Fine-tuning the ABC control rule for Mid-Atlantic fisheries

John Wiedenmann

Department of Ecology, Evolution, and Natural Resources
Rutgers, the State University of New Jersey

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Executive Summary

Eight ABC control rule alternatives for Mid-Atlantic fisheries were tested using a management strategy evaluation model for scup, summer flounder, and butterfish. These control rules varied in their maximum allowable P*, and how the P* changed as biomass declined. Performance of the control rules relative to one another was evaluated by comparing short- and long-term yields to the fishery, average and maximum variability in yield, the risk of overfishing, and the risk of driving the population to low levels. Variability in future stock productivity was incorporated in the model, and comparison of control rule performance was evaluated across 1) the baseline model run of average productivity, 2) under good future productivity only, and 3) under poor future productivity. Control performance varied by stock and by future conditions, but in general, the fixed and stepped Alternatives (produce greater benefits to the fishery, with high stable short- and long-term catches across stocks and productivity levels. However, with greater reward comes greater risk, as these control rules also had the greatest risks of overfishing and causing the stocks to become overfished, and in some cases the risk of overfishing exceeded the 50% threshold. Ramped control rules, on the other hand, had lower risks of overfishing and of becoming overfished, particularly under average and poor productivity conditions across stocks. In general, ramped options with higher maximum P* had higher yield, on average, particularly under average and good productivity. Ramped control rules had greater variability in yield overall, with the greatest variability occurring for options with more rapid changes in the target P* with biomass. For summer flounder, ramped control rules had considerably lower short-term yield than the fixed and stepped options, owing to the fact that summer flounder biomass is currently below the S_{MSY} target. Of the ramped control rules, Alternative 2 seemed the best able to balance the tradeoffs in management objectives, resulting in relatively high catch, low risks of overfishing and becoming overfished, and lower variability in catch.

Introduction

This project seeks to evaluate alternative acceptable biological catch (ABC) harvest control rules in consideration by the Mid-Atlantic Fisheries Management Council (MAFMC). The control rules are all variants of the P* approach (Shertzer et al. 2008), whereby a distribution for the overfishing limit (OFL) is created by using the point estimate from the assessment and projection models as the median of a lognormal distribution with an assumed uncertainty (determined by a specified coefficient of variation, or CV), and selecting some percentile of the distribution at or below the median (target $P^* \leq 0.5$). The MAFMC currently uses a control rule whereby the target P* depends on the estimated biomass, with a target P* of 0.4 when current spawning biomass for a stock is at or above the biomass target ($S \geq S_{MSY}$), and the target P* declining linearly as biomass falls below S_{MSY}, with the fishery shut down (target P* = 0) when biomass as below 10% of S_{MSY}. The assumed CV of the OFL varies by stocks, but CVs 1.0 are typically used by the SSC for Mid-Atlantic stocks.

This work is an extension of previous work for the Council, where a total of five control rules were evaluated for summer flounder, scup, and butterfish. The original five control rules explored are shown in Figure 1A and 1B. Two of these were "ramped" with the target P* declining linearly as biomass falls below the target spawning biomass (S_{MSY}), with the difference between these options the maximum P* at or above S_{MSY} (0.4 or 0.45). The ramped P* with a maximum P* of 0.4 (herein called Alternative 1) is current control rule. Three of the control explored either had a fixed P* of 0.4 across all levels of biomass (Alternative 3), or were fixed over ranges of biomass, with stepped changes as the estimated biomass crossed specified threshold (herein called the stepped control rules, or Alternative 4 and 5; Figure 1B). The Council was interested in exploring additional control rules, particularly ones that allowed for higher catches when the biomass is above the target. Both of these options have a maximum P* of 0.49, but differ in the biomass at which the fishery closes (10% of S_{MSY} for Alternative 6 and 30% for Alternative 8), but there are also differences in the target P* once the stock biomass exceeds S_{MSY}; Figure 1 C). The final control rule include here (Alternative 7) is another ramped option with a maximum P* of 0.4, but with closure of the fishery occurring at 30% of S_{MSY}. In addition to three controls being added to the analysis, this work included updated information from assessments for each stock (NEFSC 2017, Adams, NEFSC 2019). The previous work also split out model runs based on average trends in natural mortality and recruitment to characterize different levels of future productivity. The current work differs in that larger changes in natural mortality and recruitment were explicitly included as different formulations of the operating model (described in more detail in the Methods below). Performance of each control rule across a range of management objectives was assessed by calculating metrics that summarized risk (e.g., the probability of overfishing or of becoming overfished) and reward (e.g., high, stable yield).

Methods

The MSE simulation used for this analysis model is an extension of the work of Wiedenmann et al. (2017), which was developed to test control rule performance for generic species with different life history strategies (i.e., short, medium, and long-lived). The current model was tailored to the specific dynamics of butterfish, summer flounder and scup, with species-specific parameters obtained from recent stock assessment for each stock (NEFSC 2017, Adams, NEFSC 2019). The MSE model dynamics were nearly identical for each stock, although there were some differences, described below.

The model is a closed-loop MSE (Butterworth and Punt 1999) with three main components (operating, assessment and management submodels), and was developed in AD Model Builder (Fournier 2012). The foundation of the MSE simulation is the operating model, which determines the population dynamics of the stock and how data are generated. Data generated in the operating model are based on the true state of the population with some specified amount of observation error. The operating model generated data on fishery harvests, as well as a fishery-independent index of abundance. These data were then used in the assessment model to estimate stock status and biological reference points. The assessment model was a statistical catch at age (SCAA) model, and output from the assessment was used in the management model to determine the catch limit using a particular ABC control rule. The catch limit estimated in the management model was removed from the population, without implementation error, and the simulation loop continues for a set number of years. This process was repeated 1000 times stochastically for each stock to account for the variability in the population dynamics, data generation, and assessment estimation. At the end of each run, the true and estimated values summarizing the population and fishery dynamics were stored and used to evaluate the ability of a control rule to meet multiple management objectives.

Operating, Assessment, and Management Models

The operating model was split into two periods, the historical period and the management period. Population and fishery dynamics during the historical period are based on information obtained from stock assessments for each stock (NEFSC 2017, Adams, NEFSC 2019), including the estimated abundance and selectivity at age, the observed catch, weight and maturity ate age, and the assumed natural mortality rate. The length of the management period was 30 years, while length of the historical period varied for each stock based on the number of years of estimates available in the most recent stock assessment.

Equations governing the population and data-generating dynamics are presented in Table 1, with definitions of the variables in Table 2, and parameters defined in Table 3. A key distinction between the population dynamics between the historical and management periods is that variability in the population dynamics in the historical period is constrained around values estimated in the stock assessment. Numerical abundance at age in the historical period was fixed across ages at the estimated values from the assessment. Variability in stock size in the management period is driven by variability in recruitment, natural mortality, and fishing mortality, with the variability in fishing mortality resulting from error in assessment estimates and the specific control rule being applied. Fishery and survey data generation occurs throughout both the historical and management periods, as data generated in both periods are fed into the assessment model to estimate abundance in repeated assessments.

Equations governing the dynamics in the management period are referenced by their number in Table 1, such that the formula for calculating recruitment is referred to as Eq. T1.1. Recruitment followed the Beverton-Holt stock-recruit relationship, with bias-corrected lognormally distributed and autocorrelated deviations (Eq. T1.1). Parameters for the stock-recruit relationship were estimated using a maximum likelihood approach with the estimates of spawning biomass and recruitment from each assessment for each stock (Figure 3). 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 (Eq. T1.2). Annual abundance of recruited ages was determined from the abundance of that cohort the previous year, decreased by continuous natural and fishing mortality (Eq. T1.3). Total mortality at age was the sum of fishing and natural mortality (Eq. T1.4). Natural mortality was independent of age, but varied over time following an autocorrelated process on the log scale (Eq. T1.5). Fishing mortality at age was the product of fishing intensity of fully selected ages and selectivity at age. The model contained a single fishery with a selectivity function that could either be dome-shaped on or asymptotic (logistic). Dome-shaped selectivity was assumed for scup and summer flounder, while logistic selectivity was assumed for butterfish. The selectivity ogive varied over time as the parameters that determines the first age at peak selectivity for the dome-shaped relationship and 50% selectivity in the logistic relationship varied annually in an autocorrelated manner (Eq. T1.6). This variability was included because selectivity in a fishery can vary in response to changing regulations, fishing practices, or changes in growth, although the source for the changes was not modeled explicitly. Weight and maturity at age were fixed over time in the historical period at the observed values, and fixed during the management period as the average over the most recent five years for a given age class.

The data used in the assessment were the fishery catch (both total and proportions at age) and a fishery-independent index of abundance (both total and proportions at age). These data sets were generated by applying observation error to the true values using lognormal errors for the total index and catch, and multinomial distributions for the age compositions (Eqs. T1.7 - T1.11). The amount of observation error in the generation of the data was varied by stock, with greater variability in survey CVs for scup and butterfish, and also fewer ages sampled. The effect of doing this is that the assessment estimates are more uncertain for these stocks. The rationale for this is that there is greater variability within and across years in the survey indices for these stocks compared to summer flounder, perhaps because the survey is better suited for catching summer flounder.

The time series of catch and survey data were input into the SCAA model to estimate the abundance at age, fishing mortality rates in each year, and reference points for management. Model parameters within the SCAA were estimated using a maximum likelihood approach, with the specific parameters estimated the abundance at age in the first year, recruitments and fishing mortality rates (across years), fishery selectivity parameters, survey selectivity parameters, and survey catchability. Survey catchability and age at peak selectivity in the fishery are assumed constant over time in the assessment model, even though they were varied with time in the operating model. Natural mortality was assumed to be constant over age and time at the mean value for the given stock (Table 3). All other required SCAA inputs (i.e., maturity and weight at age) are set to the true values specified in the operating model. The SCAA model also estimated the spawning potential ratio (SPR) – based reference points for scup and summer flounder, using SPR limits of 0.4 and 0.35, respectively, as these are the ratios that define the F_{MSY} proxy for these species. For butterfish, the F_{MSY} proxy is 2/3 of the assumed M in the assessment, and the S_{MSY} proxy is calculated with Monte Carlo projections as the median spawning biomass in the final year after fishing for 50 years at F_{MSY}. Including a Monte Carlo simulation following each assessment in the MSE was computationally intensive, so deterministic projections were done using the mean estimated recruitment. Comparisons were made outside of the MSE between S_{MSY} estimates from this deterministic approach to stochastic projections, and estimates of S_{MSY} were within ± 10% of one another, with most being within ± 5%.

In the management model, a harvest control rule was applied using the estimated biomass projected from the terminal assessment year over the interval between assessments (2 years for scup and summer flounder, 3 years for butterfish). The projected biomass in the first year was calculated using the terminal abundance at age, fixed weight at age, assumed M and estimated F at age in the terminal year, with recruitment assumed equal to the estimated mean. Biomass over the remaining years was estimated in the same manner, but by fishing at the estimated F_{MSY} to produce estimates of the OFL. A given control (Figure 1) then applies a buffer to set the ABC, with the size of the buffer in most of the control rules being biomass-dependent. In such cases, the estimated spawning biomass ratio (S / S_{MSY}) in each projected year is used to calculate the size of the buffer in the control rule. Note that this approach ignores the changes in abundance that might occur by setting the ABC < OFL, which would result in $F < F_{\mathrm{MSY}}$ with accurate estimates of abundance. As a result, the deterministic projections provided more conservative estimates of the OFL because the F associated with the OFL is higher than the F associated with the ABC in most cases. The estimated ABC is then removed from the population the following year, and the resulting F is calculated using the Baranov catch equation. Control rules were applied for 30 years for each stock.

Parameterization and Model Runs

For each stock and for each control rule, the model was run for 30 years under the parameters in Table 3. To test the potential impacts that changes in productivity would have on control rule performance, two additional configurations of the operating model were explored for each stock / control rule combination. A "good" productivity run was explored where over the 30 year period the control rule is applied the mean natural mortality rate is reduced by 25% and the mean recruitment increases by 25 (although both vary over time around each mean). A "poor" productivity run was also explored where the mean natural mortality increased by 25% and the mean recruitment decreased by 25%.

Performance Measures

At the end of each run, multiple performance measures were calculated to summarize the ability of each control rule to meet a suite of management objectives (Table 4). The primary performance measures used to assess control rule performance were fishery yield, variability in fishery yield, frequency of overfishing, and the proportion of runs where the biomass dropped below the overfished threshold ($S < 0.5\ S_{MSY}$). Fishery yield was calculated over short- and long-term timespans, representing the first 5 and final 20 years, respectively. Inspection of the distribution of biomass and catch was done to ensure that transitory dynamics were not occurring in the final 15 years. The probability of overfishing was calculated as the proportion of years during the management period in which F exceeded F_{MSY}. Year-to-year variability in fishery yield was summarized by calculating the relative change yield from one year to the next, averaged across all 30 years, but also by estimating the maximum change between any two years over the entire management period.

Results

Model runs are grouped by the average, good, and poor future productivity, and median performance measures are presented by stock and productivity level in Table 4 and are also shown in Figures 3-18. Runs were also categorized based on whether the stock assessment over- or underestimated the terminal abundance, on average across assessments in the 30 year period, but for the average productivity runs only. Median performance measures by stock and assessment error are presented in Table 6. Short and long-term catch performance measures were calculated as the difference relative to the current control rule, while all other performance measures represent the actual magnitude for each Alternative. Discussion of performance here is grouped by whether the control rules were fixed or stepped (Alternatives 3, 4, and 5), or whether they were ramped (Alternatives 1, 2, 6, 7, 8).

Fixed and Stepped P Control Rules (Alternatives 3, 4 and 5).*

In general, the fixed P* and ramped P* control rules performed well across the range of objectives for all stocks, particularly under average and good future productivity. For butterfish across all productivity levels, Alternatives 4 and 5 (with a max P* of 0.45) produced the highest long-term catch (Figure 6; Table 5). These Alternatives also produced some of the highest yields for summer flounder under average and poor future productivity, and high yields (but not the highest) for scup across all productivities, and for summer flounder under good future productivity (Figures 4 and 5). Short-term catch was also calculated, but because summer flounder was the only stock below the biomass target of S_{MSY}, this was the only stock where overall control rule performance differed between short- and long-term catch. Alternatives 3 and 4 had the highest short-term yield for summer flounder, followed by Alternative 5 which had a lower target P* of 0.35 when the stock is below 75% of S_{MSY} (Figure 3). When assessments either under-or overestimated biomass, Alternatives 4 and 5 often had the highest short- and long- term catch across stocks and productivity scenario (Table 6).

The fixed and stepped control rules also had the benefit of having the lowest variability in catch, with the fixed P* of 0.4 control rule (Alternative 3) having the most stable catch overall, with average changes of 10-12% for butterfish, 8-14% for summer flounder, and 8-12% for scup across productivity scenarios. Alternative 3 also had the lowest maximum change in catch between years, with changes of 27-32% for butterfish, 26-30% for summer flounder, and 24-28% for scup across productivity scenarios. Differences in catch variability between Alternatives 3, 4, and 5 and the ramped control rules were less pronounced for Scup under average and good productivity, owing to the biomass starting well above S_{MSY} and tending to remain there over much of the 30-year period (Table 5).

Although the fixed and stepped P* control rules resulted in the most stable catch, and often very high if not the highest catch for given stock and productivity scenario, they resulted in some of the highest risks of overfishing and of causing a stock to become overfished. For scup and summer flounder under average and poor productivity, Alternatives 3-5 had a risk of overfishing below 0.5, with higher risk for control rules with a higher maximum P* (Alternatives 4 and 5) under average productivity (Figures 13 and 15; Table 5)). Similarly, the risk of becoming overfished for these stocks increased with higher maximum P* targets, and were between 15-24% for summer flounder and 21-26% for scup under average productivity (Figures 14 and 16; Table 5). Under poor productivity for summer flounder and scup, Alternative 3-5 had the highest risk of overfishing compared to the ramped control rules, and for summer flounder Alternatives 3 and 4 had a probability of overfishing above 0.5, meaning overfishing was more likely to occur than not. For summer flounder under poor productivity, these Alternative also had the highest risk of causing the stock to become overfished (87% for 3 and 4 compared to the lowest risk of 71% for Alternative 7; Figure 14). For scup under poor productivity, Alternatives 4 and 5 had risk of becoming overfished of 63 and 62%, respectively, but there was less difference overall between these and the ramped control rules (Figure 16). When assessments for scup and summer flounder tended to overestimate biomass, the risks of overfishing and of becoming overfished increased with the maximum P* allowed, so Alternative 4 and 5 had some of the highest risks overall, and exceeded the 50% overfishing threshold for summer flounder for Alternative 4, and Alternatives 3, 4, and 5 for scup (Table 6).

For butterfish across productivity scenarios, Alternatives 3,4, and 5 also had the highest risk of overfishing and of becoming overfished (Figures 17 and 18; Table 5). However, the highest risk of overfishing occurred under good productivity, with a risk of 61% for Alternative 3 and 4 and 52% for Alternative 5, compared to a risk of 10-19% for the ramped control rules (Table 5). Under good productivity for butterfish, assessment error increased leading to inflated estimates of the OFL, but this did not occur of summer flounder or scup. Although the risk of overfishing was very high under good productivity, the risk of becoming overfished was only 12-16% for these control rules, since the increased productivity kept biomass relatively high. Under average productivity for butterfish the risk of becoming overfished for Alternative 3, 4, and 5 was 65, 71, and 69%, respectively, and under poor productivity all control rules (Alternatives 1-8) resulted in a 100% chance of the stock becoming overfished (Table 5).

Ramped Control Rules (*Alternatives 1, 2, 6, 7, and 8*)

Performance across the ramped control rules was more variable across productivity runs for each stock, owing to large differences in the size of the buffer above and below S_{MSY} (Figure 1). For butterfish, Alternative 2 had consistently high long-term yield compared to the other Alternatives. Because butterfish biomass is inherently more variable due to its high natural mortality and recruitment variability, Alternative 7 and 8, which are the most conservative as the stock declines, tended to have the lowest yield for butterfish (Figure 6). For summer flounder, Alternative 2 had the highest short-term yield of all ramped control rules across productivity levels (Figure 3). Alternative 2 also had the highest long-term yield of the ramped control rules for summer flounder under poor productivity, and near the highest yield under average productivity. Under good productivity, however, Alternatives 6 and 8 with a maximum P* of 0.49 had the highest long-term yield (Figure 4; Table 5). Similarly for scup, which had biomass well above S_{MSY} at the start of the management period, highest catches occurred for Alternatives 8 and 6 under average and good productivity. Under poor productivity, however, Alternative 2 had the highest long-term yield for scup (Figure 5). When assessments tended to underestimate biomass, Alternative 2 performed well with high long-term yield across stocks compared to other ramped control rules. When assessments overestimated biomass, Alternative 2 also produced high long-term yield, but so did Alternatives 8 and 6 (Table 6).

The ramped control rules resulted in greater variability in catch compared to the fixed and stepped P* control rules. In general, the more rapidly the target P* changed with biomass, the more variable the catch was overall, particularly for stocks under poor productivity. As a result, options 7 and 8 had the greatest average variability in catch, as well as the greatest maximum change in catch between years across stocks, whereas Alternatives 1 and 2 had the lowest (Figures 7-12; Table 5). For butterfish ramped control rules resulted in average interannual changes between 15-27%, and maximum changes between 45-78% across productivity levels. For summer flounder they resulted in average interannual changes between 9-23%, and maximum changes between 31-64% across productivity levels. Finally for scup, ramped control rules resulted in average changes in catch of 8-15% and maximum changes of 24-42% (Table 5).

In general, the risks of overfishing and of becoming overfished were lower for the ramped control rules, although the differences relative to Alternative 3, 4, and 5 varied by stock and productivity scenario. Across productivity levels for each stock, all of the ramped control rules resulted in a risk of overfishing below the 50% threshold (Table 5), with higher risk with higher maximum target P*. When assessments overestimated biomass for scup, however, only the ramped options with a maximum P* of 0.4 did not cross the 50% threshold (Alternatives 1 and 7; Table 6). The risk of becoming overfished also increased with the maximum P* target, and was lowest for Alternatives 1 and 7 across stocks and productivity levels. The exception to pattern was butterfish under poor productivity, where the risk of becoming overfished was 100% across all control rules (Table 5).

Conclusions

A range of ABC control rule alternatives were tested using an MSE for scup, summer flounder, and butterfish. These control rules varied in their maximum allowable P*, and in how the P* changed as biomass declined (Figure 1). Performance of the control rules relative to one another was evaluated by comparing short- and long-term yields to the fishery, variability in yield, the risk of overfishing, and the risk of driving the population to low levels (below 50% S_{MSY}). Variability in future stock productivity (recruitment and natural mortality) were incorporated in the model, and comparison of control rule performance was evaluated across 1) the baseline (average productivity) model runs, 2) under good future conditions only, and 3) under poor future conditions. Runs were also separated based on assessment error into those that tended to under- or overestimate biomass, on average.

In general, the fixed and stepped Alternatives (3,4,5) produce greater benefits to the fishery, with high stable short- and long-term catches across stocks and productivity levels. However, with greater reward comes greater risk, as these control rules also had the greatest risks of overfishing and causing the stocks to become overfished. In some cases the risk of overfishing exceeded the 50% threshold, occurring for summer flounder and scup under poor productivity, and for butterfish under good productivity. The risk of overfishing also exceed 50% for summer flounder under Alternatives 3, and 4, and Alternative 5 for scup when the assessment overestimated biomass. Ramped control rules, on the other hand, had lower risks of overfishing and of becoming overfished, particularly under average and poor productivity conditions across stocks. In general, ramped options with higher maximum P* had higher yield, on average, particularly under average and good productivity. An exception this pattern was for butterfish under Alternative 8, which had a maximum P* of 0.49, but was also more conservative as the stock declined below S_{MSY}. For summer flounder, which started below S_{MSY}, the ramped control rules had larger differences in short-term yield with Alternatives 3, 4, and 5 compared to long-term yield. Ramped control rules had greater variability in yield overall, with the greatest variability occurring for options with more rapid changes in the target P* with biomass (Alternatives 6, 7, and 8). Of the ramped control rules, Alternative 2 seemed the best able to balance the tradeoffs, resulting in relatively high catch, low risks of overfishing and becoming overfished, and lower variability in catch compared to most of the ramped Alternatives.

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Table 1. Equations governing the population and data-generating dynamics in the operating model.

	Equation	Description
	Population, life history and fishing dynamics	
1	$R(t) = \frac{S(t-a_R)}{\alpha + \beta S(t-a_R)} e^{\varepsilon_R - 0.5\sigma_R^2}$	Stock-recruit relationship
	$\alpha = \frac{S_0(1-h)}{4hR_0} \qquad \beta = \frac{5h-1}{4hR_0}$	
	$\varepsilon_R(t) = \rho_R \varepsilon_R(t-1) + \sqrt{1-\rho_R^2}\varphi_R(t)$	
	$\varphi_R(t) \sim N(0, \sigma_R^2)$	
2	$S(t) = \sum_a m(a)w(a)N(a,t)$	Spawning biomass
3	$N(a,t) = \begin{cases} R(t) & a = a_R \\ N(a-1,t-1)e^{-Z(a-1,t-1)} & a_R < a < a_{max} \\ N(a-1,t-1)e^{-Z(a-1,t-1)} + & a = a_{max} \\ N(a,t-1)e^{-Z(a,t-1)} & \end{cases}$	Numerical abundance at age
4	$Z(a,t) = M(t) + s(a,t)F(t)$	Total mortality

5	$M(t) = \bar{M}e^{\varepsilon_M(t)-0.5\sigma_M^2}$ $\varepsilon_M(t) = \rho_M\varepsilon_M(t-1) + \sqrt{1-\rho_M^2}\varphi_M(t)$ $\varphi_M(t) \sim N(0, \sigma_M^2)$	Time-varying natural mortality
6a	$s(a,t) = \frac{1}{1+e^{-\frac{a-s_{50}(t)}{s_{slope}}}}$ $s_{50\%}(t) = \bar{s}_{50\%}e^{\varepsilon_s(t)-0.5\sigma_s^2}$ $\varepsilon_s(t) = \rho_s\varepsilon_s(t-1)1) + \sqrt{1-\rho^2}\varphi(t))$ $\varphi(t) \sim N(0, \sigma_s^2)$	Logistic selectivity at age in fishery or survey, with time varying selectivity only in the fishery
6b	$s(a,t) = \begin{cases} e^{\frac{-(a-a_{mid})}{s_{up}}} & a \leq a_{mid} \\ e^{\frac{-(a-a_{mid})}{s_{down}}} & a > a_{mid} \end{cases}$ $s_{mid}(t) = \bar{s}_{mid}e^{\varepsilon_s(t)-0.5\sigma_s^2}$ $\varepsilon_s(t) = \rho_s\varepsilon_s(t-1)1) + \sqrt{1-\rho^2}\varphi(t))$ $\varphi(t) \sim N(0, \sigma_s^2)$	Dome-shaped selectivity at age in fishery

7	$C(a,t) = \frac{s(a,t)F(t)}{Z(a,t)} w(a)N(a,t)\left(1 - e^{-Z(a,t)}\right)$ $C(t) = \sum_a C(a,t)$	Annual catch at age and total catch
	Data-generating dynamics	
8	$C_{obs}(t) = C(t)^{\varepsilon_C(t) - 0.5\sigma_C^2}$ $\varepsilon_C(t) \sim N(0, \sigma_C^2)$	Observed catch
9	$I(a,t) = q(t)s_S(a)N(a,t)$ $I(t) = \sum_a I(a,t)$ $q(t) = qe^{\varepsilon_q(t) - 0.5\sigma_q^2}$ $\varepsilon(t) \sim N(0, \sigma_q^2)$	True index of abundance
10	$I_{obs}(t) = I(t)^{\varepsilon_I(t) - 0.5\sigma_I^2}$ $\varepsilon_I(t) \sim N(0, \sigma_I^2)$	Observed index of abundance
11	$\mathbf{p}_{obs}(t) = \frac{1}{n}\boldsymbol{\Theta}(t)$ $\boldsymbol{\Theta}(t) \sim Multinomial(n, \mathbf{p}(t))$ $\mathbf{p}(t) = \frac{1}{I(t)}\left(I(a_R,t), \dots, I(a_{max},t)\right)$	Observed vector of proportion at age in fishery *f*

Table 2. Description of the index and state variables used in equations in the model (presented in Table 1). Parameter descriptions and values used are presented in Table 3.

Symbol	Description
Index variables	
t	Year
a	Age
State variables	
N	Numerical abundance
S	Spawning biomass (kg)
L	Length (cm)
w	Weight (kg)
m	Maturity (proportion)
s_s	Survey selectivity (proportion)
s_f	Fishery selectivity (proportion)
F	Fishing mortality rate (year^{-1})
M	Natural mortality rate
Z	Total mortality rate (year^{-1})
C	Total fishery catch (kg)
C_{obs}	Observed fishery catch (kg)
p_C	Proportions at age in catch
$p_{C,obs}$	Observed proportion at age in catch
I	Survey numerical index of abundance
I_{obs}	Observed survey numerical index of abundance
q	Survey catchability
p_I	Proportions at age in survey
$p_{I,obs}$	Observed proportion at age in survey

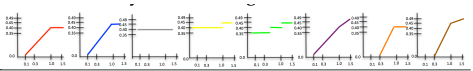
Table 3. Parameter values used in the model for each species. Note that for butterfish, the F_{MSY} reference point is set at 2/3 • M and is not based on a SPR calculation.

Parameter	Description	Butterfish	Summer flounder	Scup
a_R	Age at recruitment (to population)	1	1	1
a_{max}	Maximum age (a plus group)	5	8	8
$\bar{M}$	Mean natural mortality rate	1.22	0.25	0.2
σ_M	standard deviation of time-varying M	0.1	0.1	0.1
ρ_M	autocorrelation in M	0.3	0.3	3
h	Steepness	0.85	0.9	0.92
R_0	Virgin recruitment	7877266	48000	134111
S_0	Unfished spawning biomass	93747	150000	320732
σ_R	standard deviation of stock-recruit relationship	0.5	0.5	0.5
ρ_R	autocorrelation in recruitment	0.44	0.44	0.6
$\bar{s}_{f,peak}$	Age at maximum selectivity in dome-shaped function	3.0	5.0	4.0
$s_{f,up}, s_{f,down}$	Controls how rapidly selectivity increases / decreases	1.5 / 20.0	1.73 / 5.44	3.67 / 2.09
σ_s	standard deviation of age at 50% or peak selectivity	0.01	0.15	0.1
ρ_s	autocorrelation in selectivity	0.3	0.2	
$\bar{s}_{s,50\%}$	mean age at 50% selectivity in survey	0.5	0.5	0.5
$s_{s,slope}$	Slope of survey selectivity function	1	1	1
σ_C	standard deviation of catch estimates	0.29	0.2	0.2
σ_I	standard deviation of survey estimates	0.47	0.29	0.63
$\bar{q}$	mean catchability in survey	5×10^{-5}	5×10^{-5}	5×10^{-5}
σ_q	standard deviation of catchbility random walk	0.01	0.05	0.05
n_C	effective sample size of the catch	50	100	50
n_I	effective sample size of the survey	50	100	50
SPR_{lim}	Spawning potential ratio (SPR) that defines overfising	-	0.35	0.4
F_{MSY}	Fishing mortality rate that defines overfishing	0.81	0.3	0.22

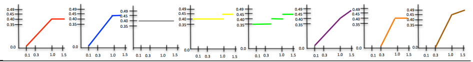
Table 4. Performance measures calculated for different time periods at the end of each model run. The average change in the catch is calculated following Punt (2003) as $\sum_{t>1}|C(t)-C(t-1)|/\sum_t C(t)$

Performance Measure	Description	Time Period(s)
Initial catch	Mean catch	first 5 years
Long-term catch	Mean catch	final 20 years
Average change in catch	Average relative interannual variation in catch	all years
Maximum change in catch	Maximum relative change in catch between any two years of the 30-year period	all years
Probability of overfishing (P_{OF})	Proportion of years when $F > F_{MSY}$	all years
Risk of becoming overfished	Proportion of runs where the stock becomes overfished ($S < 0.5\ S_{MSY}$)	all years

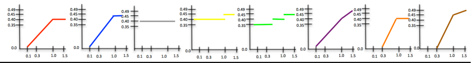
Table 5. Median performance measures for each stock by productivity scenario. Short- and long-term catch values are calculated as the difference between each control rule and the current control rule (Alt. 1), with positive and negative values meaning higher and lower catch, respectively, on average.



	Performance Measure	Productivity	Alt.1	Alt.2	Alt.3	Alt.4	Alt.5	Alt.6	Alt.7	Alt.8
Butterfish	Short-term catch	Average	0	2,754	3,823	5,575	4,592	2,077	-895	2,257
	Short-term catch	Good	0	5,248	14,250	15,755	12,452	676	-4,287	633
	Short-term catch	Poor	0	1,306	3,930	4,591	3,553	671	-497	891
	Long-term catch	Average	0	2,464	4,547	5,981	5,022	1,699	-1,200	1,894
	Long-term catch	Good	0	3,852	37,255	36,008	31,631	995	-43,270	-10,495
	Long-term catch	Poor	0	1,094	2,979	3,623	2,828	790	-183	1,063
	Max. change in catch	Average	0.38	0.41	0.27	0.27	0.29	0.44	0.45	0.52
	Max. change in catch	Good	0.5	0.51	0.32	0.32	0.31	0.49	0.64	0.59
	Max. change in catch	Poor	0.51	0.55	0.27	0.29	0.31	0.57	0.73	0.78
	Avg. change in catch	Average	0.16	0.16	0.12	0.12	0.13	0.17	0.18	0.19
	Avg. change in catch	Good	0.15	0.15	0.1	0.1	0.09	0.15	0.26	0.18
	Avg. change in catch	Poor	0.2	0.21	0.12	0.13	0.14	0.21	0.25	0.27
	Overfishing prob.	Average	0.06	0.13	0.16	0.19	0.19	0.13	0.06	0.15
	Overfishing prob.	Good	0.16	0.19	0.61	0.61	0.52	0.16	0.1	0.13
	Overfishing prob.	Poor	0.13	0.19	0.32	0.35	0.29	0.19	0.16	0.23
	Overfished prob.	Average	0.54	0.64	0.65	0.71	0.69	0.64	0.51	0.65
	Overfished prob.	Good	0.03	0.04	0.15	0.16	0.12	0.02	0.02	0.02
	Overfished prob.	Poor	1	1	1	1	1	1	1	1

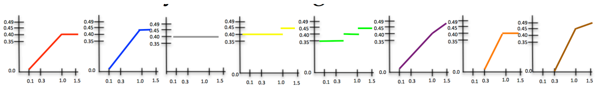


	Performance Measure	Productivity	Alt.1	Alt.2	Alt.3	Alt.4	Alt.5	Alt.6	Alt.7	Alt.8
Summer flounder	Short-term catch	Average	0	564	1,226	1,226	1,110	0	-319	216
	Short-term catch	Good	0	575	1,222	1,222	1,025	0	-304	178
	Short-term catch	Poor	0	548	1,169	1,169	1,000	0	-309	178
	Long-term catch	Average	0	579	94	566	639	451	-6	574
	Long-term catch	Good	0	1,566	-114	1,526	1,530	2,108	29	2,381
	Long-term catch	Poor	0	194	357	390	293	31	-83	169
	Max. change in catch	Average	0.36	0.42	0.26	0.31	0.34	0.45	0.4	0.51
	Max. change in catch	Good	0.31	0.34	0.27	0.3	0.31	0.4	0.32	0.4
	Max. change in catch	Poor	0.47	0.52	0.3	0.33	0.35	0.51	0.56	0.64
	Avg. change in catch	Average	0.14	0.15	0.12	0.13	0.14	0.16	0.15	0.17
	Avg. change in catch	Good	0.09	0.09	0.08	0.09	0.09	0.11	0.09	0.11
	Avg. change in catch	Poor	0.18	0.2	0.14	0.15	0.16	0.19	0.2	0.23
	Overfishing prob.	Average	0.13	0.23	0.13	0.19	0.19	0.19	0.1	0.26
	Overfishing prob.	Good	0	0	0	0	0	0.03	0	0.06
	Overfishing prob.	Poor	0.32	0.39	0.58	0.58	0.48	0.32	0.32	0.39
	Overfished prob.	Average	0.14	0.23	0.15	0.24	0.23	0.24	0.14	0.27
	Overfished prob.	Good	0.03	0.05	0.03	0.05	0.05	0.06	0.02	0.06
	Overfished prob.	Poor	0.72	0.8	0.87	0.87	0.84	0.75	0.71	0.78

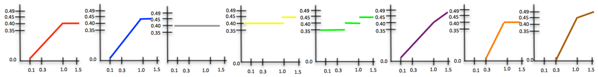


	Performance Measure	Productivity	Alt.1	Alt.2	Alt.3	Alt.4	Alt.5	Alt.6	Alt.7	Alt.8
Scup	Short-term catch	Average	0	992	0	992	992	1,861	0	1,861
	Short-term catch	Good	0	1,079	0	1,079	1,079	2,000	0	2,000
	Short-term catch	Poor	0	939	0	939	939	1,749	0	1,749
	Long-term catch	Average	0	584	84	746	685	670	-14	944
	Long-term catch	Good	0	1,592	20	1,628	1,628	2,428	0	2,670
	Long-term catch	Poor	0	111	473	502	355	-153	-28	9
	Max. change in catch	Average	0.27	0.28	0.26	0.27	0.27	0.3	0.27	0.3
	Max. change in catch	Good	0.24	0.25	0.24	0.25	0.25	0.27	0.24	0.27
	Max. change in catch	Poor	0.32	0.34	0.28	0.29	0.3	0.36	0.35	0.42
	Avg. change in catch	Average	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.12
	Avg. change in catch	Good	0.08	0.08	0.08	0.08	0.08	0.09	0.08	0.08
	Avg. change in catch	Poor	0.12	0.13	0.12	0.12	0.12	0.14	0.13	0.15
	Overfishing prob.	Average	0.1	0.26	0.1	0.23	0.23	0.29	0.1	0.32
	Overfishing prob.	Good	0	0	0	0	0	0.06	0	0.06
	Overfishing prob.	Poor	0.32	0.39	0.39	0.45	0.42	0.39	0.32	0.39
	Overfished prob.	Average	0.21	0.26	0.21	0.26	0.26	0.27	0.21	0.27
	Overfished prob.	Good	0.05	0.08	0.05	0.09	0.09	0.1	0.05	0.11
	Overfished prob.	Poor	0.55	0.61	0.57	0.63	0.62	0.6	0.55	0.63

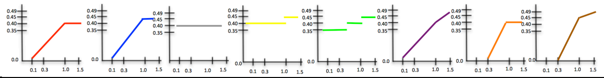
Table 6. Median performance measures for each stock for runs separated by whether or not the assessment tended to over- or underestimate biomass, on average over the 30 year period. Short- and long-term catch values are calculated as the difference between each control rule and the current control rule (Alt. 1), with positive and negative values meaning higher and lower catch, respectively, on average.



Stock	Performance Measure	Aseesment Error	Alt.1	Alt.2	Alt.3	Alt.4	Alt.5	Alt.6	Alt.7	Alt.8
Butterfish	Short-term catch	Under	-	2,844	3,257	5,386	4,707	1,844	-1,207	2,616
	Short-term catch	Over	-	2,489	2,673	5,419	5,019	2,807	-820	3,013
	Long-term catch	Under	-	2,483	4,632	6,318	5,123	1,861	-1,526	1,787
	Long-term catch	Over	-	2,354	3,281	4,910	3,970	2,239	-962	2,482
	Max. change in catch	Under	0.37	0.39	0.26	0.27	0.28	0.43	0.44	0.51
	Max. change in catch	Over	0.41	0.44	0.29	0.3	0.32	0.47	0.46	0.55
	Average change in catch	Under	0.15	0.16	0.11	0.12	0.12	0.17	0.17	0.19
	Average change in catch	Over	0.17	0.18	0.13	0.14	0.15	0.19	0.18	0.2
	Overfishing prob.	Under	0.03	0.1	0.1	0.16	0.13	0.1	0.03	0.13
	Overfishing prob.	Over	0.19	0.27	0.26	0.35	0.32	0.26	0.19	0.29
	Overfished prob.	Under	0.47	0.57	0.59	0.66	0.63	0.55	0.43	0.57
	Overfished prob.	Over	0.7	0.8	0.77	0.82	0.83	0.83	0.68	0.82



Stock	Performance Measure	Aseesment Error	Alt.1	Alt.2	Alt.3	Alt.4	Alt.5	Alt.6	Alt.7	Alt.8
Summer Flounder	Short-term catch	Under	-	462	1,643	1,651	1,245	43	-394	24
	Short-term catch	Over	-	866	771	901	899	218	-106	699
	Long-term catch	Under	-	846	115	917	878	712	-19	1,026
	Long-term catch	Over	-	335	141	402	476	182	92	349
	Max. change in catch	Under	0.34	0.37	0.24	0.28	0.31	0.41	0.37	0.45
	Max. change in catch	Over	0.4	0.46	0.3	0.35	0.39	0.51	0.43	0.58
	Average change in catch	Under	0.13	0.14	0.11	0.12	0.13	0.15	0.14	0.16
	Average change in catch	Over	0.15	0.16	0.13	0.14	0.15	0.19	0.16	0.19
	Overfishing prob.	Under	0	0	0	0	0	0	0	0.06
	Overfishing prob.	Over	0.32	0.47	0.39	0.52	0.48	0.45	0.32	0.48
	Overfished prob.	Under	0	0.01	0	0.02	0.01	0.02	0	0.04
	Overfished prob.	Over	0.29	0.5	0.32	0.5	0.48	0.5	0.3	0.57



Stock	Performance Measure	Aseesment Error	Alt.1	Alt.2	Alt.3	Alt.4	Alt.5	Alt.6	Alt.7	Alt.8
Scup	Short-term catch	Under	-	2,844	3,257	5,386	4,707	1,844	-1,207	2,616
	Short-term catch	Over	-	2,489	2,673	5,419	5,019	2,807	-820	3,013
	Long-term catch	Under	-	2,483	4,632	6,318	5,123	1,861	-1,526	1,787
	Long-term catch	Over	-	2,354	3,281	4,910	3,970	2,239	-962	2,482
	Max. change in catch	Under	0.23	0.24	0.23	0.23	0.24	0.26	0.23	0.26
	Max. change in catch	Over	0.34	0.37	0.32	0.34	0.34	0.38	0.34	0.4
	Average change in catch	Under	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Average change in catch	Over	0.14	0.14	0.13	0.14	0.14	0.15	0.14	0.15
	Overfishing prob.	Under	0	0	0	0	0	0	0	0
	Overfishing prob.	Over	0.47	0.55	0.52	0.58	0.58	0.55	0.45	0.58
	Overfished prob.	Under	0.01	0.03	0.01	0.03	0.03	0.03	0.01	0.03
	Overfished prob.	Over	0.44	0.51	0.45	0.51	0.51	0.53	0.44	0.54

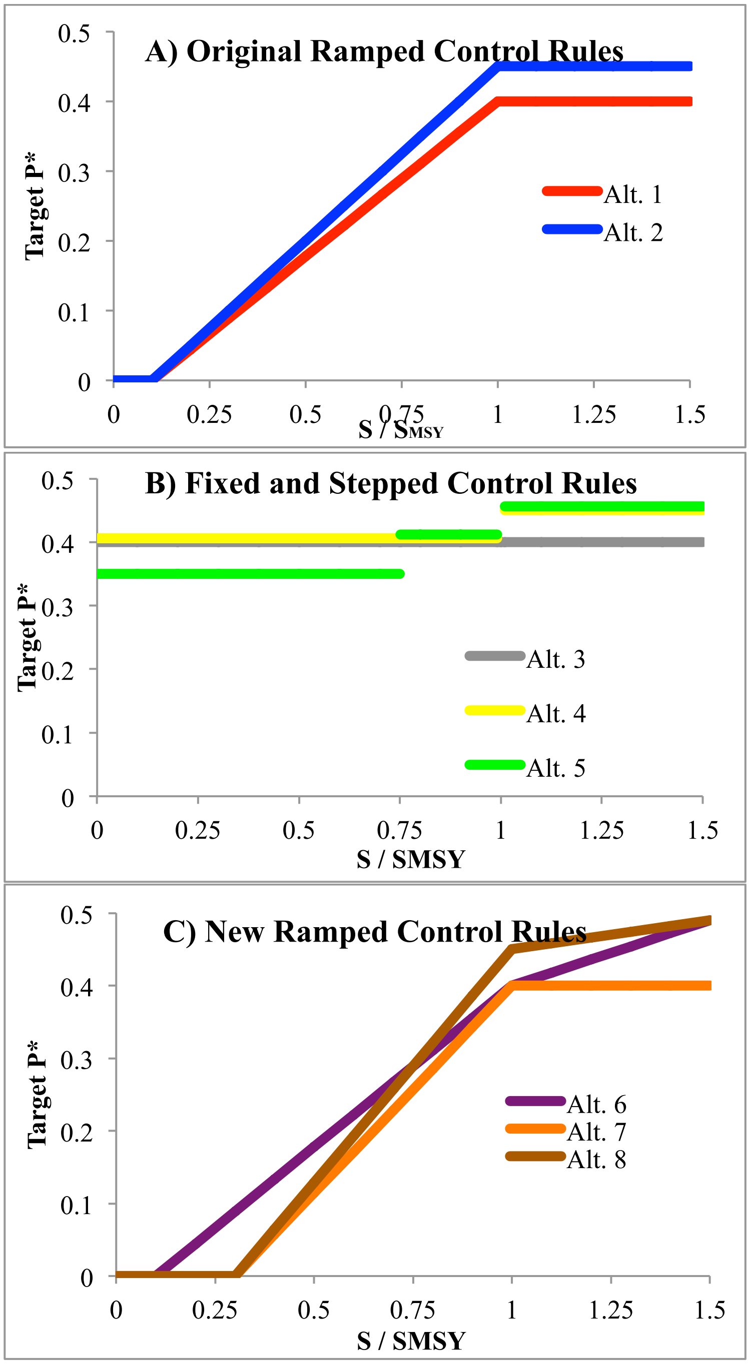


Figure 1. Control rules explored in this work, showing the target P*. Those in panel C are new from the previous work. Alternatives 3-5 (panel B) are offset slightly to prevent overlap. Colors for all control rules will be used consistently throughout this report.

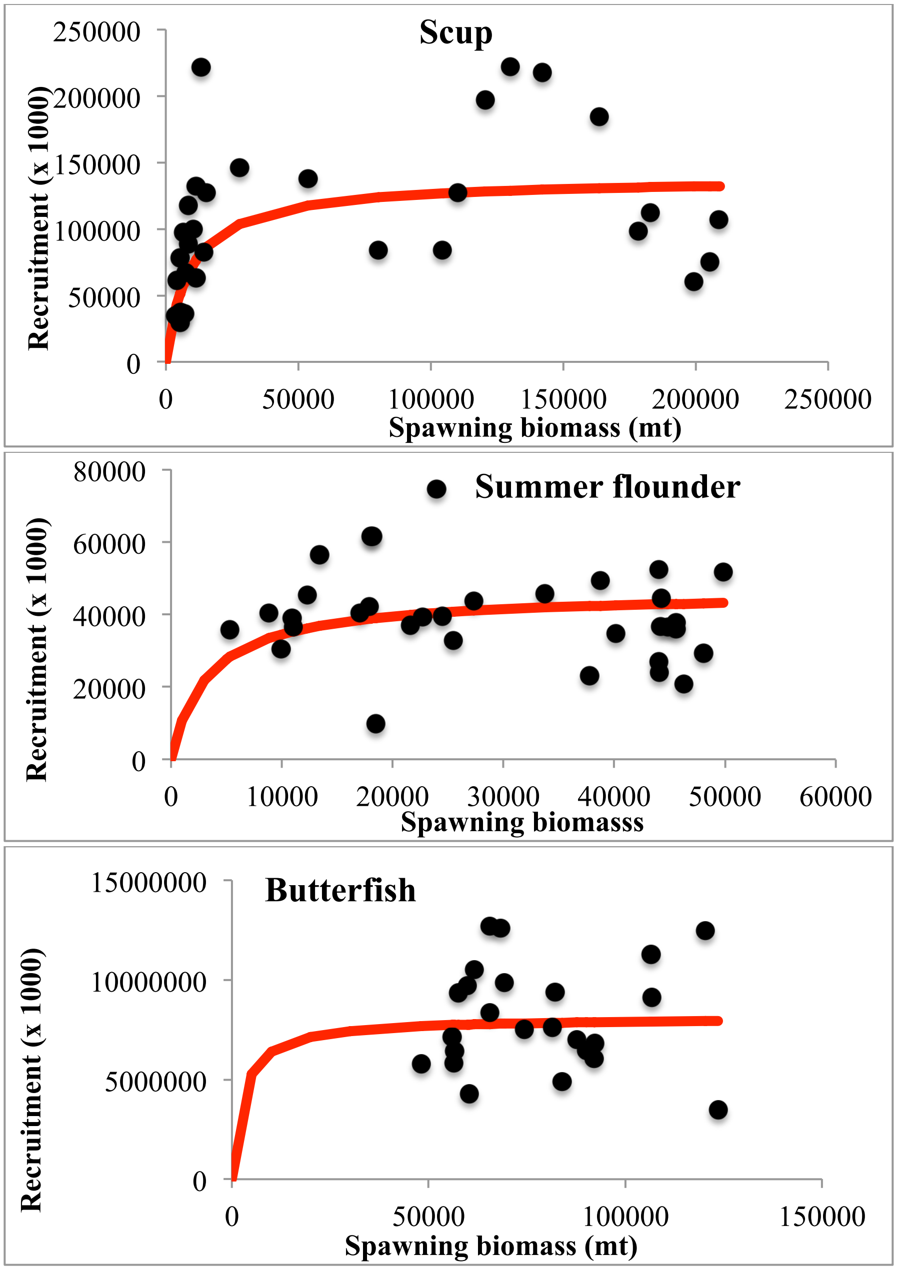


Figure 2. Stock-recruit relationship for each stock based on maximum likelihood fits of the Beverton-Holt model (red line) to the estimates of spawning biomass and recruitment (black circles) from the most recent stock assessment for each stock.

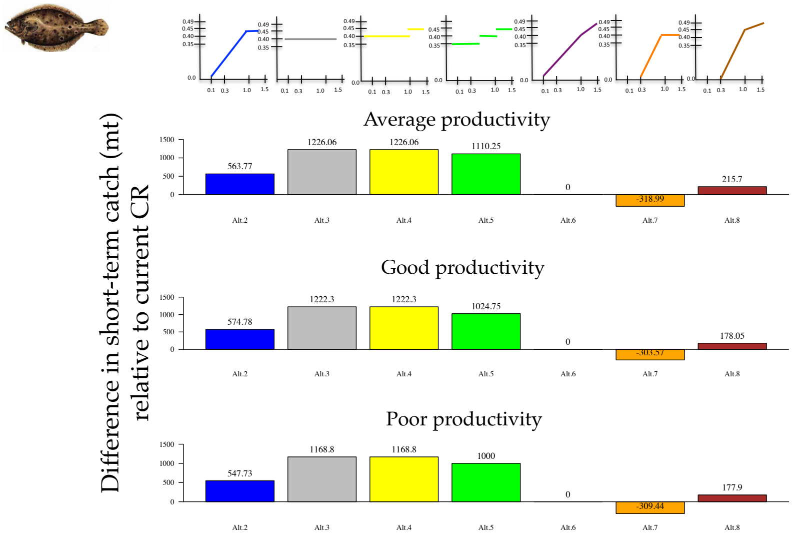


Figure 3. Difference in average catch in first 5 years of control rule implementation for summer flounder for each alternative control rule relative to the current control rule.

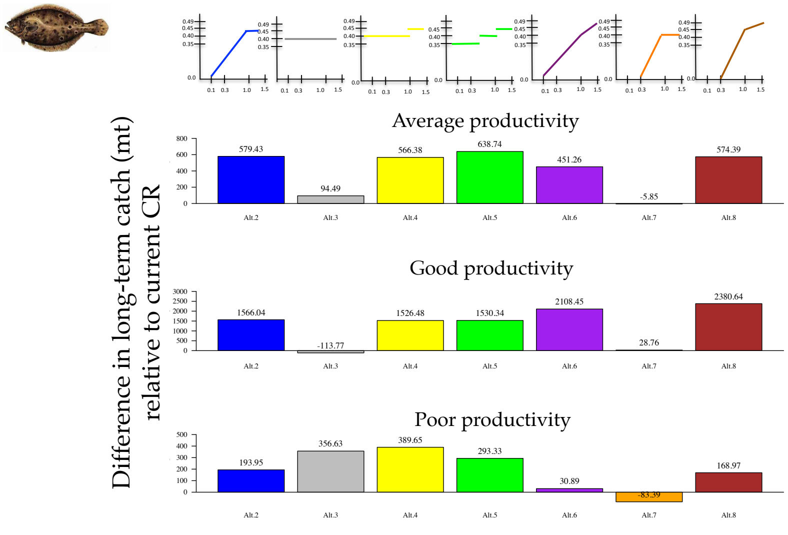


Figure 4. Difference in average catch in final 20 years of control rule implementation for summer flounder for each alternative control rule relative to the current control rule.

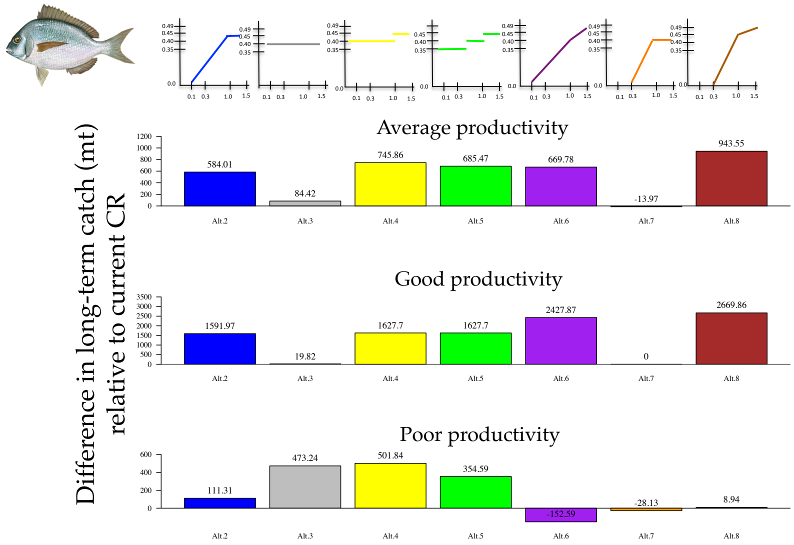


Figure 5. Difference in average catch in final 20 years of control rule implementation for scup for each alternative control rule relative to the current control rule.

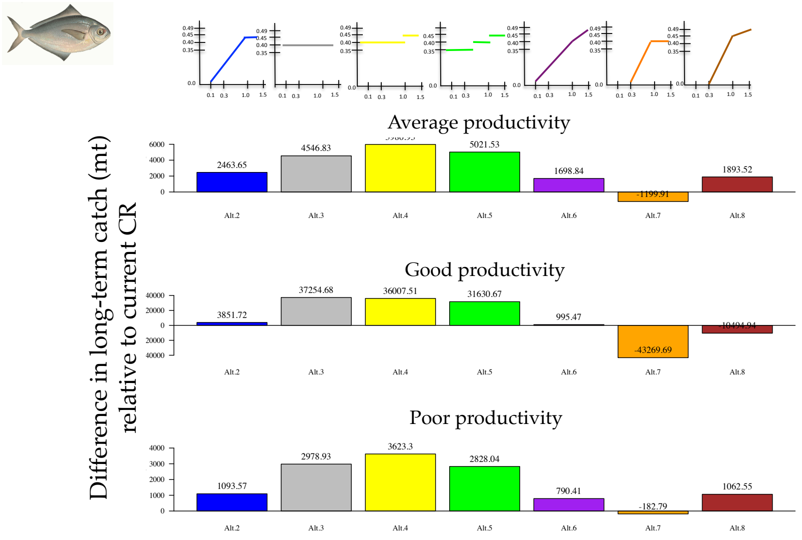


Figure 6. Difference in average catch in final 20 years of control rule implementation for butterfish for each alternative control rule relative to the current control rule.

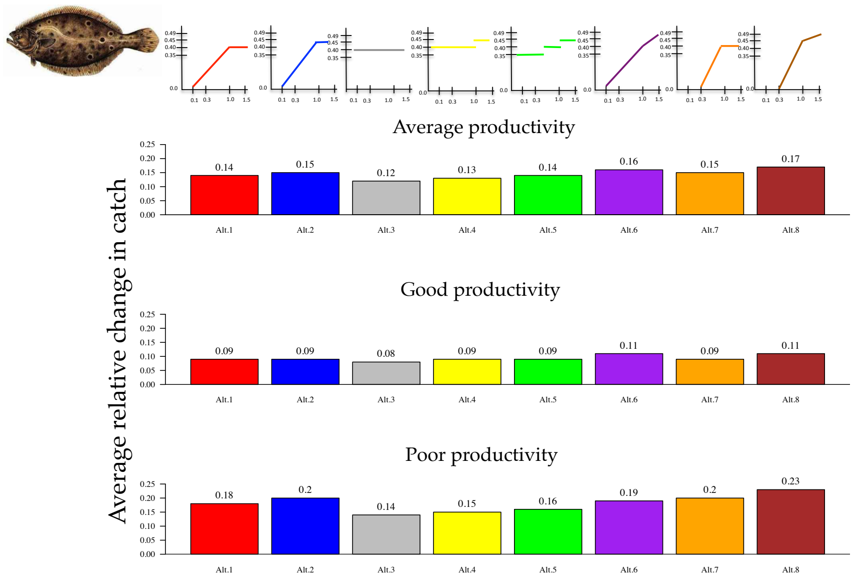


Figure 7. Change in relative catch for summer flounder between years averaged over the entire 30 year period.

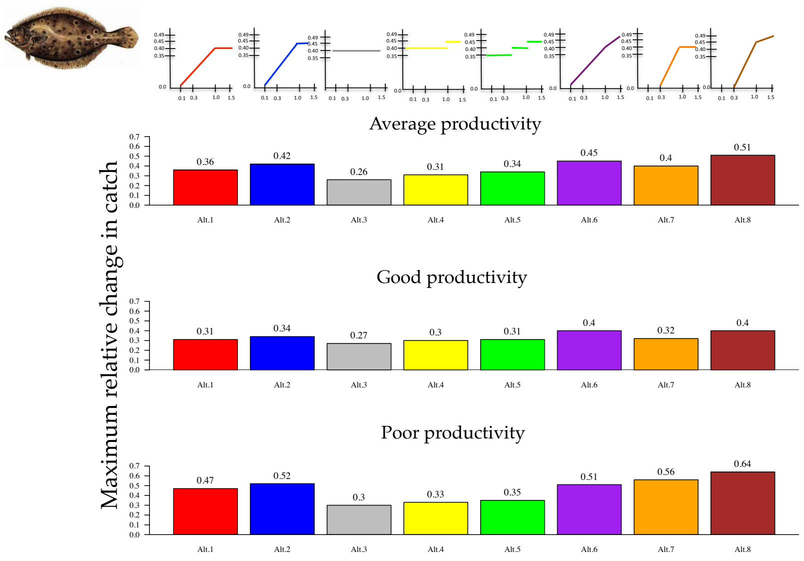


Figure 8. Maximum change in relative catch for scup between any two years over the entire 30-year period.

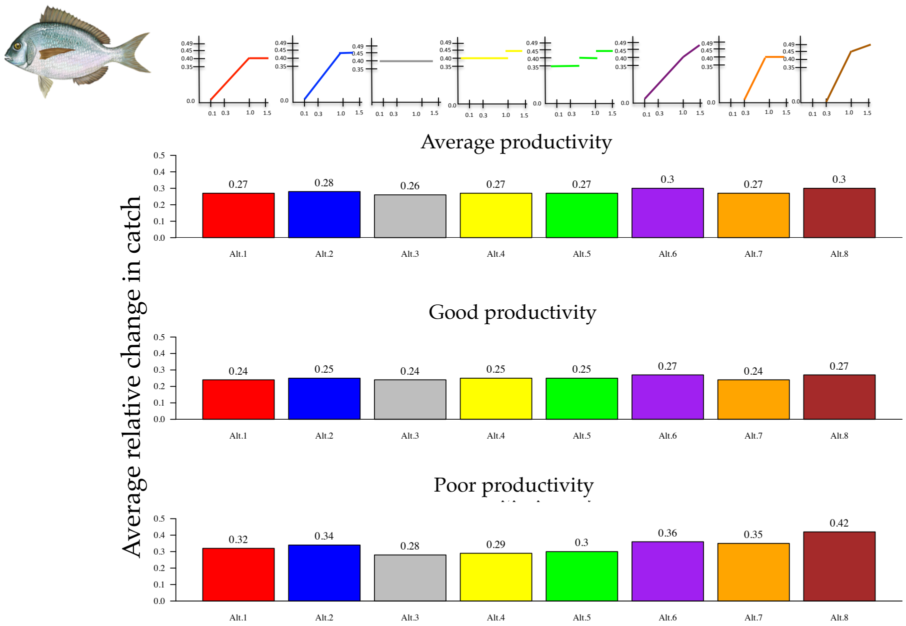


Figure 9. Change in relative catch for scup between years averaged over the entire 30-year period.

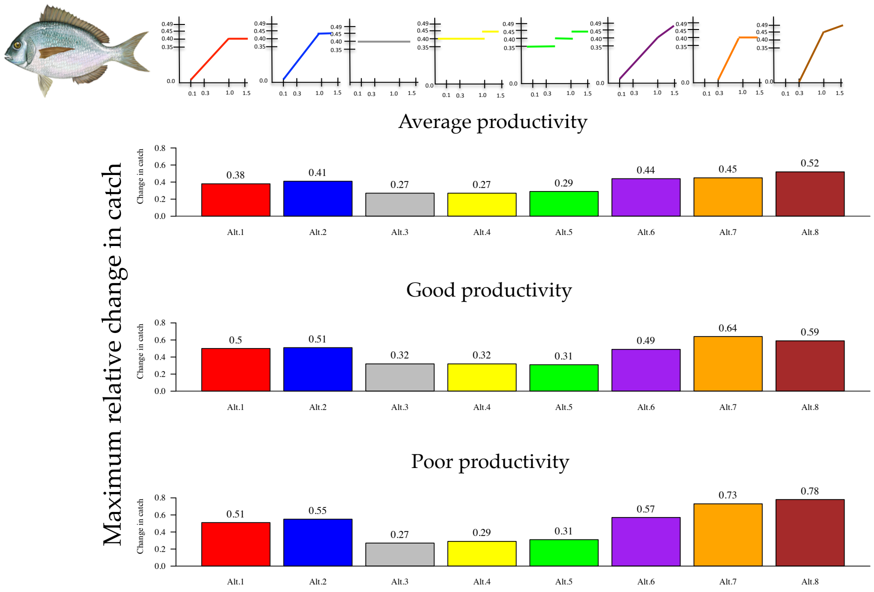


Figure 10. Maximum change in relative catch for scup between any two years over the entire 30-year period.

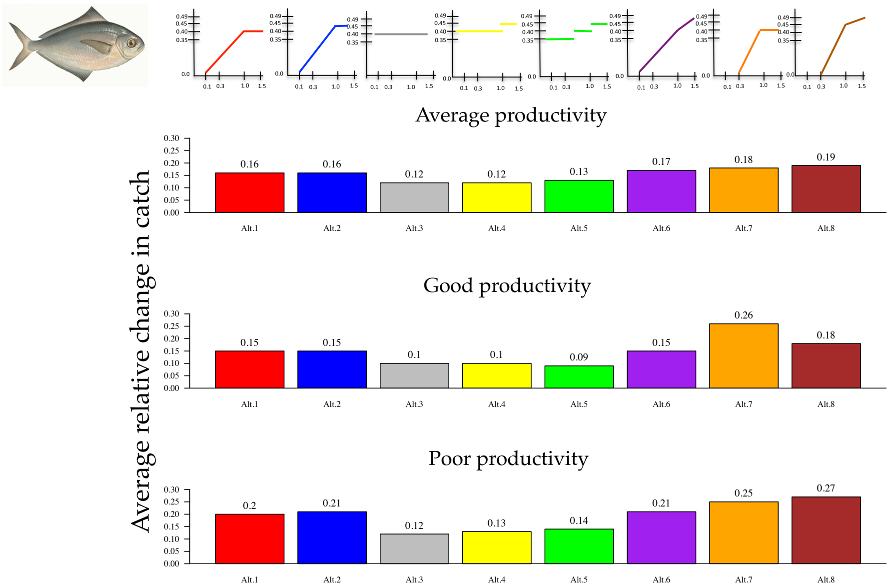


Figure 11. Change in relative catch for butterfish between years averaged over the entire 30-year period.

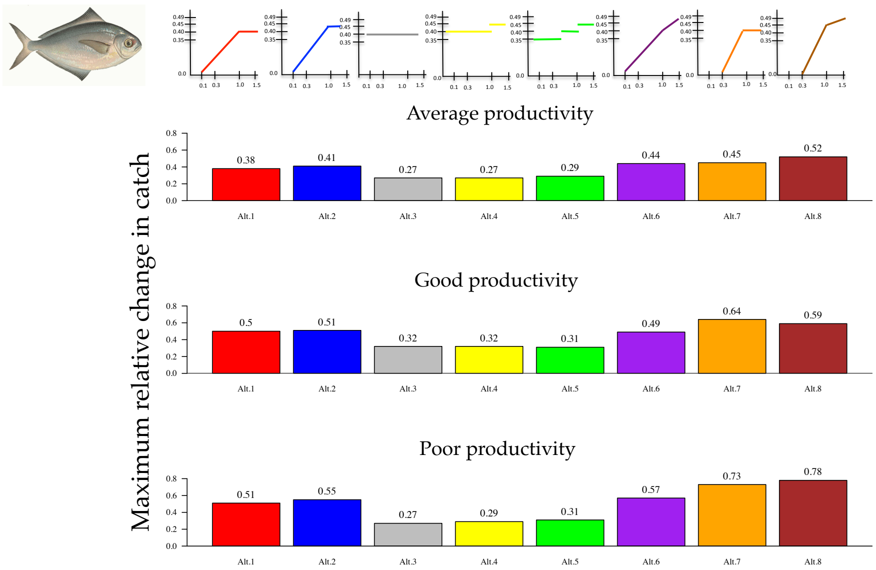


Figure 12. Maximum change in relative catch for scup between any two years over the entire 30-year period.

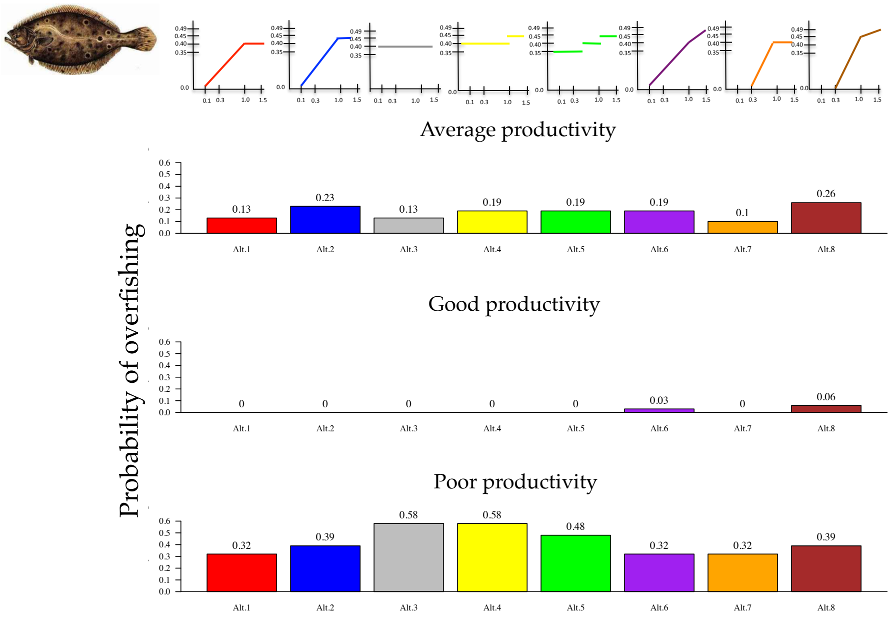


Figure 13. Median probability of overfishing for summer flounder by control rule.

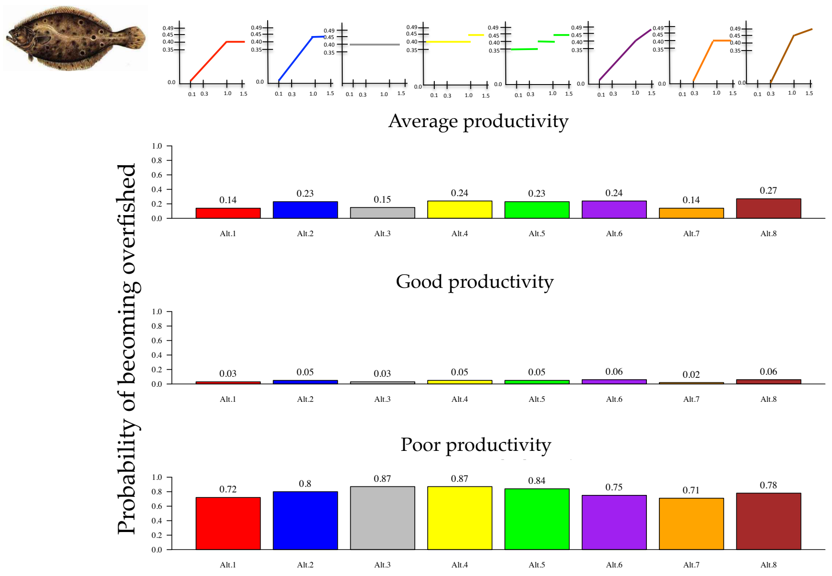


Figure 14. Median probability of becoming overfished for summer flounder by control rule.

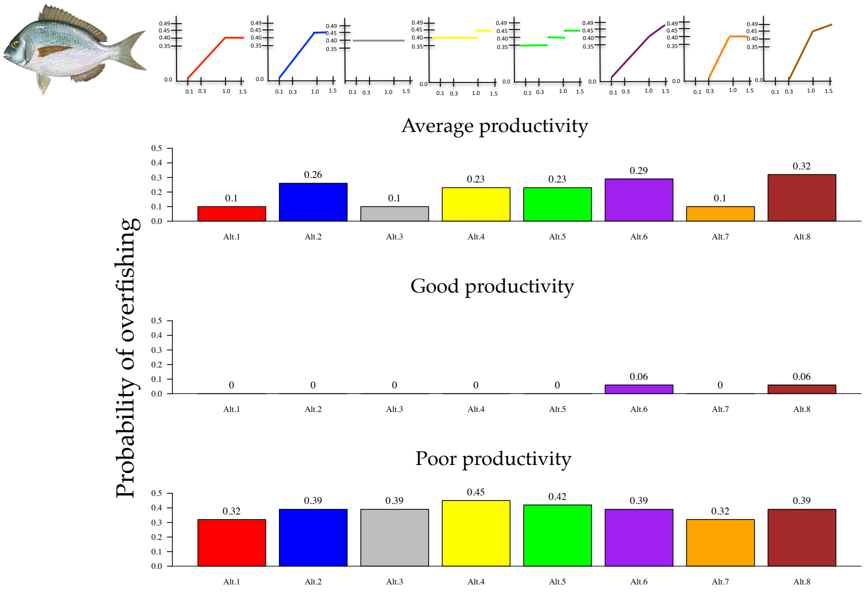


Figure 15. Median probability of overfishing for scup by control rule.

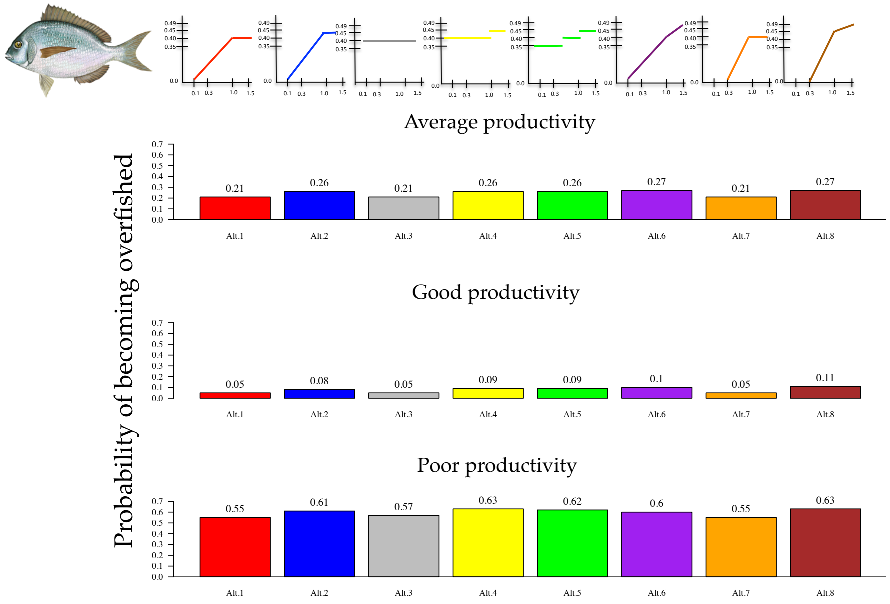


Figure 16. Median probability of becoming overfished for scup by control rule.

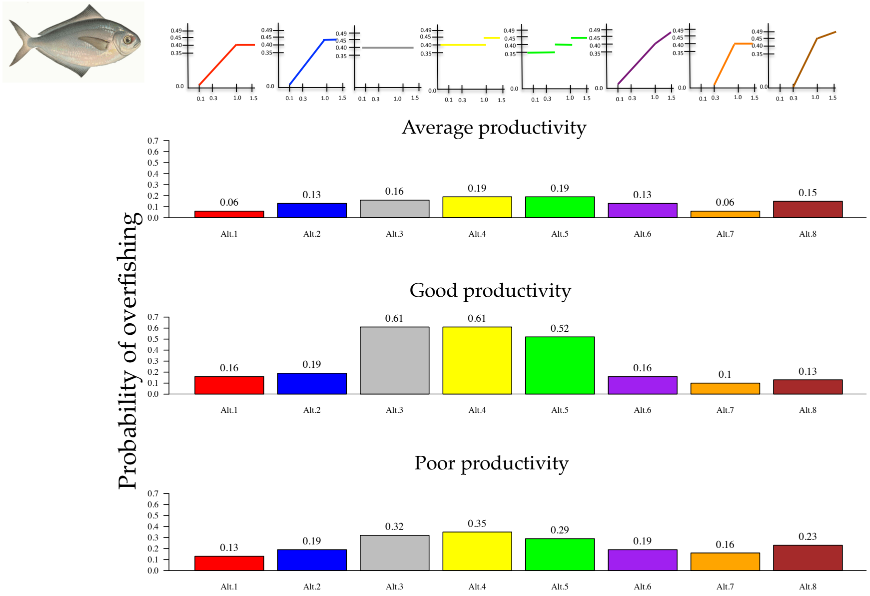


Figure 17. Median probability of overfishing for butterfish by control rule.

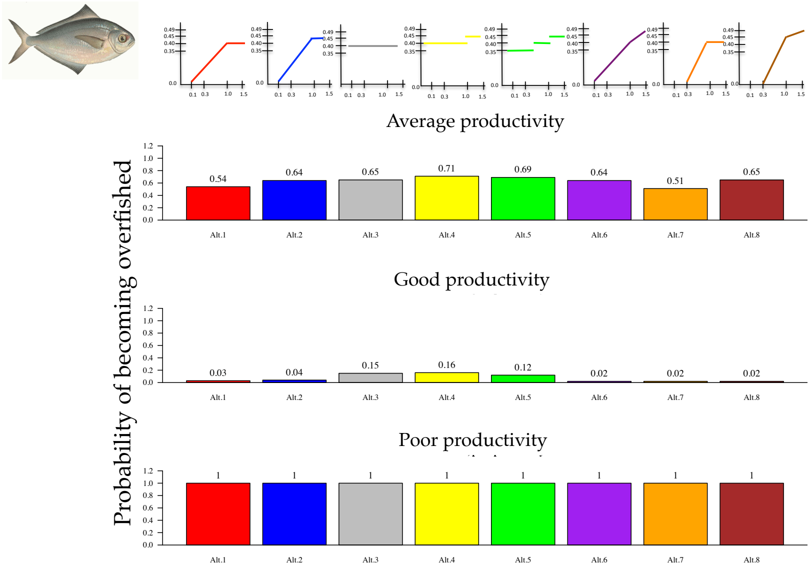


Figure 18. Median probability of becoming overfished for butterfish by control rule.