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HOW UNCERTAINTY IN NATURAL MORTALITY AND STEEPNESS MAY AFFECT PERCEPTION OF STOCK STATUS AND FISHERY SUSTAINABILITY IN ATLANTIC SURFCLAM: A SIMULATION ANALYSIS

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ABSTRACT The Atlantic surfclam (*Spisula solidissima*) is an important commercial fishery resource on the U.S. MidAtlantic continental shelf. Although the 2016 stock assessment found that surfclams are neither overfished nor is overfishing occurring, uncertainty in the scale of spawning stock biomass persists. As a consequence of this uncertainty, the MidAtlantic Fishery Management Council (MAFMC) lowered the acceptable biological catch in 2016. A simulation analysis was developed for Atlantic surfclam to estimate the overfishing risk associated with the catch recommendation and its adherence to the MAFMC risk policy. Operating models conditioned on the 2016 stock assessment model structure generated simulations of the surfclam population, with alternative models to represent uncertainty in steepness (h) of the stock-recruitment curve and natural mortality (M). Simulations were forecasted under a variety of management procedures and evaluated with estimation models that spanned uncertainty in h and M. Results showed that current management decisions are more conservative than the stated risk-tolerance policies, though overestimating steepness in assessment models could lead to the misrepresentation of an overfished stock as within management thresholds. Further analysis evaluated future economic viability of the fishery by estimating proportion of fishable clam patches given forecasted biomass and historical observations of clam density. The proportion of fishable patches able to support fishery economic sustainability was generally stable despite biological uncertainties, though declined with increasing fishing pressure. This work contributes to the efforts to evaluate environmentally and economically sustainable fishery management strategies.

KEY WORDS: Atlantic surfclam, stock assessment, forecast, uncertainty, risk-tolerance

INTRODUCTION

Many sources of uncertainty impact determination of fishery management targets [e.g., acceptable biological catch (ABC)] for all managed commercial and recreational fisheries (Rosenberg & Restrepo 1994, Roughgarden & Smith 1996, Punt et al. 2016). In the face of these uncertainties, fishery managers often make explicitly conservative management decisions and reserve fishery resources (Walters 1984, Hilborn 1987, Francis & Shotton 1997), though how these decisions relate to the risk-tolerance policy of management councils is rarely evaluated (Shertzer et al. 2008, Wiedenmann et al. 2017, Prager & Shertzer 2019). Simulation analysis based on alternative operating models (OMs) allows managers to evaluate alternative control rules and the relative importance of various sources of uncertainty to make decisions that conform to the designated risk-tolerance policy of the management council.

The Atlantic surfclam (*Spisula solidissima*) is a historically important resource for the north- and Midatlantic commercial fisheries (McCay et al. 2011, Hofmann et al. 2018), though uncertainties in population dynamics complicate determination of management targets (Munroe et al. 2016, Hennen et al. 2018, Timbs et al. 2018). The 2016 stock assessment determined that the surfclam stock was not overfished ($SSB > SSB_{Threshold}$) and overfishing was not occurring ($F > F_{Threshold}$; NEFSC 2017). Though the stock was not overfished, there was substantial uncertainty around the estimate of absolute spawning stock biomass (SSB) from the assessment model. This led the MidAtlantic Fishery Management Council (MAFMC) to decrease the ABC from 60,313 metric tons (mt) to 45,524 mt (MAFMC 2017) (this decision was later reversed). The fishery quota has long been set at 26,218 mt, below the ABC, as a result of economic constraints within the fishery. Despite the absence of a precise SSB estimate, relative biomass of the surfclam stock was estimable from the assessment, and biological reference points relative to biomass were based on the ratio of terminal to unfished SSB. The fishing mortality (F) reference points were more difficult to define in the absence of precise biomass estimates, but were ultimately derived from $F_{Threshold}$, estimated outside the stock assessment model at $0.12\ y^{-1}$ (Hennen et al. 2018).

Uncertainty in the absolute SSB can be largely attributed to fishery-independent survey estimates of catch per unit effort (CPUE). Relatively low dredge efficiency early in the time series (Hennen et al. 2012, NEFSC 2017), uncertainty in the methodology used to calibrate dredge efficiency (Hennen et al. 2012, Poussard et al. 2021), patchiness of surfclam spatial distribution (Timbs et al. 2019), and range shifts influencing survey design (Jacobson & Hennen 2019) led to a relatively uninformative time series of CPUE from 1982 to 2011. In 2012, a new fishery-independent sampling system began on a vessel with higher dredge efficiency (Hennen 2018) and an improved survey design was implemented in 2016 (Jacobson & Hennen 2019), though too few observations were yet available to the 2016 assessment to overcome historical sampling error for a more certain estimate of SSB.

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In addition to an uninformative survey CPUE time series, commercial dredges rarely select clams less than 120 mm, approximately an age-5 surfclam (Munroe et al. 2013, Chute et al. 2016, Kuykendall et al. 2017), limiting the information available for young individuals. As the broodstock-recruitment relationship is also uninformed, estimates of recruitment success (or failure, quantified as the deviation in recruitment from the S–R curve) in stock assessment models are lagged and only become estimable when clams reach minimum size for gear-selectivity. Further uncertainty in future stock status persists, as steepness of the broodstock-recruitment curve and natural mortality are likely to vary with warming of the northwest Atlantic (Pershing et al. 2015, Saba et al. 2016, Friedland et al. 2020). This warming has instigated large-scale and rapid changes in recruitment, mortality, and stock distribution (Hennen et al. 2018). These uncertainties have led the MAFMC to make conservative management decisions for the surfclam fishery, though adherence to the MAFMC risk-tolerance policy has not been evaluated.

A simulation analysis was developed for Atlantic surfclam to evaluate potential consequences of uncertainty in steepness of the stock-recruit curve and natural mortality on management decisions and the efficacy relative to the risk-tolerance policy of the management council. Multiple OMs were created with alternative parameterizations of steepness of the broodstock-recruitment curve and natural mortality that reflected uncertainties in these population dynamics. Simulations were generated from the alternative model structures and forecasted with a series of harvest control rules. Forecasted status of simulated stocks was compared with performance indicators that captured objectives of the management council (e.g., risk that a stock becomes overfished or overfishing occurs) and the commercial fishery (e.g., future availability of fishable surfclam patches). To the latter point, the assessment model estimates SSB and fishing mortality compared with thresholds of overfished and overfishing, but regional density of the biomass for the patchy stock is not informed by the assessment. The commercial fishery relies on a minimum clam density to permit landings of greater than 1 cage hr^{-1} to remain profitable (1 cage = 32 surfclam bushels; Powell et al. 2015). Thus, although the stock may remain within management thresholds, the dispersion of the stock at lower biomass or higher fishing may beget an unprofitable fishery. Accordingly, a secondary objective for this work was to generate estimates of future availability of fishable surfclam patches from assessment model outputs. With recognition that surfclam density and distribution is patchy (Timbs et al. 2019), the relationship between estimated biomass and historical observations of clam density were used to evaluate the forecasted risk of stock reduction to unfishable levels, albeit still meeting control rule thresholds for stock sustainability.

MATERIALS AND METHODS

Assessment Model Structure

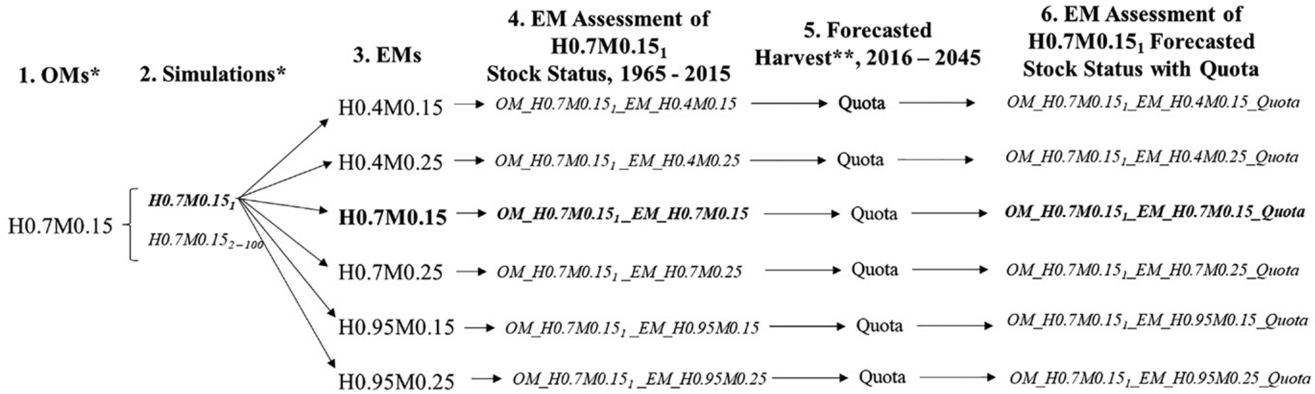
Operating models were conditioned on the 2016 assessment model, which was an application of Stock Synthesis version 3.24 (SS3.24; Methot & Wetzel 2013, NEFSC 2017). The 2016 stock assessment for Atlantic surfclam included two SS models representing independent surfclam populations on Georges Bank and southwest of Georges Bank (termed Northern and Southern, respectively) due to limited data availability for the Northern region. Data and model structure for the Southern population, which supports the largest fraction of the surfclam fishery (NEFSC 2017), served as the basis of this simulation analysis. To use upgrades to forecasting, the Southern model was translated from SS v3.24 to v3.30 (Methot et al. 2020), though this translation did not alter model convergence or results.

The Southern surfclam model incorporates the commercial fishery and three indices of abundance from the Northeast Fishery Science Center (NEFSC) dredge surveys. One index for survey trend and an associated scalar are available for the NEFSC research dredge that operated from 1982 to 2011. In 2012, the NEFSC survey transitioned to a modified commercial dredge. Two observations from 2012 and 2015 are available to the Southern model from the modified commercial dredge. Surveys occurred approximately once every 3 y over the 1982 to 2015 time period. The commercial fishery provides landings in metric tons and length-compositions collected by randomized port-sampling. Length-composition data are also available for the research dredge and modified commercial dredge surveys, in addition to conditional age-at-length compositional data. Variance adjustment factors are used to moderate sample sizes of fleet-specific length-compositions. These factors were removed during generation of simulated data, but reinstated during subsequent model runs. A variety of growth and selectivity parameters are estimated in the assessment model, though natural mortality (M = 0.15) and steepness of the Beverton–Holt broodstock-recruitment curve (h = 0.95) are fixed parameters. Operating models changed the fixed value of M and h but otherwise maintained the assessment model structure.

Simulation Analysis

Six model structures were used to evaluate risk from potential management strategies given uncertainty in steepness and natural mortality. Three values of h (0.40, 0.70, and 0.95) and two values of M (0.15, 0.25 y^{-1}) were specified in alternative OMs. For comparison, the stock assessment assumed M = 0.15 y^{-1} and h = 0.95, and included a sensitivity analysis with h = 0.33 (NEFSC 2017). Hennen et al. (2018) assumed h = 0.30 as a lower bound for sensitivity analyses. The lower bound on steepness used herein was raised to 0.40, informed by empirical estimates of steepness values ranging from about 0.40 to 0.99 for hard clam (*Mercenaria mercenaria*) populations in the MidAtlantic (Peterson 2002, Kraeuter et al. 2005). Few estimates of natural mortality rate are available (Weinberg 1999, Narváez et al. 2015), but rapid shifts in range suggest geographic variation in mortality rate (Kim & Powell 2004, Weinberg et al. 2005, Hofmann et al. 2018). Maximum ages (ranging between 20 and 30+ y of age) recorded regionally suggest local mortality rates in the core of the stock as high as 0.2 y^{-1} and as low as 0.12 y^{-1} (Munroe et al. 2016, Hennen et al. 2018). As these observations emphasize local increases in mortality rate, a higher mortality rate was preferentially examined, and natural mortality was set at 0.15 y^{-1} and 0.25 y^{-1} (Hennen 2018). The naming convention of OMs [and later estimation models (EMs)] followed the format of h (steepness value) M (natural mortality value), such that the base OM following the assessment model parameters of h = 0.95 and M = 0.15 y^{-1} is named H0.95M0.15.

All model structures were used as both OMs and alternative EMs, so efficacy of management strategies were evaluated under circumstances, where M and h parameters are



* Six alternative OMs, same structure as EMs listed in step 3
** 100 simulations generated by each OM, 600 total simulated stocks
*** Five options for forecasted harvest, see Table 1

Figure 1. Schematic of a simulated surfclam stock through the simulation analysis conducted here. Here, the operating model (OM), H0.7M0.15, is used as the example. Operating model H0.7M0.15 generates 100 simulations of the stock characterized by a steepness of 0.7 and a natural mortality of 0.15 y^{-1}. This schematic follows the trajectory of $H0.7M0.15_1$, the first of the 100 simulations generated by H0.7M0.15. Once the simulation is generated, it is assessed by each of the six alternative EM structures. Estimation model H0.7M0.15 is the same model structure as the generating OM, H0.7M0.15, and, thus, represents a self-test of the simulated population, marked in bold. Each EM assesses the stock status of $H0.7M0.15_1$ during the period of simulated data, 1965 to 2015. The EM assessment of $H0.7M0.15_1$ is then forecasted with Quota catch without error for the duration of the 30-y forecast, 2016 to 2045. This process is performed for each of the five alternative management strategies, producing 30 forecasted assessments for the simulation $H0.7M0.15_1$. This is repeated for each of the 100 simulations generated by each of the six OMs. In total, 18,000 forecasted simulations are generated across OMs, EMs, and management strategies.

incorrectly specified from the "true" value in the OM. Each OM generated 100 simulations of a surfclam stock using a parametric bootstrap function internal to SS (Fig. 1). This function first uses maximum likelihood estimation to generate expected data values from input observations (Methot et al. 2020). New observations that fit within the specified error distributions were generated using the expected data values and associated standard deviations. These new data simulations of the surfclam stock span the level of uncertainty reported for observations of catch, survey, length, and age compositions.

Simulations were conditioned from 1965 to 2015 and were forecasted under alternative management procedures for 30 y through 2045. To simulate stochasticity in recruitment, forecasted recruitment deviations were randomly generated from a normal distribution built with the 2016 assessment estimates of log recruitment deviations, N(0.0, 0.68). The forecasted recruitment estimates were not bias-adjusted. Simulations were forecasted with five alternative management strategies applied without error to each simulation during the forecast period (Table 1). The forecasted simulation was then assessed by each of the six alternative EMs, one of which performed a self-test, as each OM was matched by an EM of the same configuration (EM = OM). In a self-test, the EM estimated the time series of simulated data with less than 5% error, presenting a "true" interpretation of the forecasted simulated stock (Deroba et al. 2015). Those simulations were then cross-tested by an alternatively configured EM structure (EM! = OM). The forecasted estimates of stock status were compared between the self- and cross-tests, where the difference between forecasted estimates of stock status represented the error associated with misspecifying either or both steepness and natural mortality. Six hundred simulations across the six OMs were generated and each was evaluated under 30 configurations of EM structure and management control rule. A total of 18,000 simulated forecasts were generated and assessed.

Evaluation of Risk

The current assessment model states that SSB_{Target} is equal to 50% of the unexploited SSB_0, which is calculated in each model configuration at the beginning of the time series in

TABLE 1.

Management strategies evaluated for Atlantic surfclam.

Management rule	Catch or *F*	Relevance to fishery
Quota	Catch = 26,218 mt	Long-term fishery-implemented quota
ABC_Low	Catch = 45,524 mt	ABC assigned by MAFMC in 2016 (MAFMC, 2017)
ABC_High	Catch = 60,313 mt	ABC assigned by MAFMC before 2016 and again in 2018
$F_{0.12}$	$F = 0.12\ y^{-1}$	MSY Proxy presented in NEFSC (2017)
$F_{0.4}$	$F = 0.4\ y^{-1}$	Hypothetical upper boundary on fishing mortality

Catch is reported as metric tons (mt), and fishing mortality is total fishing mortality rate per year.
ABC, acceptable biological catch.

1965. The threshold that a surfclam stock becomes overfished is ½ of SSB_{Target}, thus, a stock is overfished if SSB < ½ SSB_{Target}. Both SSB_{Target} and $SSB_{Threshold}$ are presented and compared with forecasted biomass estimates. The total number of simulations that became overfished during the forecasted period was reported for each combination of OM, EM, and management strategy. Estimates of F_{MSY} generated by each of the OMs (hereon, SSF_{MSY}) are reported, though the definition of overfishing used herein follows the MAFMC threshold from 2016, $F_{Threshold} = 0.12$ y^{-1}, a proxy generated externally from the SS model by NEFSC (2017). Maximum *F* observed in forecasts for each OM, EM, and management strategy are reported and compared with the Overfishing Threshold, where overfishing is occurring if $F > F_{Threshold}$. The MAFMC states that the probability of overfishing should not exceed 40% (MAFMC 2020). This threshold was used to determine whether the probability that a simulation became overfished or that overfishing occurred was within the risk-tolerance policy of the MAFMC.

Evaluation of Control Rule Consequences on Clam Density and Fishery Profitability

The commercial surfclam fishery relies on a catch rate of at least 1 cage hr^{-1} to maintain economic sustainability (NEFSC 2017). The surfclam population is characteristically patchy, thus, the fishery relies on targeting dense patches of surfclam. One cage per hour equates approximately to a clam density of 0.22 clams m^{-2} under typical conditions and average gear efficiency (Powell et al. 2015). This level of clam density or greater is hereon described as "fishable." Though total surfclam biomass may remain within management targets, thresholds for overfished and overfishing do not consider potential impacts of management strategies for maintaining a sufficient number

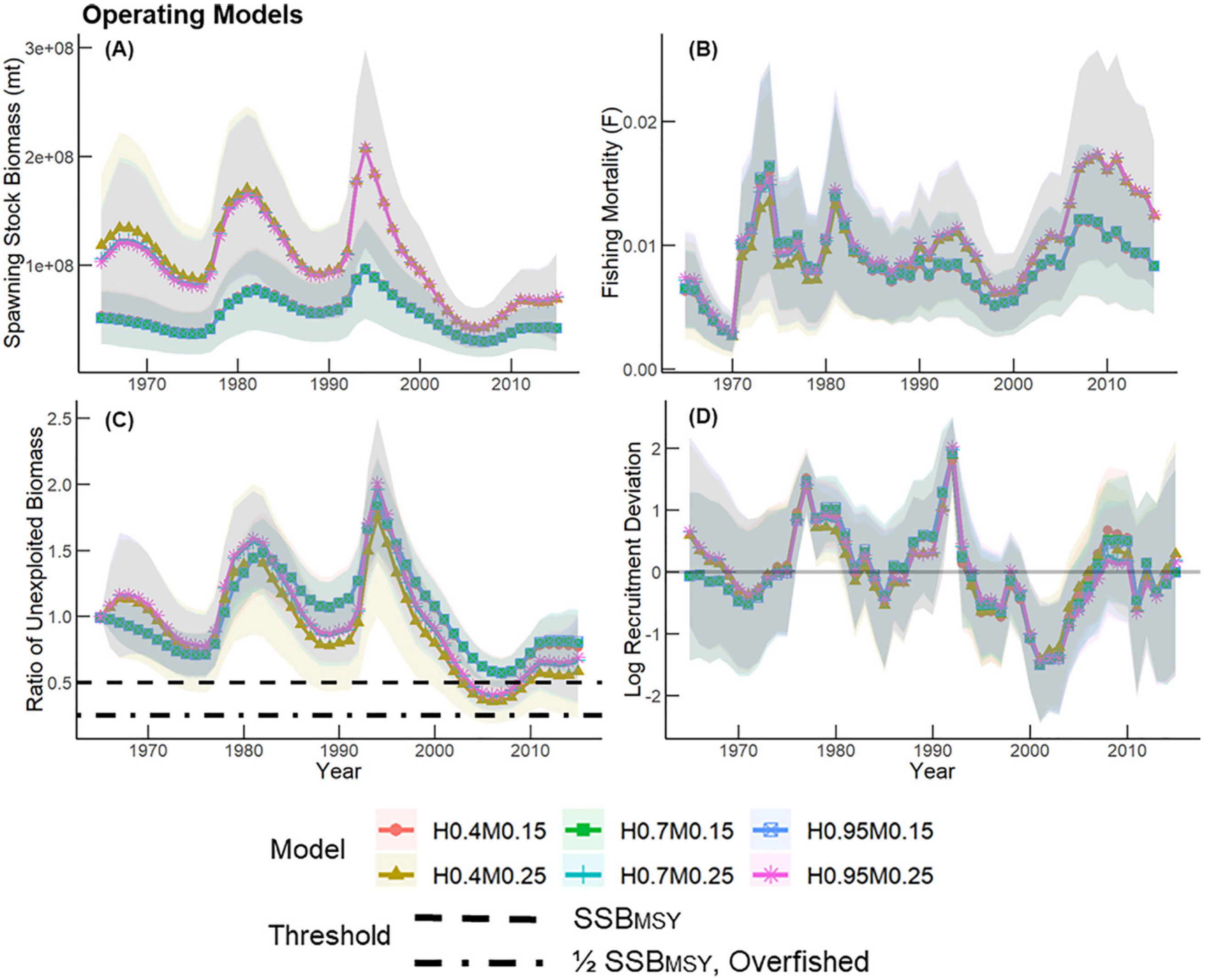


Figure 2. Summary of time series estimates from six alternative OMs. Lines represent the estimate, and shaded grays are the confidence intervals. Dark gray shading indicates where confidence intervals overlap among models. Plots are time series estimates of (A) spawning stock biomass in metric tons, (B) fishing mortality rate (yr^{-1}), (C) ratio of current biomass to unexploited biomass (SSB_{yr}/SSB_0), and (D) log recruitment deviations from the specified broodstock-recruitment curve. Values in plot (C) are ratios and independent of scale, thus, the common SSB_{Target} (½ SSB_0) and $SSB_{Threshold}$ ($SSB <$ ¼ SSB_0) are marked with horizontal lines.

TABLE 2.

Table of biomass and fishing mortality thresholds estimated by the six alternative operating models.

Operating model	SSB_{Target}, ½ SSB_0 (million mt)	$SSB_{Threshold}$, ½ SSB_{Target} (million mt)
H0.4M0.15	23	12
H0.4M0.25	58	29
H0.7M0.15	22	11
H0.7M0.25	54	27
H0.95M0.15 (Base Model)	22	11
H0.95M0.25	57	29

SSB_{Target} is defined as 50% of the unexploited biomass and reported in metric tons. The $SSB_{Threshold}$ is ½ of SSB_{Target}.
SSB, spawning stock biomass.

of fishable patches of clams to support the fishery. To inform both on the effect of external management measures invoking stock sustainability goals and within-fishery management decisions impacting fishery viability, an evaluation of the influence of stock patchiness on fishery performance, which may act independently of stock sustainability goals, is also presented. Observations of clam density m^{-2} are available from both the research dredge and modified commercial dredge surveys between 1997 and 2015. The 2016 assessment model estimated the ratio of unexploited biomass (SSB_{yr}/SSB_0) in each of these years, and these estimates were used in a simple linear regression to predict the percent of fishable survey tows (those that yielded greater than 0.22 clams m^{-2}). The estimated ratio of unexploited biomass for the final year of forecast from each simulation was then used in this regression to estimate the forecasted percent of fishable tows available to support the economic sustainability of the fishery.

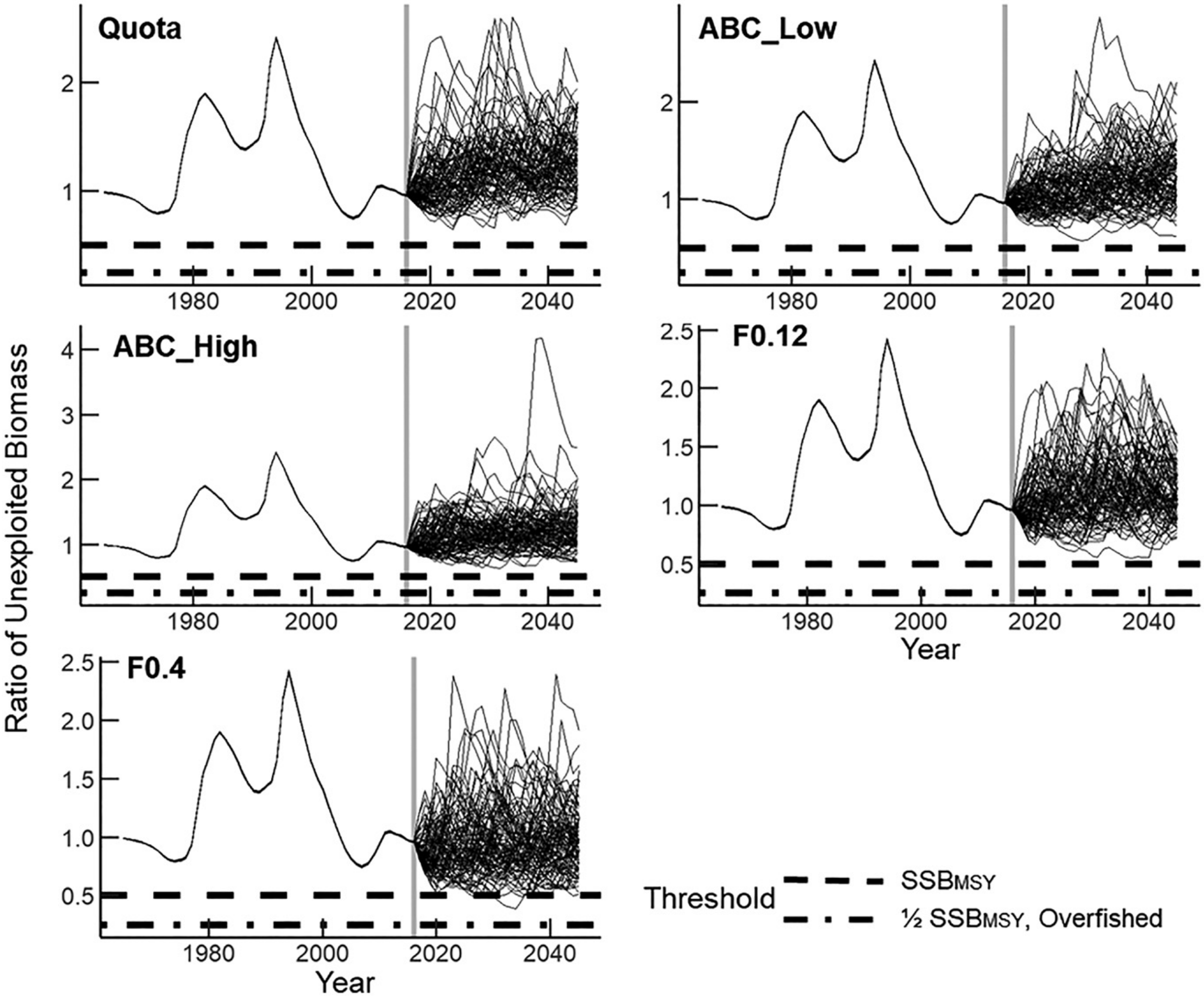


Figure 3. Time series of ratio of unexploited biomass for each of the 100 simulations generated by the OM H0.95M0.15 and assessed using the identical EM, H0.95M0.15. Each simulation was forecasted with five alternative management strategies that remained constant throughout the forecast period. The gray vertical line indicates the beginning of the forecasted time period.

TABLE 3.

Percent of self-tested simulations (OM = EM) harvested according to each management strategy that forecasted SSB below $SSB_{Threshold}$ (Table 2) during the forecast period.

	Management (% overfished simulations)					
OM	**Quota**	**ABC_Low**	**ABC_High**	**F0.12**	**F0.4**	**% Total**
H0.4M0.15	0.00	0.00	0.00	0.00	2.00	**0.40**
H0.4M0.25	1.00	0.00	1.00	1.00	3.00	**1.20**
H0.7M0.15	0.00	0.00	0.00	0.00	0.00	**0.00**
H0.7M0.25	0.00	0.00	0.00	0.00	0.00	**0.00**
H0.95M0.15	0.00	0.00	0.00	0.00	0.00	**0.00**
H0.95M0.25	0.00	0.00	0.00	0.00	0.00	**0.00**
% Total	**0.17**	**0.00**	**0.17**	**0.17**	**0.83**	–

Gray scale indicates an increasing percentage of overfished simulations. Each OM generated 100 simulations, and each of those simulations was forecasted by of the five alternative management strategies.
OM, operating model; ABC, acceptable biological catch.

RESULTS

Stock Status of Operating Models

The six alternative OMs estimated similar trends in surfclam biomass over time, though scale of biomass estimates varied with natural mortality (Fig. 2). Initial SSB estimates for models configured with $M = 0.25\ y^{-1}$ were nearly twice as high as those for OMs configured with $M = 0.15\ y^{-1}$. Therefore, SSB_{Target} for OMs with $M = 0.15\ y^{-1}$ were on the scale of 22 million mt, whereas SSB_{Target} estimates for OMs with $M = 0.25\ y^{-1}$ were nearly double, on the scale of 50 million mt (Table 2). Steepness had minimal impact on scale of biomass or estimates of recruitment deviation because biomass estimates remained high and above the point of the broodstock-recruitment curve, where recruitment decreases with decreasing spawning biomass. Estimated fishing mortality across OMs was relatively similar for the duration of the time series, never exceeding $F = 0.03\ y^{-1}$, below the $F_{Threshold}$ proxy of $F = 0.12\ y^{-1}$ (Fig. 2). Some divergence between F estimates occurred after 2005, with models configured with $M = 0.25\ y^{-1}$ estimating slightly higher (~0.01) fishing mortality. Estimates of SSF_{MSY} output from each of the OMs ranged from 0.69 to 0.71 y^{-1}, more than 20 times the maximum estimate of fishing mortality throughout the time series (Fig. 2). This high SSF_{MSY} estimate was not approved as the overfishing definition in the 2016 stock assessment, and the Overfishing Threshold was instead calculated externally to the assessment model (NEFSC 2017, Hennen 2018). Similarly, OM-derived SSF_{MSY} estimates are not examined as prospective Overfishing Thresholds for forecasted simulations, though their potential causes and implications are considered more thoroughly in the discussion.

The ratio of unexploited biomass across OMs also demonstrates considerable coherence among trends in biomass estimates. All models estimate a sharp increase in biomass in the early 1980s and mid-1990s. The decline from these peaks occurs most quickly in models with high natural mortality. The three OMs with $M = 0.25\ y^{-1}$ fall below the SSB_{Target} during the mid-2000s and finish the time series with the lowest estimated ratio of unexploited biomass, though all models remain above $SSB_{Threshold}$. Finally, estimates of recruitment deviations show minor divergence at the beginning of the time series, though across models, the time series of recruitment deviation estimates are largely coherent. Strong interactions between parameterizations of h and M were not apparent across the time series described in Figure 2, though H0.4M0.25 had the lowest ratio of unexploited biomass at the end of the time series.

Simulations and Forecast

Forecasts of simulations generated by the base OM, H0.95M0.15, self-tested with EM of the same parameterization, EM H0.95M0.15, and forecasted with each of the five alternative management strategies are presented in Figure 3 as an example of forecasted time series. As the OM and EM for these forecasts are the same, time series of biomass estimates before the beginning of the forecast period are identical. At the beginning of the forecast period, divergence occurs based on recruitment deviations and forecasted management. Independent of which management strategy was implemented, few simulations fall below the threshold for SSB_{Target} and no simulations fall below.

Assessment of Overfished Simulations

Simulations generated and self-tested by OMs H0.4M0.15 and H0.4M0.25 were the only forecasts that fell below $SSB_{Threshold}$ determined by the respective OM model (Table 3). Not surprisingly, the most extreme management strategy of $F_{0.4}$, fishing above the F_{MSY} proxy, $F_{Threshold}$, of $F = 0.12\ y^{-1}$, was responsible for the majority of simulations that became overfished. Three percent of H0.4M0.25 and 2% of H0.4M0.15 simulations became overfished when managed with $F_{0.4}$. Operating model H0.4M0.15 only became overfished when managed according to F0.4, though at least one simulation of OM H0.4M0.25 became overfished in four of the five alternative management strategies.

Estimation model estimates of forecasted stock status for simulations generated by each OM were then examined. Though no self-tested simulations of OMs H0.7M0.15, H0.7M0.25, H0.95M0.15, or H0.95M0.25 became overfished across management strategies, EMs H0.4M0.15 and H0.4M0.25 estimated 1%–8% of simulations became overfished (Table 4). As with self-tested simulations, simulations were interpreted as overfished most frequently when simulations were managed according to $F_{0.4}$. Eight percent of simulations generated by OM H0.95M0.25, assessed by EM H0.4M0.15, and managed at $F_{0.4}$ became overfished. In general, OMs parameterized with $M = 0.25\ y^{-1}$ had the highest overfished percentage across management strategies and EMs. The most diverse set of overfished simulations were seen with EM H0.4M0.25, most of which were accounted for by OMs with $M = 0.25\ y^{-1}$, though H0.4M0.15 also became overfished by $F_{0.12}$ and $F_{0.4}$ when assessed by EM H0.4M0.25.

Estimation model H0.4M0.15 had the greatest total percentage of overfished simulations, most of which were managed with $F_{0.4}$. Time series of forecasted simulations managed under the highest ($F_{0.4}$) and lowest (Quota) harvest policies are displayed in Figure 4. Although many simulations fall below SSB_{Target} when fished at Quota, no simulation generated from any OM falls below $SSB_{Threshold}$. The median trajectory for the forecasted time series of each OM is increasing, though there

TABLE 4.

Percent of overfished simulations generated by each OM and assessed by each EM.

Model		Management strategy (% overfished simulations)				
OM	**EM**	**Quota**	**ABC_Low**	**ABC_High**	**F0.12**	**F0.4**
H0.4M0.15	**H0.4M0.15**	**0.00**	**0.00**	**0.00**	**0.00**	**2.00**
	H0.4M0.25	0.00	0.00	0.00	1.00	2.00
	H0.7M0.15	0.00	0.00	0.00	0.00	0.00
	H0.7M0.25	0.00	0.00	0.00	0.00	0.00
	H0.95M0.15	0.00	0.00	0.00	0.00	0.00
	H0.95M0.25	0.00	0.00	0.00	0.00	0.00
H0.4M0.25	**H0.4M0.15**	0.00	0.00	0.00	0.00	6.00
	H0.4M0.25	**1.00**	**0.00**	**1.00**	**1.00**	**3.00**
	H0.7M0.15	0.00	0.00	0.00	0.00	1.00
	H0.7M0.25	0.00	0.00	0.00	0.00	0.00
	H0.95M0.15	0.00	0.00	0.00	0.00	0.00
	H0.95M0.25	0.00	0.00	0.00	0.00	0.00
H0.7M0.15	**H0.4M0.15**	0.00	0.00	0.00	0.00	1.00
	H0.4M0.25	0.00	0.00	0.00	0.00	1.00
	H0.7M0.15	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	H0.7M0.25	0.00	0.00	0.00	0.00	0.00
	H0.95M0.15	0.00	0.00	0.00	0.00	0.00
	H0.95M0.25	0.00	0.00	0.00	0.00	0.00
H0.7M0.25	**H0.4M0.15**	0.00	1.00	0.00	0.00	3.00
	H0.4M0.25	1.00	0.00	0.00	2.00	2.00
	H0.7M0.15	0.00	0.00	0.00	0.00	0.00
	H0.7M0.25	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	H0.95M0.15	0.00	0.00	0.00	0.00	0.00
	H0.95M0.25	0.00	0.00	0.00	0.00	0.00
H0.95M0.15	**H0.4M0.15**	0.00	0.00	0.00	0.00	2.00
	H0.4M0.25	0.00	1.00	0.00	0.00	0.00
	H0.7M0.15	0.00	0.00	0.00	0.00	0.00
	H0.7M0.25	0.00	0.00	0.00	0.00	0.00
	H0.95M0.15	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	H0.95M0.25	0.00	0.00	0.00	0.00	0.00
H0.95M0.25	**H0.4M0.15**	0.00	0.00	0.00	0.00	8.00
	H0.4M0.25	0.00	0.00	1.00	1.00	4.00
	H0.7M0.15	0.00	0.00	0.00	0.00	4.00
	H0.7M0.25	0.00	0.00	0.00	0.00	0.00
	H0.95M0.15	0.00	0.00	0.00	0.00	0.00
	H0.95M0.25	**0.00**	**0.00**	**0.00**	**0.00**	**0.00%**

Self-tested simulations, where OM = EM are shown in Bold. Increasing gray scale indicates a greater percentage of overfished simulations. Threshold for overfished was determined by the EM that assessed the simulation suggesting the perception of the stock by fisheries managers if the steepness and/or natural mortality are misspecified.
OM, operating model; EM, estimating model; ABC, acceptable biological catch.

is a clear disparity among OMs based on natural mortality. Operating models parameterized with $M = 0.15$ y^{-1} have higher SSB estimates throughout the forecast. This persists when simulations were fished at $F_{0.4}$. When simulations are fished at $F_{0.4}$, immediate decline in median trajectory occurs at the onset of the forecast, and many more simulations fall below SSB_{Target} than when managed at Quota. Some simulations also fall below $SSB_{Threshold}$ and a few stocks crash to zero SSB.

Occurrence of Overfishing

The $F_{Threshold}$ proxy presented in the 2016 assessment of $F_{Threshold} = 0.12$ y^{-1} was used as the Overfishing Threshold. Overfishing is first examined for forecasts of simulations, where EM = OM, representing the "true" fishing mortality estimate, then compared with fishing mortality estimates from all simulations assessed with each EM. Fishing mortality unsurprisingly is driven by management strategy, and $F_{0.4}$ results in overfishing in 100% of simulations (Fig. 5). Managing with $F_{0.12}$ resulted in overfishing of 69%–84% of simulations. The percent of simulations experiencing overfishing was greatest in simulations with high natural mortality, and this carried through to simulations managed with ABC_High. Between 2% and 4% of high mortality simulations experienced overfishing from managing at ABC_High, whereas low mortality simulations remained below the Overfishing Threshold. Overfishing occurred in slightly differing proportions between simulations assessed by EM = OM and all simulations forecasted with each EM, though no clear pattern or direction of these differences was observed. Estimation model H0.4M0.25 estimated overfishing of less than 1% of simulations managed with ABC_Low, though managing at quota estimated no overfishing across EMs.

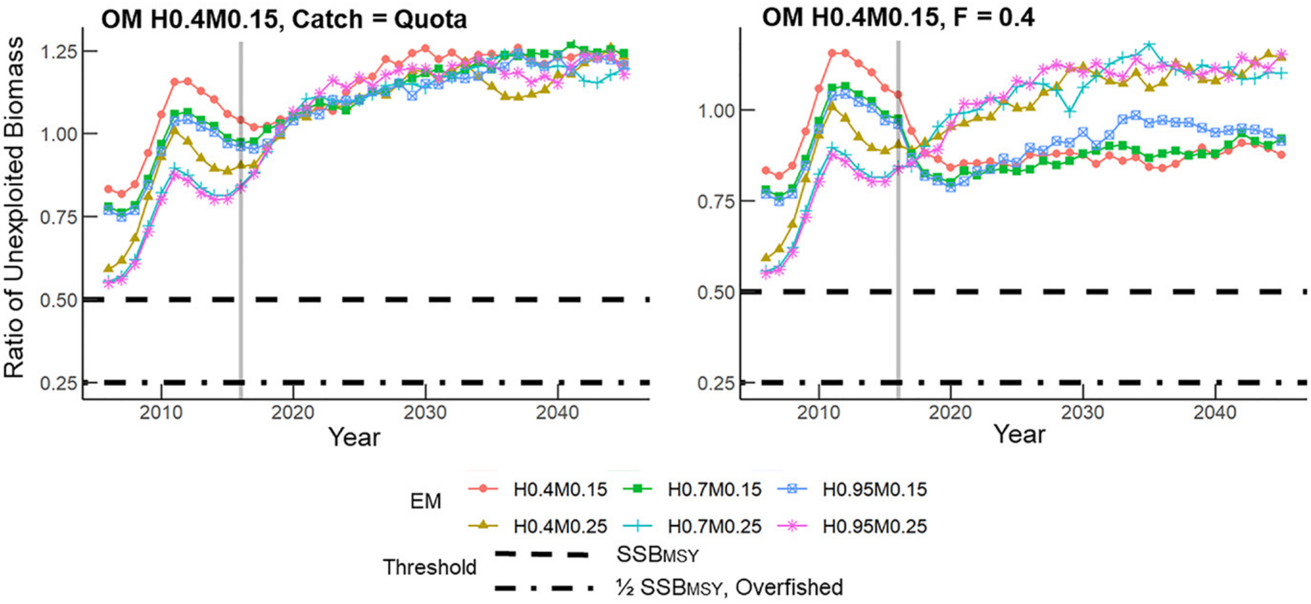


Figure 4. Median forecasted SSB time series for simulations of OM H0.4M0.25 harvested according to the Quota of 26,218 mt (left) and fishing mortality of $F = 0.4$ y^{-1} (right).

Fishery Profitability

The annual percent of fishable tows observed by the NEFSC survey ranged from 20% to 45% and was significantly related to estimated ratio of unexploited biomass (SSB_{yr}/SSB_0) from the 2016 stock assessment ($P < 0.01$, $r^2 = 0.80$; Fig. 6). Since EMs are an interpretation of the stock, whereas OMs act as the true realization of the generated stock, forecasted estimates of percent fishable tows are only displayed for self-tests of simulations (OM = EM; Deroba et al. 2015). Across models, forecasted estimates of percent fishable tows were in line with observations by the NEFSC survey, between 25% and 50%. Estimated percent of fishable tows for H0.4M0.15 declined the most with increasing fishing mortality, suggesting low steepness could compound with low natural mortality to limit proportion of fishable tows (Fig. 7). Percent fishable tows from high mortality models responded less to increasing fishing pressure, though lowest percent across models was generally observed at $F_{0.12}$ and $F_{0.4}$.

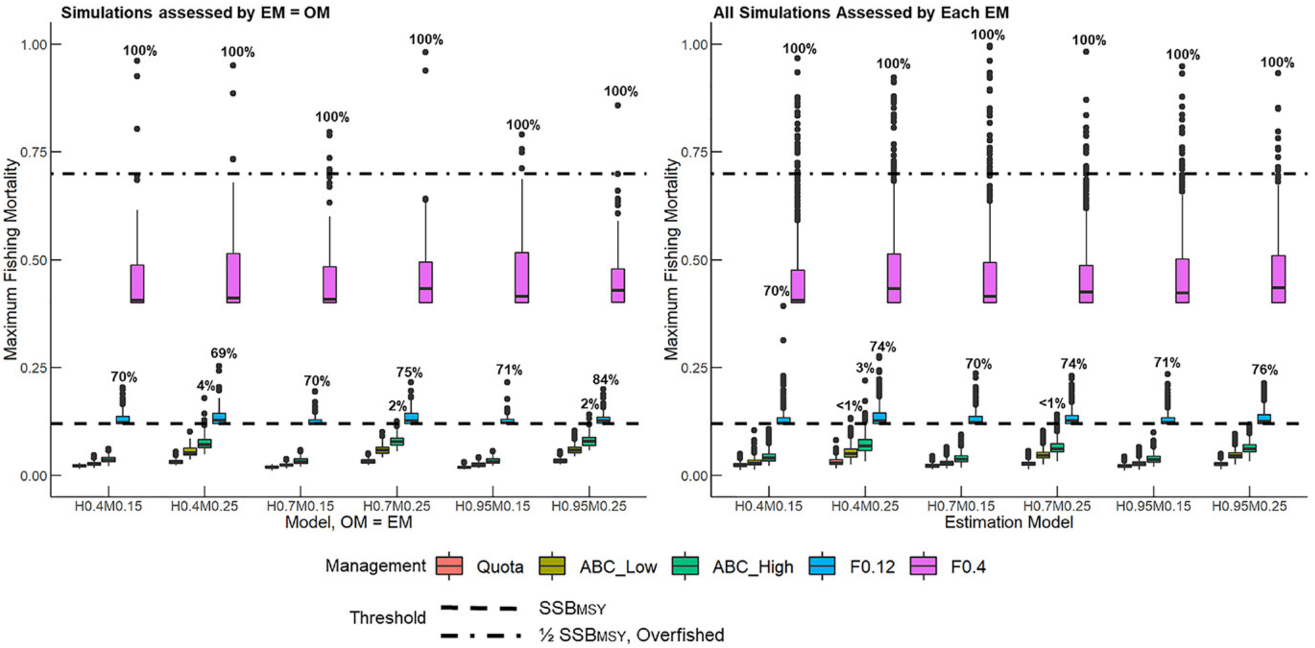


Figure 5. Maximum fishing mortality y^{-1} observed during the forecast of a simulation. Top plot separates models by OM, representing the "true" fishing mortality. Bottom plot is maximum fishing mortality estimated by EMs. If simulations from a management strategy and EM passed the Overfishing Threshold of $F_{Threshold} = 0.12$ y^{-1}, the percent of simulations that did so is displayed.

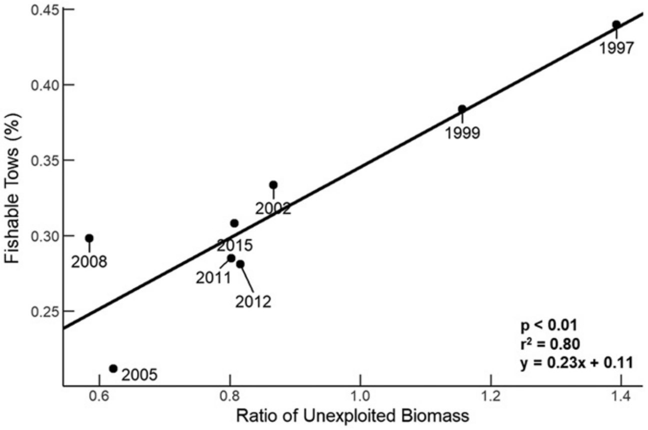


Figure 6. Each point indicates the percent of NEFSC survey tows that were "fishable," defined as capturing more than 0.22 clams m^{-2} (Powell et al. 2015) in each year the survey was performed between 1997 and 2015. The *x*-axis is the ratio of unexploited biomass (SSB_{yr}/SSB_0) in each corresponding year estimated by the 2016 stock assessment.

DISCUSSION

Despite uncertainty in natural mortality and steepness, the Atlantic surfclam Southern stock appears to be robust to overfishing across a variety of management strategies. The Atlantic surfclam quota has remained stable because the 1980s and below the ABC because of economic constraints within the fishery. In the simulations presented here, across all model specifications, fishing at Quota never permitted fishing mortality to rise above the assessment proxy for $F_{Threshold} = 0.12\ y^{-1}$ and fewer than 1% of simulations forecasted with ABC_Low breached this threshold. ABC_High and $F_{0.12}$ led to overfishing in many simulations, especially those with high natural mortality. Management strategies $F_{0.12}$ and $F_{0.4}$ fell outside of the risk-tolerance policy of the MAFMC, overfishing the stock in reference to $F_{Threshold} = 0.12\ y^{-1}$ in more than 40% of simulations across OM and EM structures.

Managing at $F_{0.4}$ was also the strategy that caused the most simulations to become overfished, especially for stocks with high natural mortality or if the assessment model overestimated steepness. For example, although 3% of simulations generated by OM H0.4M0.15, assessed by the identical EM H0.4M0.15 and forecasted with $F_{0.4}$ became overfished, no EM with steepness greater than 0.4 perceived this overfished state. To a lesser extent, this is true for H0.4M0.25 as well. These simulations suggest that although the broodstock-recruitment curve is not well understood for surfclam, if the steepness is in fact low, assessments parameterized with high steepness may not detect an overfished state. Though EMs with steepness values of 0.4 or 0.7 predicted some overfished simulations, fewer than 40% of simulations became overfished, within the MAFMC risk-tolerance policy.

Across OM and EM structures, managing with $F_{0.4}$ was responsible for the greatest proportion of overfishing and the most overfished simulations. It is important, however, to note that $F_{0.4}$ is an extreme management strategy used herein to juxtapose the comparatively conservative quota and ABCs. The surfclam fishery is a high volume, relatively low-value fishery, which depends on high CPUE to meet economic requirements. The fishery is not constrained by the current quota and unlikely to pursue fishing at such volumes that would decrease profit margins, a consequence of fewer fishable tows predicted in forecasts of this management strategy. Simulating management at $F_{0.4}$ does add credence to the external development of F_{MSY} proxies ($F_{Threshold}$) for the surfclam stock, however. F_{MSY} based on the stock assessment has never been used for surfclam management. Rather, F_{MSY} has been based on a population simulation conducted outside of the stock assessment framework (Hennen 2018). One of the primary reasons for this is that the surfclam stock has been near or above SSB_{Target} throughout the observed time series and consequently unable to inform on the broodstock-recruitment relationship at low stock size. In addition, the 2016 surfclam stock assessment was highly uncertain in scale. An F_{MSY} value from the assessment (i.e., SSF_{MSY}) would also be highly uncertain, and potentially inappropriate for management. Managers, therefore, chose to set the *F* threshold based on *F* values from a selected portion of the time series during which fishing was thought to have little measurable effect on the indices of stock abundance (a period

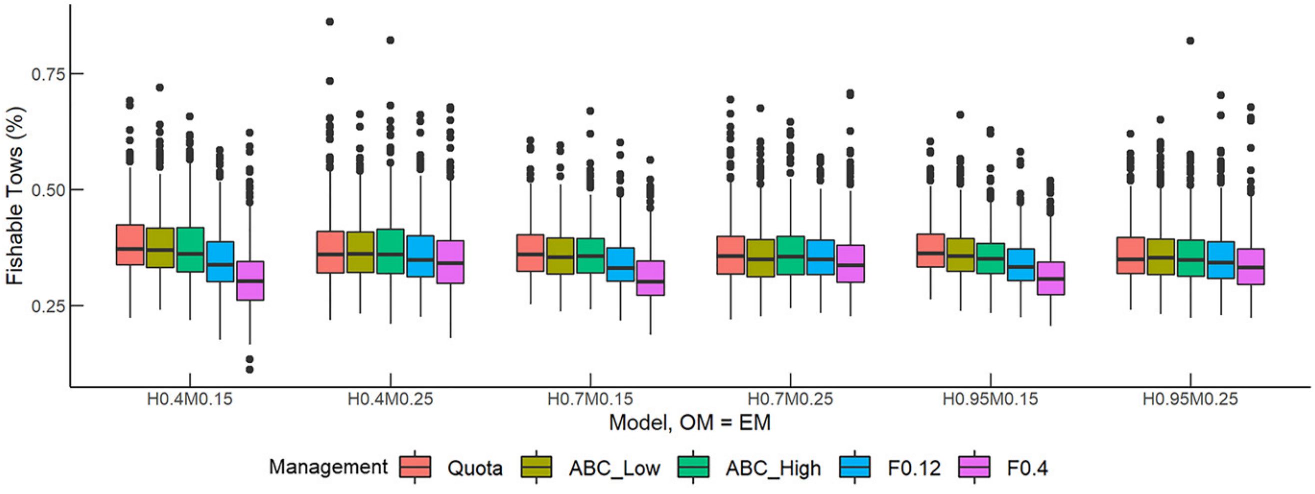


Figure 7. Percent of fishable tows estimated from the ratio of unexploited biomass (SSB_{yr}/SSB_0) in the terminal year of forecast for each simulation where EM = OM.

of relatively low intensity fishing). The current F threshold for management is an expansion of the average F over this period (Hennen 2018).

Results presented here reinforce the reasons behind the external derivation of $F_{\text{Threshold}}$ and the potential risk of using SSF_{MSY} output from the assessment model as the management threshold. Despite differences in scale of absolute biomass across OMs, SSF_{MSY} estimates varied little among OMs independent of steepness or natural mortality, ranging between 0.69 and 0.71 y^{-1}. These high estimates could be a result of delayed selectivity in the fishery. As mentioned previously, although Atlantic surfclam fully mature by age-2 (Chintala & Grassle 1995), the fishery begins to select for clams around age-5. With spawning biomass outside of the fishery selectivity, SS converges on a high estimate of SSF_{MSY}, one that is much larger than any historical estimates of fishing mortality. Given the number of simulations that became overfished when fishing at $F_{0.4}$, setting a threshold for overfishing at $SSF_{MSY} = 0.70\ y^{-1}$ could lead to an overfished stock before overfishing is detected by management, especially with the consideration of uncertainty around steepness.

The issue of fishery selectivity carries through to natural mortality and the uncertainty in scale of absolute biomass of the surfclam stock. Operating models with high natural mortality estimated nearly double the unexploited stock size as the low mortality counterparts. Punt et al. (2021) explained why natural mortality can contribute uncertainty to biomass estimates. As with the commercial fishery, the surfclam survey largely observes clams of age-5 and older, making it difficult to estimate the unexploited equilibrium age distribution of younger clams. Higher natural mortality increases the rate of decline in numbers at age, requiring a greater equilibrium number of age-0 clams to support the observed numbers of age-5 + individuals. Given early maturity, the larger number of young clams contributes to the greater SSB. Above age-5 when age-distribution data is more available, equilibrium age distributions between OMs with $M = 0.15\ y^{-1}$ and $0.25\ y^{-1}$ largely correlate, which may explain why estimates of F are similar across OMs, though scale of biomass varies.

The prospective influence of ocean warming on increasing natural mortality rates across some portion of the surfclam stock (Munroe et al. 2013, 2016, Narvaez et al. 2015, Hofmann et al. 2018) fuels concerns for how changes in natural mortality may alter the actual or perceived scale of biomass and uncertainty in future assessments. Atlantic surfclam are sensitive to temperatures exceeding 21°C (Munroe et al. 2013), and modern warming of the northwest Atlantic is thought to be a driver of mortality events at the inshore and southern extents of the stock (Kim & Powell 2004). Furthermore, increased observations of recruitment events further north and offshore of their typical range suggest a changing distribution (Hofmann et al. 2018). These events are coincident with declines in patchiness (Timbs et al. 2019) and maximum size over much of the geographic range (Munroe et al. 2013, 2016) with potential consequences to regional mortality and economics of the commercial fishery (Powell et al. 2015, 2016).

The surfclam fishery is unusual in being a low-value high-volume fishery in which the target species is sedentary and, thus, the economics of the fishery are directly determined by local variations in density. Profitability of the commercial surfclam fishery is dependent on the number and density of clam patches. This is a long-understood constraint that (at least in part) led the industry to impose a quota cap to limit the chance of a reduction in clam stock density to a level that would result in a limitation of fishable locations and economically feasible catch rates (Adelaja et al. 1998, Rountree 2015). This quota cap has been and continues to remain below the ABC management control rule designated by the Council and has likely contributed to the sustainability of the Atlantic surfclam stock, a fishery that the stock assessment has never designated as overfished nor noted the occurrence of overfishing (NEFSC 2017). Results presented here demonstrate that the quota cap and ABCs are conservative to the risk-tolerance policies of the MAFMC, though in the face of global warming and potential shifts in surfclam distribution, alternate management approaches, such as rotating closures may need to be explored to insulate the fishery from unexpected declines (Kuykendall et al. 2017). One important outcome of this analysis is to reenforce the effectiveness of the quota cap in sustaining the fishery; that is, operationally, the fishery could well be in jeopardy, whereas stock sustainability goals continue to be met because the sustainability goals depend on stock-wide metrics, whereas the fishery depends on local densities.

Although fishery economics may falter from decreases in fishable patches before an overfished status is determined, these results suggest that if population and fishery dynamics persist in a large status-quo manner for the foreseeable future (save for moderate recruitment variation), proportion of fishable patches will remain high enough to support the current commercial fishery. The time series of NEFSC survey tows demonstrate that although the fishery has remained relatively consistent since the 1990s, clam density and biomass has fluctuated over that same period. Environmental conditions are likely to affect population dynamics of the surfclam stock inconsistently throughout their distribution, reinforcing the difficulty of forecasting the stock in a dynamic and warming ocean. This work demonstrates that even with uncertainties in steepness and natural mortality, the surfclam stock is unlikely to become overfished or experience overfishing from currently implemented management strategies. The consequences of overestimating steepness in forecasts, however, demonstrate that variation in steepness or mortality could result in misrepresentation of an overfished stock under high fishing pressure. Population dynamics of surfclam are stochastic and that stochasticity is, at least in part, related to environmental conditions that are rapidly changing in the northwest Atlantic. Future evaluations are needed to determine how the population varies in forecasts when population dynamics parameters are allowed to vary in a multiyear or decadal fashion. Variable growth or temporal variability in the rate of range recession inshore and expansion offshore could be the uncertainties of focus in future simulation analyses and management.

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