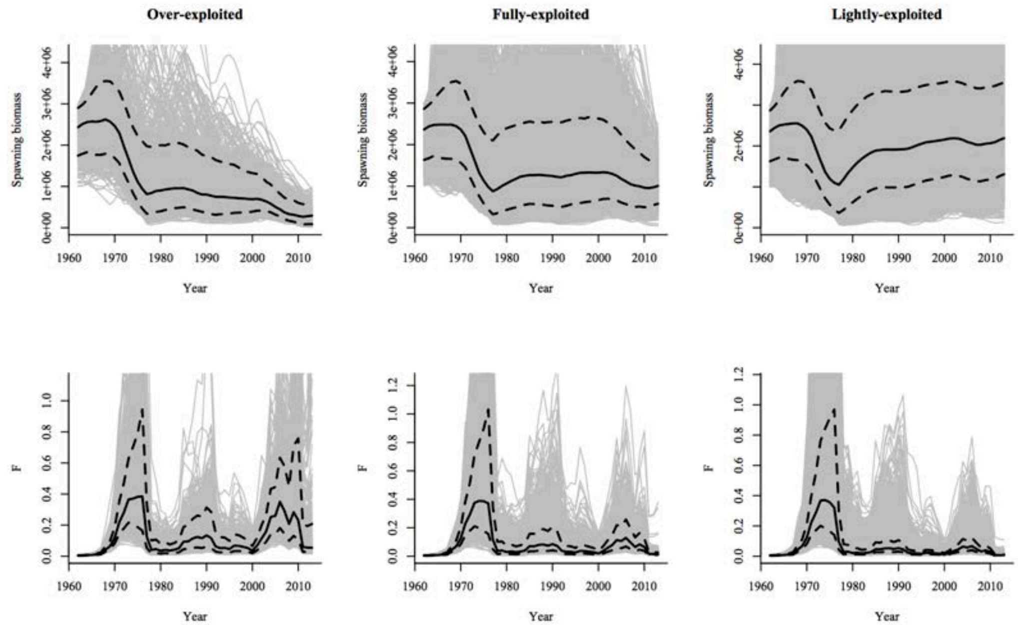

Figure 13. Trajectories of spawning biomass and fishing mortality by year from the base model. Runs are grouped according to the value of S / S_{MSY} in the final year, with over exploited referring to runs with the final $S / S_{MSY} < 0.5$, fully-exploited referring to runs with $0.5 \leq S / S_{MSY} < 1.25$, and lightly-exploited referring to runs with $S / S_{MSY} \geq 1.25$. Gray lines represent individual runs, while the solid and dashed black lines represent the median and the 90% confidence intervals, respectively.

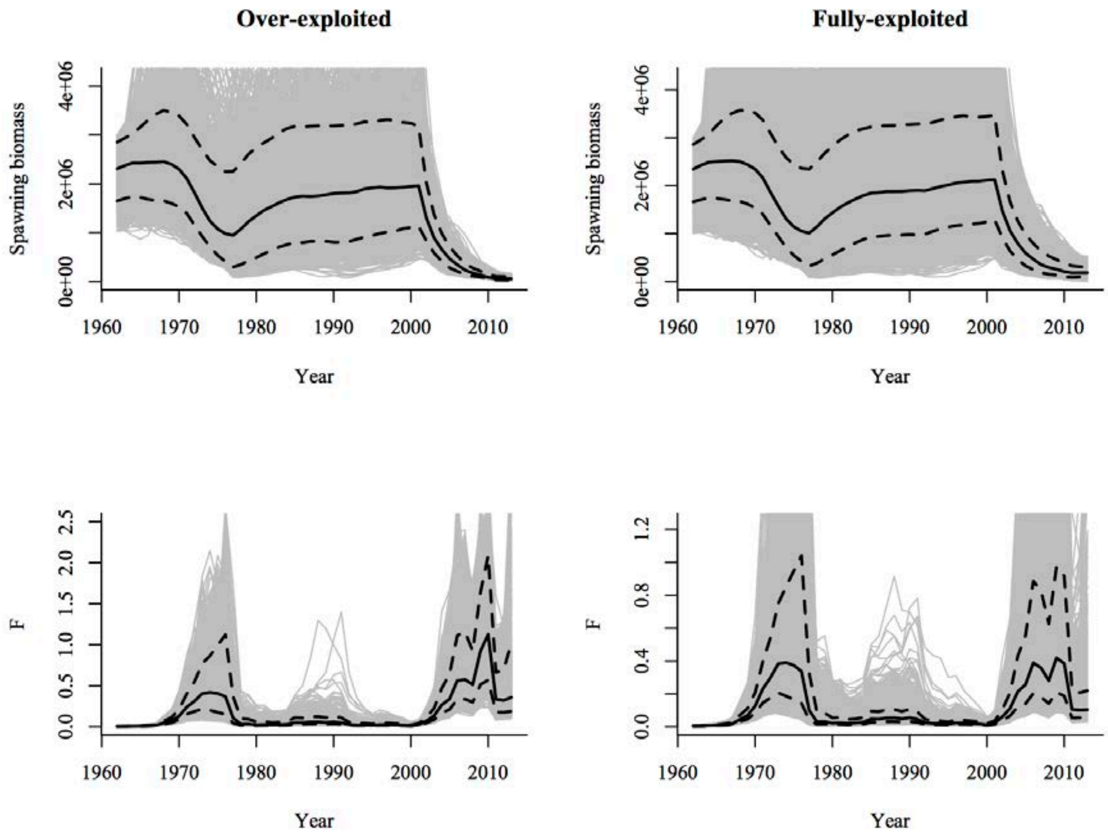

Figure 14. Trajectories of spawning biomass and fishing mortality by year from the M-ramp model (where M is double in year 2002). Runs are grouped according to the value of S / S_{MSY} in the final year, with over exploited referring to runs with the final $S / S_{MSY} < 0.5$, and fully-exploited referring to runs with $0.5 \leq S / S_{MSY} < 1.25$. Gray lines represent individual runs, while the solid and dashed black lines represent the median and the 90% confidence intervals, respectively

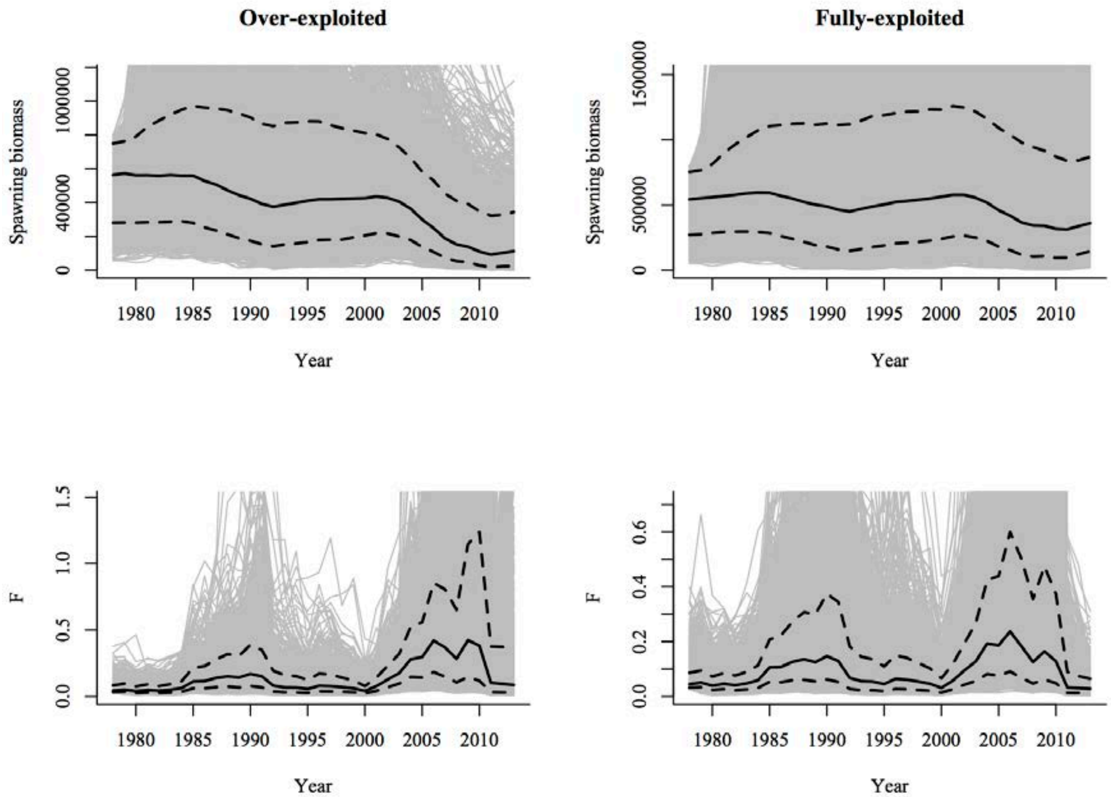

Figure 15. Trajectories of spawning biomass and fishing mortality by year from the truncated model that used only catch data from 1978-2014. Runs are grouped according to the value of S / S_{MSY} in the final year, with over exploited referring to runs with the final $S / S_{MSY} < 0.5$, and fully-exploited referring to runs with $0.5 \leq S / S_{MSY} < 1.25$. Gray lines represent individual runs, while the solid and dashed black lines represent the median and the 90% confidence intervals, respectively

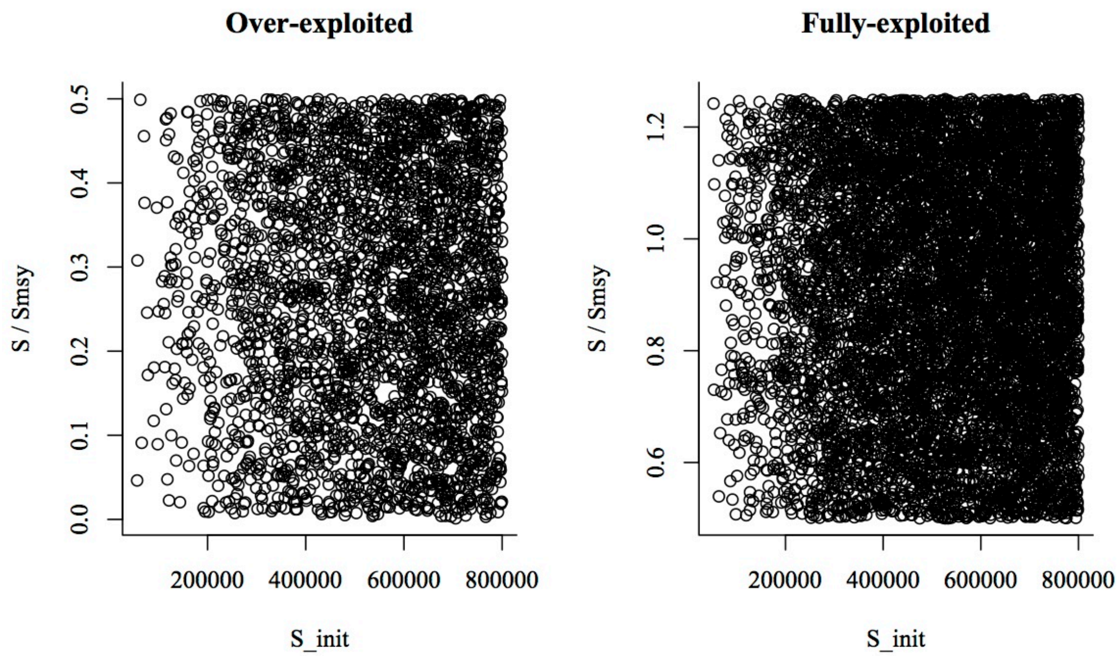

Figure 16. Relationship between initial biomass (S_{init}) and the depletion level (S / S_{MSY}) in the final year of the model for the over- and fully-exploited runs.

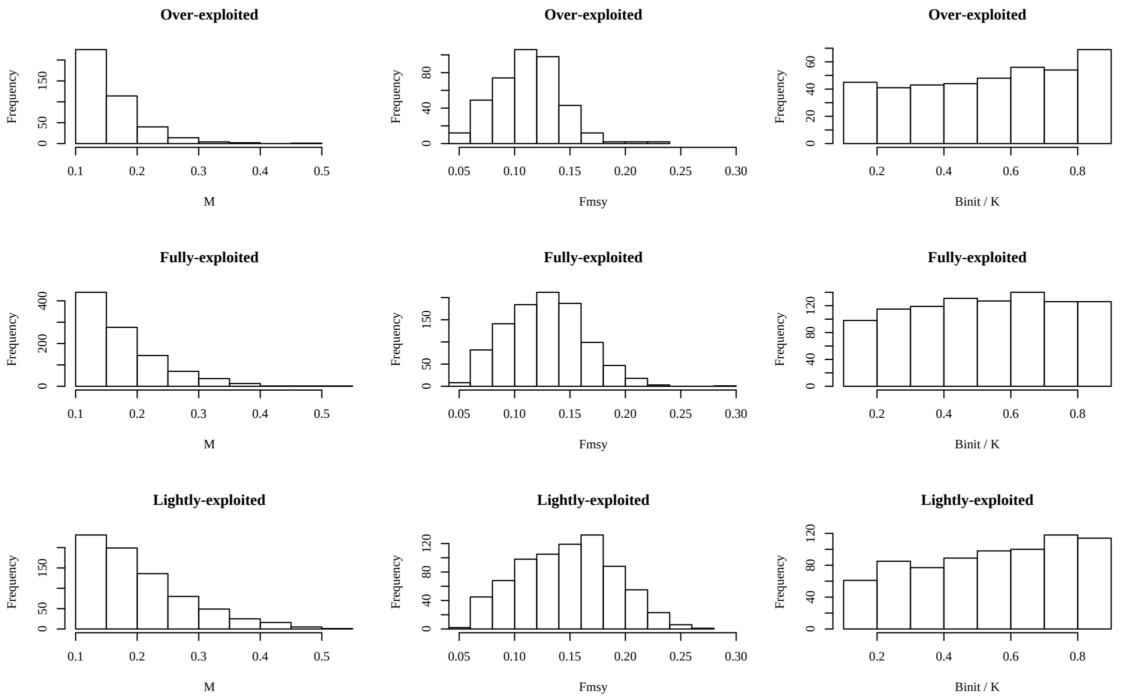

Figure 17. Kept parameters for M, F_{MSY}, and B_{init} / K from the DB-SRA model. Many parameter combinations result in biomass either falling below 0, or are unable to result in an assumed level of depletion ($B_{current}$ / K), and the model run is discarded. For DB-SRA K is equivalent to $B_{0.}$

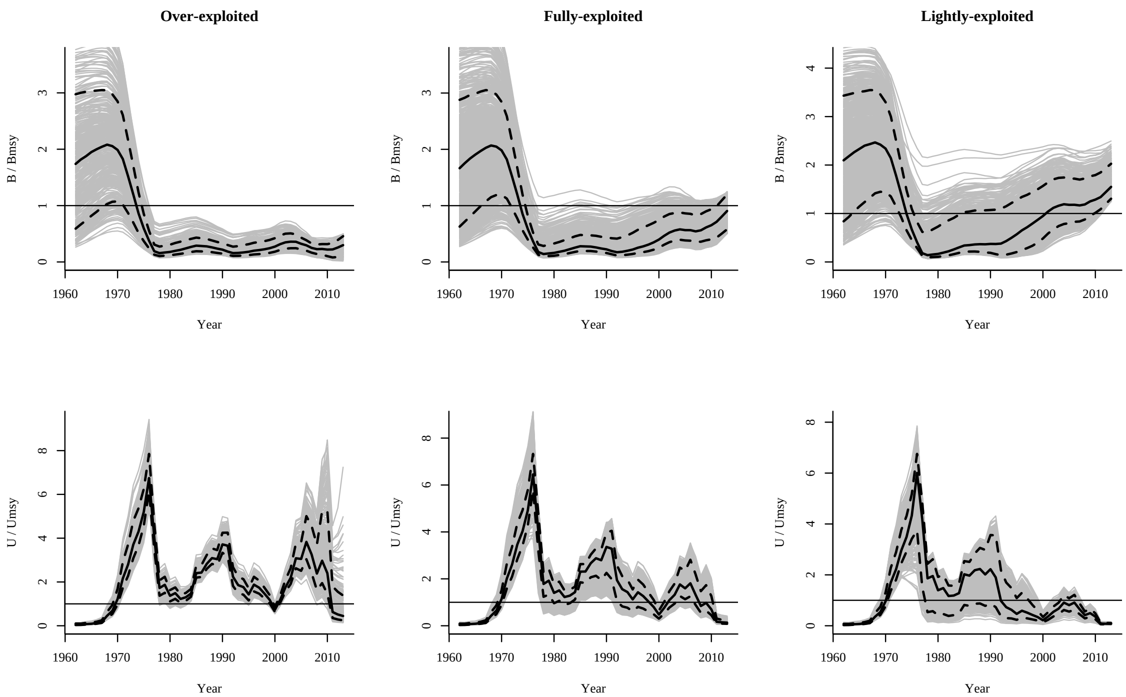

Figure 18. Trajectories of B / B_{MSY} and U / U_{MSY} from DB-SRA. DB-SRA estimates harvest fraction (U) and not F. Runs are grouped according to the value of B / B_{MSY} in the final year, with over exploited referring to runs with the final B / B_{MSY} < 0.5, fully-exploited referring to runs with $0.5 \leq$ B / B_{MSY} < 1.25, and lightly-exploited referring to runs with B / $B_{MSY} \geq 1.25$. Gray lines represent individual runs, the solid black line represents the median of each grouped set of runs, and the dashed black lines represent the 95% confidence intervals for the runs. A horizontal line at 1 is added as a reference.

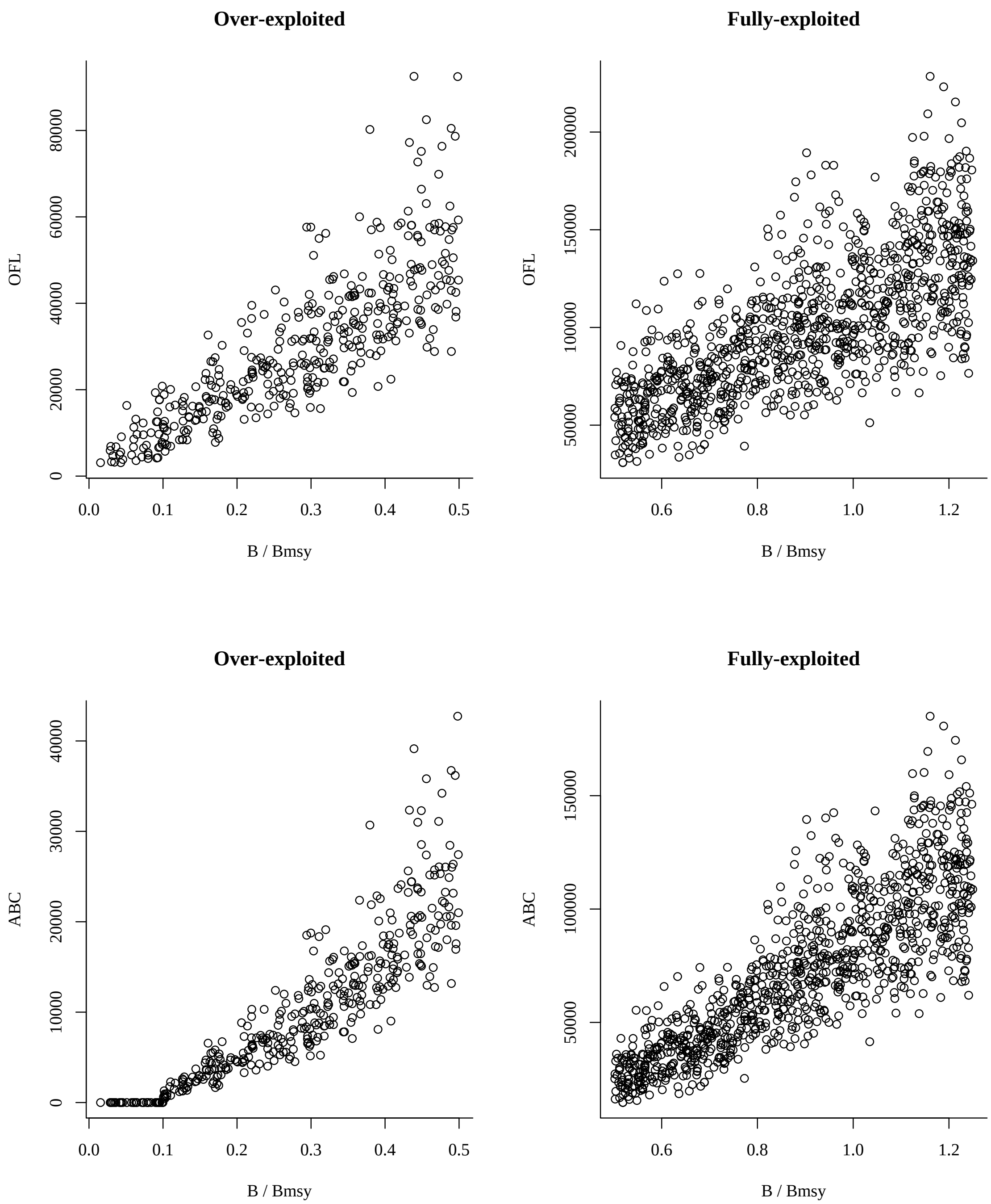

Figure 19. Estimates of the OFL and ABC using DBSRA as a function of B / B_{MSY}. The ABC was calculated by applying the Mid Atlantic threshold P* control rule with an assumed CV of 1.0 for the OFL distribution.

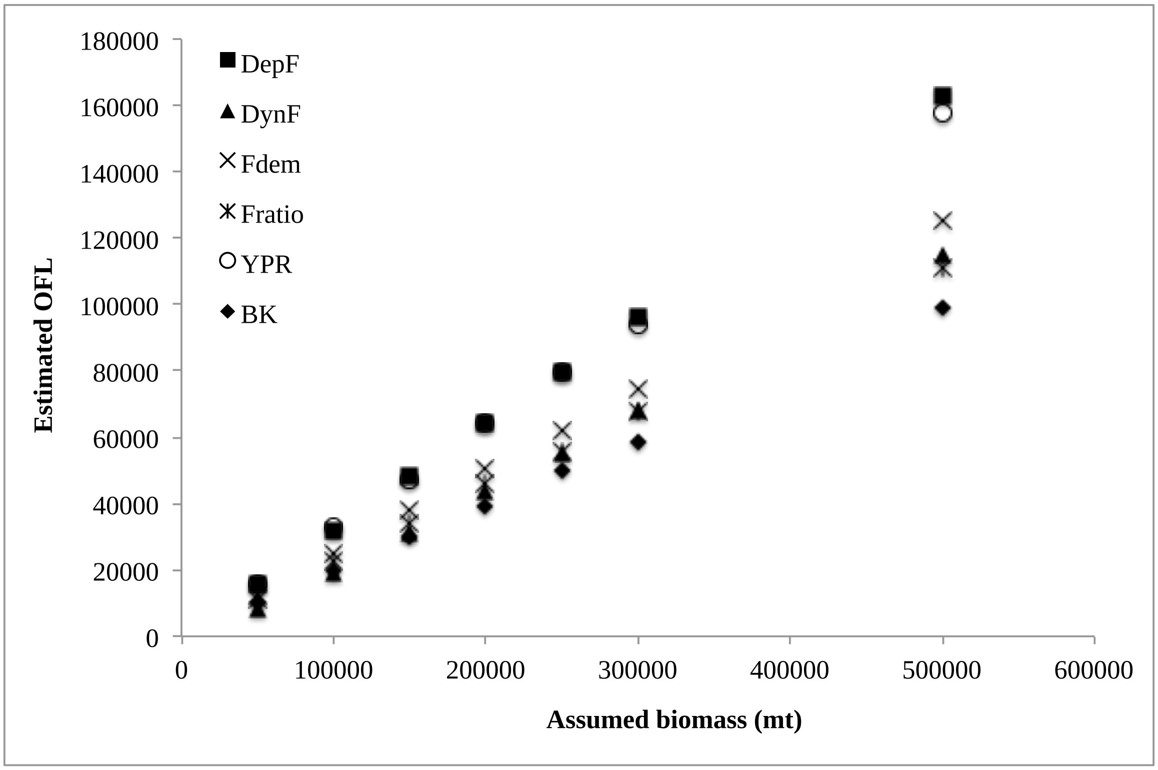

Figure 20. Estimated catch as a function of the assumed biomass from different data-poor control rules available in the DLMtool package.

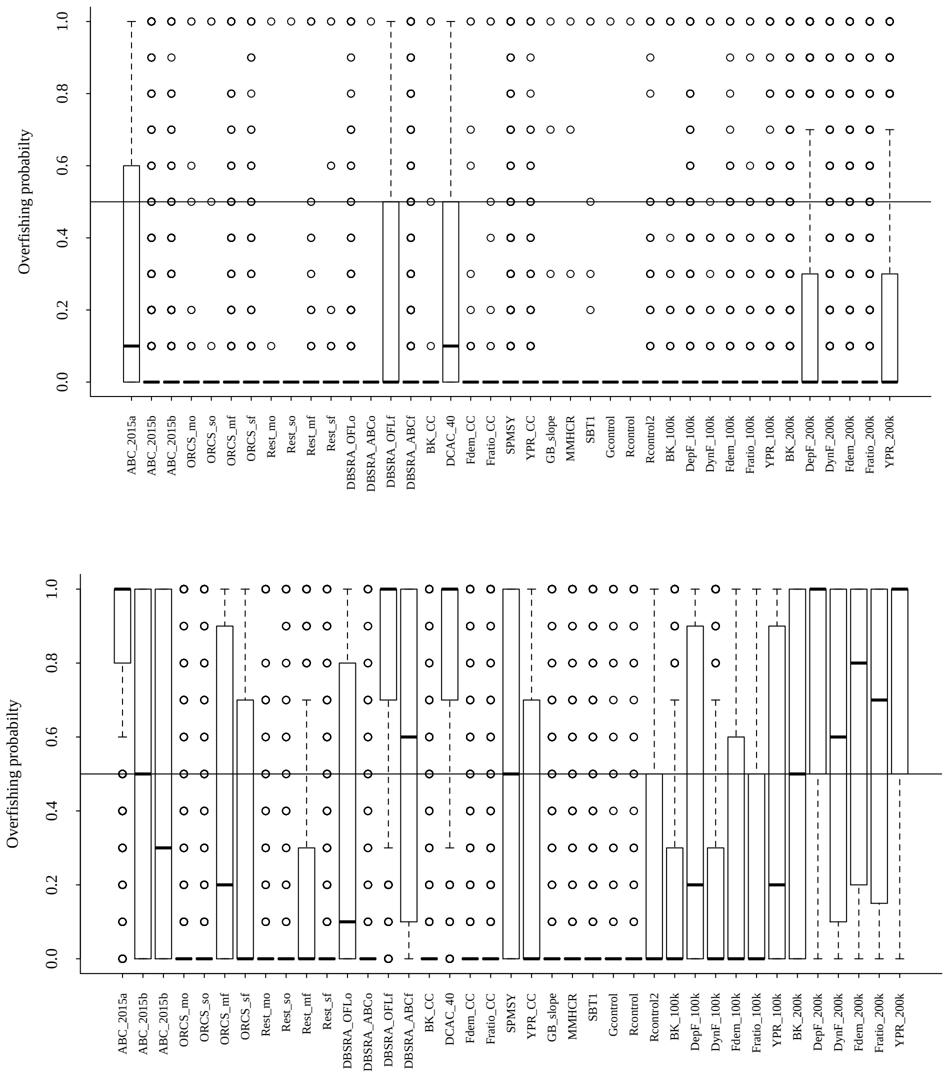

Figure 21. Probability of overfishing in the next 10 years across control rules explored in this analysis for mackerel that are currently fully-exploited (top) and over-exploiter (bottom). ABC_2015a,b,c represent the options considered for 2015 by the MAFMC, with b representing the chosen ABC. The ORCS and Restrepo (Rest) approaches were applied using the median and stable catches assuiming the population was over-exploited (denoted mo and so in the Figure, respectively) and fully-exploited (denoted mf and sf). DB-SRA was applied using the median OFL and ABC estimates for over and fully-exploited population sizes (Table 11; denoted ABCo or ABCf for the over- and fully-exploited cases, respectively). Control rules that required an estimate of biomass (Table 10) are shown assuming a current abundance of 100,000 and 200,000 mt (denoted 100k and 200k, resepctiely).

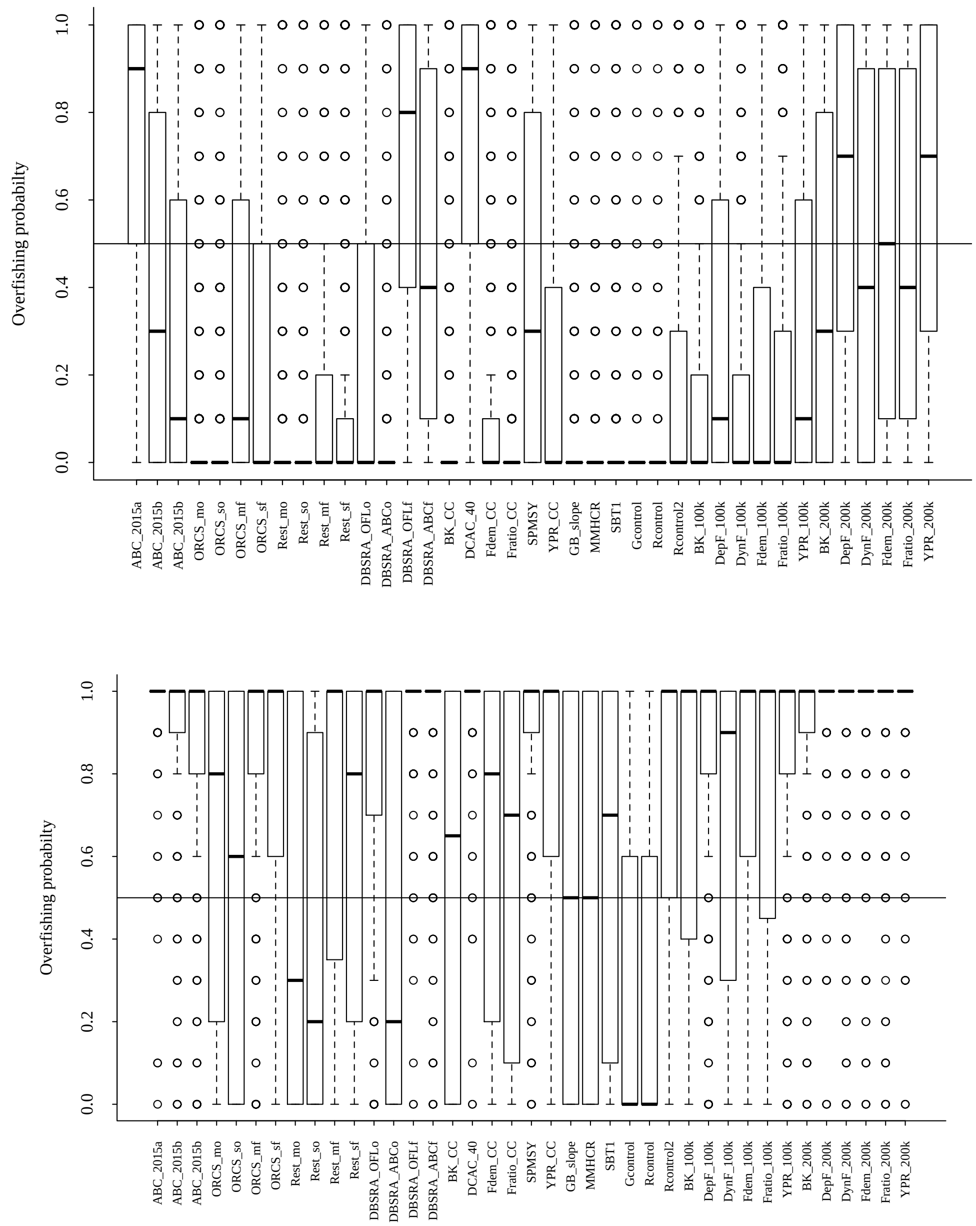

Figure 22. Similar to Figure 21, but for the M-ramp model runs where *M* was doubled starting in year 2002.

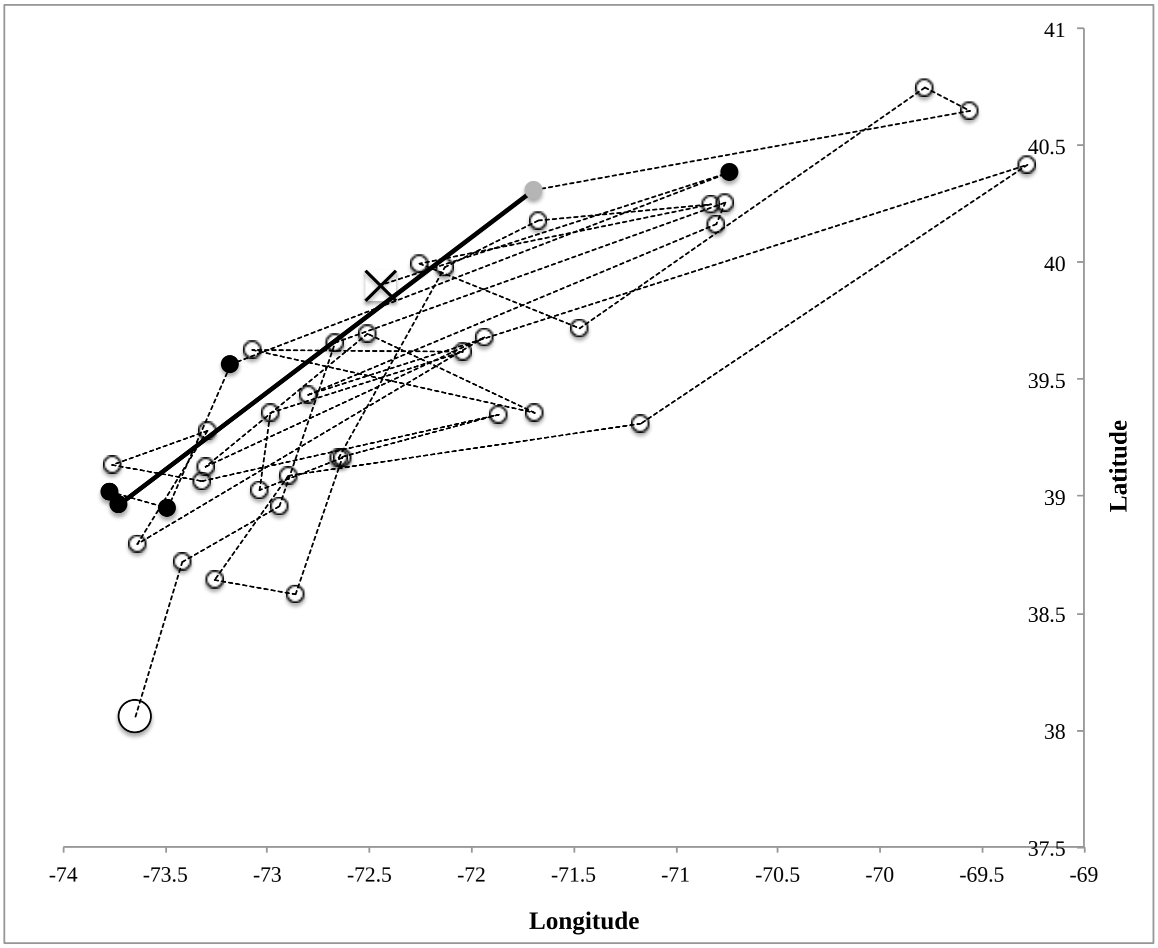

Figure 23. Latitude and longitude of the centroid of the biomass distribution from the NEFSC spring survey from 1968 (large open circle) to 2008 (large X). The bold line connects the centroid position from 2002 (gray filled circle) to 2003. Black filled circles represent 2003 through 2007. Centroid locations were provided by Malin Pinsky of Rutgers University.

Appendix 1. Input file used in the DLMtool package.

Name	Mackerel									
Year	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
	2010	2011	2012	2013	2014					
Catch	7353	6831	7978	9092	13405	16533	23496	34181	90495	135917
	234872	382794	415830	436609	367534	309951	259052	80209	28345	33042
	25545	30806	27548	32559	40638	71609	70692	80394	82492	74121
	83823	71253	37523	31759	31905	27454	39797	38505	34602	30176
	20591	38497	62169	79979	110797	98417	112008	79246	52518	65744
	49597	12888	12535	12751	14762					
Abundance index									1.89	0.01
	2.39	3.44	1.75	24.89	2.41	0.47	0.69	0.27	0.95	0.17
	0.74	8.07	0.96	0.15	2.72	2.04	1.36	6.96	4.08	1.02
	1.58	6.08	4.18	4.39	4.57	5.65	12.4	2.5	3.8	7.23
	7.87	17.88	8.69	12.21	9.12	4.43	11.13	6.31		
	13.22	16.56	6.28	8.87	4.95	3.77				
Duration t	55									
Average catch over time t	85077									
Depletion over time t	NA									
M	0.4									
FMSY/M	0.9									
BMSY/B0	0.35									
MSY	NA									
BMSY	NA									
Age at 50% maturity	1.9									
Length at first capture	20									
Length at full selection	30									
Current stock depletion	NA									
Current stock abundance	NA									
Von Bertalanffy K parameter	0.1									
Von Bertalanffy Linf parameter	44.59									
Von Bertalanffy t0 parameter	-2.42									
Length-weight parameter a	0.00000325									
Length-weight parameter b	3.3									
Steepness	0.8									
Maximum age	10									
CV Catch	0.2									
CV Depletion over time t	0.5									
CV Average catch over time t	0.221									
CV Abundance index	0.45									
CV M	0.4									
CV FMSY/M	0.3									
CV BMSY/B0	0.045									
CV current stock depletion	0.5									
CV current stock abundance	1									
CV von B. K parameter	0.1									
CV von B. Linf parameter	0.05									
CV von B. t0 parameter	0.1									
CV Age at 50% maturity	0.2									
CV Length at first capture	0.2									
CV Length at full selection	0.2									
CV Length-weight parameter a	0.1									
CV Length-weight parameter b	0.1									
CV Steepness	0.1									
Sigma length composition	0.2									
Units	metric tons									
Reference OFL	NA									
Reference OFL type	NA									
CAA_bins	1	2	3	4	5	6	7	8	9	10
CAA 1962	16.1	2.8	15.2	3.8	1.2	1.6	1.4	0.8	0.4	0.4
CAA 1963	1.1	4.2	1.3	26.3	6	0.3	0.2	0.2	0.2	0.2
CAA 1964	12.9	7	4.1	4	19.4	4.1	3.9	0.7	0.8	0.2
CAA 1965	9	3.6	2.9	4	5.2	19.5	4.2	4	0.7	0
CAA 1966	24	11.5	5.3	2.6	4.7	7.9	21.8	0.5	0.2	0

CAA 1967	0.8	26.7	19.8	3.5	3.3	5.1	6.1	32.3	0.3	0
CAA 1968	161.5	64.8	64.1	41.5	15.6	7.2	1	1.8	11	0.1
CAA 1969	8.7	269.7	165.9	66.4	6	3.2	2.3	3.2	2.3	11.1
CAA 1970	198.6	55.4	530.6	164.9	28.2	7.1	5.4	10.3	10.4	7.7
CAA 1971	77.4	297.1	128.1	572.9	206.5	35.3	9.8	4.2	5	17.5
CAA 1972	22.1	85.7	257.4	184.1	397.2	88.7	25.4	4.2	8.3	11.3
CAA 1973	165.8	292.3	289.3	237.7	198.5	207	34.9	12.2	4.5	6.1
CAA 1974	101.3	257.4	281.1	110.6	122.2	119.6	117.9	28.2	7.5	4.4
CAA 1975	382.6	447	121.9	108.1	63	72.5	55.3	53	13	3.7
CAA 1976	13.4	364.6	286.7	91.5	56.5	29.3	43.1	36.7	24.2	15.4
CAA 1977	2.1	27.9	103.8	55.4	12.5	10.2	5.7	6.5	3.9	4.4
CAA 1978	0.1	0.2	4.7	17.4	13.3	8.4	4.7	2.2	4.5	7.3
CAA 1979	0.4	0.6	1.3	7.1	18.6	13.1	6.2	2.6	2.2	6.5
CAA 1980	1.2	10.9	3.3	1.9	6.9	13.8	7.6	3.4	2.2	5.2
CAA 1981	16.1	7.1	9.2	1.4	2	6.1	11.7	4.9	2.5	3.5
CAA 1982	3.7	11.8	2.7	9.1	1.2	1.9	3.4	8.4	2.9	5.1
CAA 1983	2.2	15.3	6.5	1.9	7	0.7	1.2	5.5	10.2	6.5
CAA 1984	0.5	40.4	27.2	3.2	1.2	4.6	0.6	0.7	3.4	14
CAA 1985	3.1	1.6	123	32.5	2.9	1	4	0.4	0.7	14.9
CAA 1986	1.3	12.7	6.7	100.9	25.4	2.1	0.7	3.2	0.2	6.1
CAA 1987	4.2	14.6	14.6	7.7	110.1	17.8	2.5	0.4	2.1	3.5
CAA 1988	1	13	10.3	10	11.7	106.8	23	2.6	1.2	5.6
CAA 1989	3.9	17.2	11	7.3	7.1	2.4	88.6	5	0.9	2.3
CAA 1990	4.1	29.4	47.1	8.4	6.6	4.5	0.8	55.2	2.6	1.2
CAA 1991	1.4	14.6	56.4	24.6	6.5	3.9	3.3	1	27.3	1.2
CAA 1992	0.7	6.8	5.3	25.7	15.4	2.1	1.6	1.3	1.3	16.7
CAA 1993	1.5	9.2	11.3	6.2	16.5	8.9	1.9	0.8	1.1	8.4
CAA 1994	5	6.4	29	28.7	9.2	28	7.5	1.3	0.5	5.7
CAA 1995	18.5	20.7	2.7	9.5	8.2	3.2	10.3	3.2	0.3	0.9
CAA 1996	7.7	35	25.8	1.9	12.7	9.9	2.6	10.2	2.3	1.5
CAA 1997	6.9	22	23.4	11.1	1.1	8.5	6.8	2.8	7.2	1.9
CAA 1998	2.3	29.8	19.1	16.7	8.7	1.2	5.9	4.1	1	2.4
CAA 1999	1.7	6.7	23.9	14.2	9.2	4.8	1.5	2.9	2	1.3
CAA 2000	26.1	9.6	6.2	10.3	4.4	3.3	0.7	0.1	0.2	0.4
CAA 2001	9.1	76.9	23.8	7.5	9.9	2.4	2.1	0.7	0.2	0.3
CAA 2002	9.9	12.4	120	14.2	5.3	9.7	3.1	0.8	0.2	0.1
CAA 2003	10.2	23.9	26.5	121.9	14	5	4.9	0.3	0	0
CAA 2004	37.6	77.9	22.3	25.2	121.1	9.1	2.8	0.9	0.2	0
CAA 2005	18.7	101	63.2	12.9	9.4	70.2	2.2	3.2	0.1	0
CAA 2006	24.7	22.2	129.2	44.7	10.6	8.5	39.2	1	0.1	0
CAA 2007	2.5	52.8	39.4	64.2	13.9	2.2	1.7	6.5	0.2	0
CAA 2008	18.4	19.6	54.9	13.9	18.5	2.9	0.5	0.3	1.2	0