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A Management Strategy Evaluation of Rebuilding Revision Rules for Overfished Rockfish Stocks

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Abstract

Under the U.S. Sustainable Fisheries Act, Rebuilding Plans must be developed for overfished stocks. Rebuilding Plans typically include analyses to determine the minimum time to recover to B_{MSY} and the fishing mortality that is consistent with stock recovery within the required timeframe and with specified probability P_{MAX}. Seven rockfish stocks are currently under Rebuilding Plans adopted by the Pacific Fishery Management Council (PFMC). Progress toward meeting rebuilding objectives must be evaluated at least every second year, which could lead to changes to how these stocks are managed. Although a harvest control rule has been adopted by the PFMC for healthy stocks, and methods for conducting the initial analyses needed to develop Rebuilding Plans for overfished stocks are well established, there are presently no agreed upon methods ("Rebuilding Revision Rules") for (1) assessing adequacy of progress toward rebuilding and (2) altering Rebuilding Plans, given a change in stock status. To assist decision-making, we conducted a management strategy evaluation (MSE) to compare alternative Rebuilding Revision Rules using a suite of performance measures selected to quantify likely PFMC goals for rebuilding. The results of the MSE show that (1) adjustments to harvest rates occur often, (2) a policy that attempts to maintain the original P_{MAX} tends to be overly responsive to noise, and (3) setting P_{MAX} to a high value provides a buffer against uncertainty.

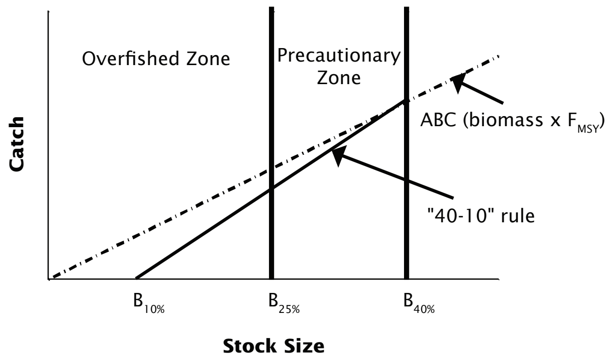

Figure 1. The 40-10 control rule used by the Pacific Fishery Management Council (PFMC).

Introduction

The Pacific Fishery Management Council (PFMC) Groundfish Management Plan (PFMC 2004) includes 82 species of roundfish, rockfish, and sharks, of which 62 are rockfish (*Sebastes* and *Sebastolobus* spp.). Under the U.S. Sustainable Fisheries Act, "Conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the OY [optimum yield] from each fishery for the U.S. fishing industry," while the Groundfish Fishery Management Plan includes the goal to "prevent overfishing and rebuild overfished stocks by managing for appropriate harvest levels and prevent, to the extent practicable, any net loss of habitat of living marine resources." In this paper "overfishing" means that the current fishing mortality rate exceeds that associated with obtaining maximum sustainable yield (MSY) and "being in an overfished state" means that the current spawning output is less than a minimum stock size threshold (MSST).

The scientific component of the management system for West Coast groundfish species involves conducting quantitative assessments to estimate stock status and fishing impacts relative to specified reference points and applying a control rule to determine harvest guidelines. The control rule (Fig. 1) involves calculating an allowable biological catch based on an estimate of F_{MSY}, the fishing mortality at which maximum sustainable yield is achieved, and reducing this catch if the stock size is estimated to be below the proxy for B_{MSY} (40% of the unfished spawning output, B_0). In practice, F_{MSY} for rockfish species is not estimated based on fitting a stock-recruitment relationship, but is instead set to a proxy fishing mortality rate equivalent to a spawning potential ratio (SPR) of 50% (Ralston 2002, PFMC 2004). Fishing mortality rate, F, is expressed in terms of its effect on SPR (spawning output-per-recruit relative to that in an unfished state), because this standardizes for differences in growth, maturity, fecundity, natural mortality, and fishery selectivity patterns to some extent.

The MSST for groundfish species managed by the PFMC is $0.25B_0$. Stocks estimated to be below $0.25B_0$ have been designated by NOAA Fisheries to be "overfished," requiring the development of a Rebuilding Plan. The period for rebuilding is to be as short as practicable, taking into consideration the biology of the stock and the needs of the fishing community, and is not to exceed 10 years, unless the biology, environmental conditions, or other factors dictate otherwise. The technical requirements for a rebuilding analysis involve a sequence of calculations (Jacobson and Cadrin 2002). First, the minimum time for an overfished population to have a 50% probability of recovery to the proxy for B_{MSY} if there was no fishing in the future, T_{MIN}, is calculated. If T_{MIN} is greater than 10 years, as is the case for most rockfish, the technical guidance provided by NOAA Fisheries is that the rebuilding period should not exceed T_{MAX}, defined as T_{MIN} plus one mean generation time (i.e., the average age of the maternity function). Analysts then conduct projections based on a range of fishing mortality levels to determine the relationship between the probability of recovery to the proxy for B_{MSY} by T_{MAX} and the impact of rebuilding on catches and fishing mortality. Based on these, and other, considerations, the PFMC selects its intended probability of recovery to the proxy for B_{MSY} by T_{MAX} (P_{MAX}) and hence a target fishing mortality level (or SPR) and a target year for recovery. This year, referred to as T_{TARGET}, must lie between T_{MIN} and $T_{MAX,}$ and corresponds to the year in which recovery to 0.4 B_0 is predicted to occur with 50% probability

Seven rockfish species off the U.S. West Coast (bocaccio *Sebastes paucispinis*, cowcod *S. levis*, canary rockfish *S. pinniger*, darkblotched rockfish *S. crameri*, Pacific ocean perch *S. alutus*, widow rockfish *S. entomelas*, and yelloweye rockfish *S. ruberrimus*) are currently designated as overfished (see Table 1 for rebuilding parameter values). T_{TARGET} for these species ranges from 2023 (bocaccio) to 2090 (cowcod). The differences in T_{TARGET} among species reflects the PFMC's selected trade-off between the rate at which recovery occurs and the short- to medium-term impact of rebuilding on fishing communities. In general, the PFMC selected higher T_{TARGET}s for species for which management measures would have a larger impact on the catches of species that are not overfished, but are caught together with overfished species.

The need to satisfy the requirements for Rebuilding Plans leads to a substantial increase in the demands for technical analyses (Restrepo et al. 1999) and the results of rebuilding analyses, although considered to be the best available science, are nevertheless subject to considerable uncertainty (e.g., Punt 2003, Punt and Methot 2005). For example,

Table 1. Rebuilding parameter values for the seven overfished rockfish species.

Species	T_{MIN}	T_{MAX}	P_{MAX}	T_{TARGET}
Darkblotched rockfish	2014	2047	0.8	2030
Pacific ocean perch	2012	2042	0.7	2027
Canary rockfish	2057	2076	0.6	2074
Bocaccio	2018	2032	0.7	2023
Cowcod	2062	2099	0.6	2090
Widow rockfish	2026	2042	0.6	2038
Yelloweye rockfish	2027	2071	0.8	2058

forecasts of the future size of the darkblotched rockfish stock under the current Rebuilding Plan became markedly more optimistic following a change to the assumed value for the natural mortality rate (Rogers 2005).

It should be expected therefore that the results of rebuilding analyses in the future will not conform exactly with the expectations based on the original rebuilding analysis. The question that arises, then, is whether the fishing mortality rate used to set harvest guidelines specified as part of a Rebuilding Plan should be changed, and if so how? A further consideration is that data now available may show that the original basis for the Rebuilding Plan is no longer valid (e.g., because the values assumed for natural mortality or stock recruitment steepness have changed markedly). A second consideration is that councils are required to decide whether progress toward rebuilding is adequate no less frequently than every second year, although there is no formal definition of "adequate" at present, which precludes an objective evaluation of whether progress is acceptable.

This paper introduces the idea of "Rebuilding Revision Rules," i.e., extensions to the current control rules that measure progress toward rebuilding and make appropriate adjustments to Rebuilding Plans as needed. The study evaluates several candidate Rebuilding Revision Rules using an MSE framework (Smith 1994). The focus of our work is on the consequences of changes to assessments resulting from the analysis of new data; it being taken for granted that major changes to the stock assessment (e.g., a change to the stock structure assumption underlying the assessment) will lead to the need for revision to the Rebuilding Plan.

This paper is based on the guidelines for rebuilding in force when the analyses were conducted; these guidelines may have been revised somewhat since. Specifically, the analyses of this paper were conducted before a court decision (Natural Resources Defense Council [NRDC] v. NMFS, 421 F.3d 872 [9th Cir. 2005]) based on a lawsuit originally filed in opposition to management measures for darkblotched rockfish was handed down. It seems likely that the way Rebuilding Plans are developed for overfished groundfish species will change in response to this court decision, but at present, what these changes will be is unknown. It seems likely, however, that the need for Rebuilding Plans, measuring progress toward rebuilding, and adjusting Rebuilding Plans in the light of new information will remain.

Methods

The MSE approach uses Monte Carlo simulation techniques to evaluate management strategies. In context of this paper, a management strategy includes how the data are collected, how stock assessments are conducted using the data, and how the results of the assessments are used to determine management actions for overfished species (the control rules, and the Rebuilding Revision Rules that are applied to evaluate whether progress is adequate and, if needed, to adjust fishing mortality). Although account could have been taken of implementation uncertainty (Rosenberg and Brault 1993, Francis and Shotton 1997) due to actual removals differing from those that were intended, this compliance aspect is not considered here.

The MSE approach involves the following steps to evaluate a set of candidate management strategies (Punt et al. 2001, Punt 2003).

1. Identification of the objectives that the candidate management strategies are aiming to satisfy, and quantification of these objectives using a small set of performance measures.

2. Specification of the set of alternative management strategies (in this case, specifications for how assessments and rebuilding analyses are conducted and the Rebuilding Revision Rules).

3. Development and parameterization of a set of alternative operating models that represent different states of the “true” system being managed.

4. Simulation of the future using each management strategy. For each step of the projection period, the simulations involve the following steps.

    a. generation of the data available to the stock assessment;

    b. application of the stock assessment method to the data to determine inputs to rebuilding analyses and Rebuilding Revision Rules;

c. determination of the harvest guideline for the next year, either based on a rebuilding analysis (if this is the first year that the stock is identified to be overfished) or using the Rebuilding Revision Rules (if the stock is already overfished); and

d. determination of the biological implications of this harvest guideline by setting the catch for the "true" population represented in the operating model to the estimated harvest guideline.

The harvest guideline is not updated every year in the simulations of this paper, but rather every fourth year. This reflects the frequency with which regular assessments for West Coast groundfish species are likely to be conducted. Each simulation trial (i.e., an operating model variant combined with a candidate management strategy) involves 20-100 simulations of an 80-year period. Although 100 (or more) simulations for each simulated scenario would have been ideal, the computational requirements of the calculations (in particular the need to conduct assessments and rebuilding analyses every fourth year) restricted the number of simulations. Twenty simulations are, however, adequate to capture the qualitative impact of the factors that underlie a simulated scenario.

The operating model

The operating model used here is essentially identical to that used by Punt (2003). It includes an age-structured population dynamics model in which recruitment is governed by a Beverton-Holt stock-recruitment relationship with lognormal deviations (σ_R=0.6), natural mortality that is independent of age and equal to 0.15 yr^{-1}, and a single fishery, the selectivity of which is time-invariant and dome-shaped. The values for the biological and technological parameters of the operating model are based somewhat loosely on those for widow rockfish off the U.S. West Coast (Williams et al. 2000). The stock is fished down to below the overfished level of 0.25 B_0 (to either 0.1 B_0 or 0.15 B_0) after 26 years of catches when a Rebuilding Plan is first implemented. The simulations are based on a status when a Rebuilding Plan is first implemented of 0.1 B_0 or 0.15 B_0 so that there is a reasonable probability that a stock assessment would have detected that the stock was depleted to below 0.25 B_0.

The data available to the assessment are catches, weight- and fecundity-at-age and natural mortality (all known exactly), catch-rate-based indices of abundance, survey indices of abundance, catch age-composition data, and survey age-composition data. The survey is assumed to be conducted tri-annually from 28 years before the stock is declared overfished (survey CV = 0.5; effective sample size for the survey age-composition data = 100) while the catch-rate indices and

Table 2. The specifications that define the alternative "true" scenarios considered in the simulations.

Scenario	True initial biomass	Steepness	Autocorrelation in recruitment	Natural mortality (yr^{-1})	σ_R
A – Base case	0.1 SB_0	0.4	0	0.15	0.6
B – Depletion = 0.15	0.15 SB_0	0.4	0	0.15	0.6
C – Steepness = 0.7	0.1 SB_0	0.7	0	0.15	0.6
D – With autocorrelation	0.1 SB_0	0.4	0.707	0.15	0.6
E – M = 0.1 yr^{-1}	0.1 SB_0	0.4	0	0.1	0.6
F – M = 0.2yr^{-1}	0.1 SB_0	0.4	0	0.2	0.6
G – σ_R= 1	0.1 SB_0	0.4	0	0.15	1

the catch age-composition data are assumed to be available in all years when the catch is non-zero. The CV for the catch-rate indices is set to 0.4 and the effective sample size of the catch age-composition data is set to 100. On the U.S. West Coast, these specifications correspond to a data rich stock.

Table 2 summarizes the parameters of the seven operating model scenarios we considered. These are based on specifying the depletion when the management strategy is first applied (either 0.1 B_0 or 0.15 B_0), the steepness of the stock-recruitment relationship ($h = 0.4$ or $h = 0.7$), whether recruitment is temporally autocorrelated, the true value of M (0.1 yr^{-1}, 0.15yr^{-1}, or 0.2 yr^{-1}), and the extent of variation in recruitment, σ_R (0.6 or 1).

The stock assessment

The method of stock assessment is a statistical catch-at-age analysis (e.g., Fournier and Archibald 1982), which mimics the common use of the stock synthesis framework (Methot 2000) when conducting assessments of rockfish species off the U.S. West Coast. The population dynamics model underlying the assessment is essentially identical to the operating model. The estimable parameters of the stock assessment model are the annual recruitments and the parameters of the selectivity function. Parameter values are estimated by minimizing an objective function in which the catch rate data and the survey indices of abundance are assumed to be lognormally distributed and the catch and survey age-composition data are assumed to be multinomially distributed. For simplicity, the stock assessment assumes the correct effective sample sizes and coefficients of variation for the data. The outcomes from the assessment model are (a) an estimate of spawning output at the start of year $n + 1$ divided by the pre-fishery spawning output, where year *n* is the last year for which catch data are available, and (b) estimates of the spawning output and recruitment time-series. In reality, there is a time-lag between the last year for which data are available and the year for which a harvest guideline is set, but this complication is ignored here.

Rebuilding analyses

There are many ways that a rebuilding analysis can be conducted (e.g., PFMC 2001, Punt and Methot 2005). The following steps, which have formed the basis for several recent rebuilding analyses for rockfish species off the U.S. West Coast (e.g., Methot and Rogers 2001, He et al. 2003), are followed when conducting simulated rebuilding analyses.

1. B_0 is calculated by multiplying the spawning output-per-recruit in the absence of exploitation by the arithmetic average recruitment for the first 10 years of the assessment period.

2. The method for generating future recruitment is selected. Recruitment for some future year *y* is either generated by (1) randomly sampling a recruitment from the most-recent 20-year time series of estimated recruitments or (2) by multiplying the spawning output for year *y* by a recruits-per-spawning output ratio selected at random from the most-recent 20 years. The choice between these two approaches depends on whether recruits or recruits-per-spawning output is more stable (Punt and Methot 2005).

3. T_{MIN}, the time to rebuild to $0.4B_0$ with 50% probability in the absence of fishing, is calculated by projecting the population forward from the estimated age-structure at the start of the year when the stock was declared overfished (which may differ from that for the current year) 1,000 times in which fishing mortality is set equal to zero and recruitment is stochastic; T_{MIN} is then the median of the distribution for the year in which the spawning output exceeds $0.4\ B_0$.

4. T_{MAX}, the maximum time allowable for rebuilding is then calculated. In this paper T_{MAX} is set equal to T_{MIN} plus one mean generation time because the biology of the simulated populations implies that recovery to $0.4B_0$ cannot occur within 10 years.

5. Given values for T_{MAX} and P_{MAX}, the appropriate rebuilding SPR is determined by projecting the population forward 1,000 times with stochastic recruitment for a range of levels of fishing mortality (and hence SPRs) from the age-structure of the population at the start of the current year.

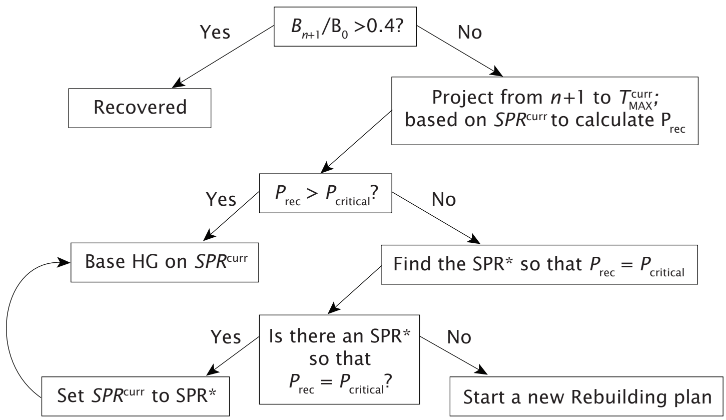

Figure 2. Flowchart of the reference Rebuilding Revision Rule.

Rebuilding Revision Rules

Several candidate Rebuilding Revision Rules are considered. All of these are based on a pre-specified and fixed value for P_{MAX}. A rebuilding analysis is assumed to have been conducted when the stock was first declared overfished (year 41), which led to values for T_{MIN}, T_{MAX}, and the rebuilding SPR that corresponds to an estimated probability of recovery of P_{MAX} by T_{MAX}. These values define the initial values for T_{MIN}^{curr}, T_{MAX}^{curr}, and SPR^{curr}, the "current" values for T_{MIN}, T_{MAX} and the SPR used to determine future harvest guidelines (HGs). The Rebuilding Revision Rules are applied after a stock assessment is conducted which provides updated estimates of the status of the stock as well as the probability of recovery if fishing mortality (i.e., SPR) remains at its current level. The alternative Rebuilding Revision Rules are all variants of a "reference" rebuilding rule. The reference rule is based on the idea that (1) performance is adequate as long as the estimated probability of rebuilding by T_{MAX} remains above 0.5 (allowing the probability of recovery to fall below 0.5 would be inconsistent with the guidance provided by NOAA Fisheries that the rebuilding period should not exceed T_{MAX}) and (2) that the entire Rebuilding Plan must be redefined if there is no SPR for which the estimated probability of rebuilding to T_{MAX} is at least 0.5. The reference rule therefore does not modify the SPR if progress is adequate; increases the SPR (reduces fishing mortality) if progress is inadequate, but recovery by T_{MAX} with 50% probability is still possible; and only changes T_{MAX} if it is impossible to recover by T_{MAX} with at least 50% probability. The base case value of P_{MAX} is 0.6 for the reference rule, which operates as follows if a stock assessment has been conducted in year *n* (Fig. 2).

a. If $B_{n+1} / B_0 > 0.4$, rebuilding is completed. Note, however, that the actual resource may or may not have rebuilt to 0.4 B_0 even though this is assessed to be the case because the assessment is based on data subject to sampling error.

b. Project the population from year $n + 1$ until T_{MAX}^{curr} using SPR^{curr} to determine future harvest guidelines and to compute the probability, P_{rec}, that the stock will rebuild to $0.4B_0$ at least once by T_{MAX}^{curr}.

c. If P_{rec} is larger than a critical value, $P_{critical} = 0.5$, progress is considered to be adequate and the harvest guidelines for the next four years are based on SPR^{curr}.

d. If P_{rec} is less than $P_{critical}$, progress is deemed to be inadequate and some measures need to be taken to reduce fishing mortality to improve the probability of recovery, i.e.,

   1. Determine if there is an SPR (and hence fishing mortality) such that the probability of rebuilding by T_{MAX}^{curr} from the current state of the stock is $P_{critical}$ (this SPR is denoted SPR^*).

   2. If $SPR^* < 1$ (i.e., recovery with probability $P_{critical}$ is possible by T_{MAX}^{curr}) then set SPR^{curr} to SPR^* and base the harvest guidelines for the next four years on SPR^*.

   3. If there is no SPR such that the probability of recovery from the current state of the stock to $0.4B_0$ by T_{MAX}^{curr} is at least $P_{critical}$, a new Rebuilding Plan is needed. This involves redefining T_{MIN} and T_{MAX} and hence SPR^{curr} is based on starting the new Rebuilding Plan from the stock size in year n+1. However, only T_{MAX} is changed if the new SPR is lower than the old (i.e., the new fishing mortality rate is higher).

We identified five alternatives to the reference rule:

1. “No change.” This alternative maintains the initial SPR throughout the rebuilding period. While not necessarily a viable Rebuilding Revision Rule, it sets a standard against which the other alternatives can be compared.

2. “At least P_{MAX}.” This alternative involves setting $P_{critical}$ equal to P_{MAX}, i.e., the SPR on which future harvest guidelines are based is increased if the probability of rebuilding drops below P_{MAX} (rather than 0.5).

3. “Attain P_{MAX}.” This alternative involves adjusting the SPR every time a new assessment is conducted so that the probability of rebuilding is always estimated to be P_{MAX}. This option differs from the “At least

P_{MAX}" option because the SPR can be decreased (fishing mortality increased) if the probability of rebuilding exceeds P_{MAX}.

4. "$P_{MAX} = 0.8$." This alternative is identical to the reference rule, except that $P_{MAX} = 0.8$.

5. "With phase." This option involves not revising a Rebuilding Plan between years $T_{MAX}^{curr} - 5$ and T_{MAX}^{curr} to avoid making large changes to SPR (and hence catches) when a stock is believed to be close to the target level.

The five alternatives are only a small subset of those that might be constructed by varying the features of the reference rule. They were chosen to capture a range of alternatives from nonadaptive ("No change") to highly adaptive ("Attain P_{MAX}") and to consider a more conservative alternative ("$P_{MAX} = 0.8$"). The "With phase" option avoids making large changes to SPR (and hence catches) when a stock is believed to be close to the target level and would be expected to reduce the number of times there is a need to redefine the Rebuilding Plan.

Performance measures

There are many statistics that could be used to summarize the performance of a management strategy. This study focuses on five principal management goals: (a) a high probability of the stock recovering by the T_{MAX} selected when the Rebuilding Plan was originally developed, (b) high catches during rebuilding, (c) low interannual variation in catches, (d) stability in the Rebuilding Plan (i.e., minimizing changes to the value of T_{MAX}), and (e) simplicity. The first three of these five goals are typical of those commonly selected when conducting an MSE. The fourth goal is included because it measures the "administrative cost" of a management strategy; changing the SPR used to set the harvest guideline and changing harvest guidelines themselves is relatively straightforward administratively. In contrast, changing T_{MAX} may require an amendment to the Fishery Management Plan. The importance of the goal of simplicity cannot be overstated. It is likely that the PFMC would select a simple set of Rebuilding Revision Rules over a more complicated set even if the performance of the more complicated set was marginally better than that of the simple set, purely because of the need for the public to know how decisions are made regarding the management of overfished stocks.

The performance measures used to quantify these five goals are

1. The "rebuilding ratio," the ratio of the number of years before the stock was assessed to be rebuilt divided by the number of years that it was expected that rebuilding would take based on the

original Rebuilding Plan, i.e., if the rebuilding ratio exceeds unity then rebuilding is perceived to have taken longer than originally expected.

2. A measure of the variability of the catches (abbreviation AAV), defined as:

$$AAV = 100\frac{\sum_{y}\left|C_y - C_{y+1}\right|}{\sum_{y} C_y} \qquad (1)$$

where C_y is the catch during year y.

3. The average catch during the years when the resource was under a rebuilding plan.

4. The average catch during the first ten years of the rebuilding period.

5. The number of times it was necessary to change the value of T_{MAX}.

Note that the rebuilding ratio is based on the perception that the stock has recovered, rather than the stock having actually recovered. This is because this performance measure relates to what the decision makers would actually see. Also, the simulated use of the management strategy stops once it is perceived by the stock assessment that recovery to $0.4B_0$ has occurred. The performance measures include both short- and long-term catches because the short-term catch reflects the likely immediate impact on the fishery.

Results and discussion

Results for a single operating model and management strategy

It is illustrative to examine detailed results for a few individual simulations before attempting to interpret the values for the performance measures (which integrate performance over years and simulations). Figure 3 shows detailed results for two realizations based on the reference management strategy and the "base case" operating model. As noted above, P_{MAX} is 0.6 for the reference management strategy, and the SPR used to set harvest guidelines is increased (fishing mortality reduced) if the probability of recovery by the current T_{MAX} drops below 0.5. The length of the x-axes in the panels in Fig. 3 is defined by the number of years until the stock assessment indicates that recovery to the proxy for B_{MSY} of 0.4 B_0 has occurred.

The left panels of Fig. 3 summarize the decisions arising from the reference management strategy; the solid line indicates SPR^{curr} (the

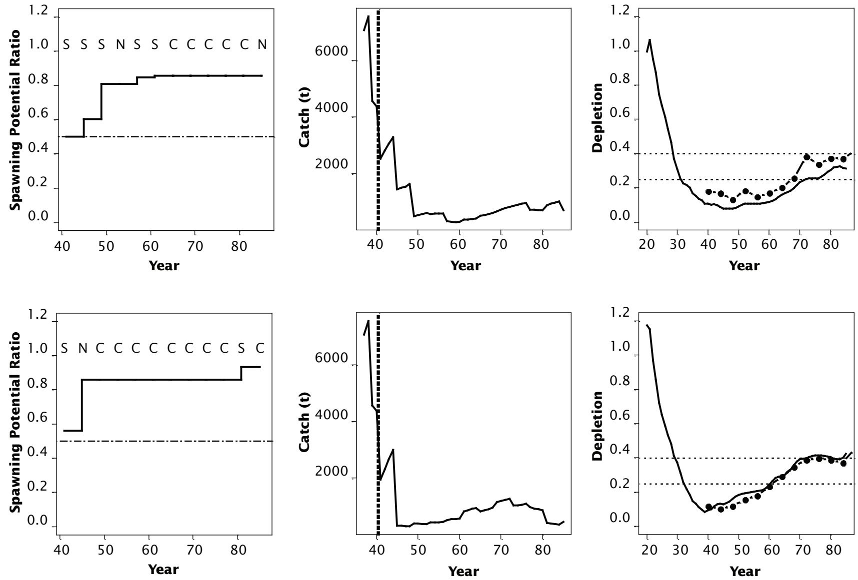

Figure 3. Results of two illustrative simulations for the reference management strategy and the "base case" operating model. The left panels summarize the decisions arising from the reference management strategy: the solid line indicates *SPR*^{curr} and dashed horizontal line is the spawning potential ratio (SPR) proxy for F_{MSY}. The letters in the upper parts of the left panels indicate whether SPR is increased ("S"), whether the SPR is unchanged from its previous value ("C"), or whether it is necessary to implement a new Rebuilding Plan ("N"). The center panels show the time-trajectories of catch. The vertical lines in these panels indicate the first year in which the management strategy is used to set the harvest guideline. The right panels show the true (solid lines) and assessment model-based estimates of depletion (solid dots) along with the thresholds that define the proxy for B_{MSY} and the minimum stock size threshold (MSST).

SPR used to determine the harvest guideline) each year (the dashed horizontal line is the SPR proxy for F_{MSY}; harvest guidelines cannot be based on a SPR lower than this) while the letters in the upper part of the panel indicate whether *SPR*^{curr} is increased so that the probability of rebuilding remains at least 0.5 ("S"), whether the SPR is unchanged from its previous value ("C"), or whether it is necessary to implement a new Rebuilding Plan (which would involve changing T_{MAX} and well as *SPR*^{curr}) ("N").

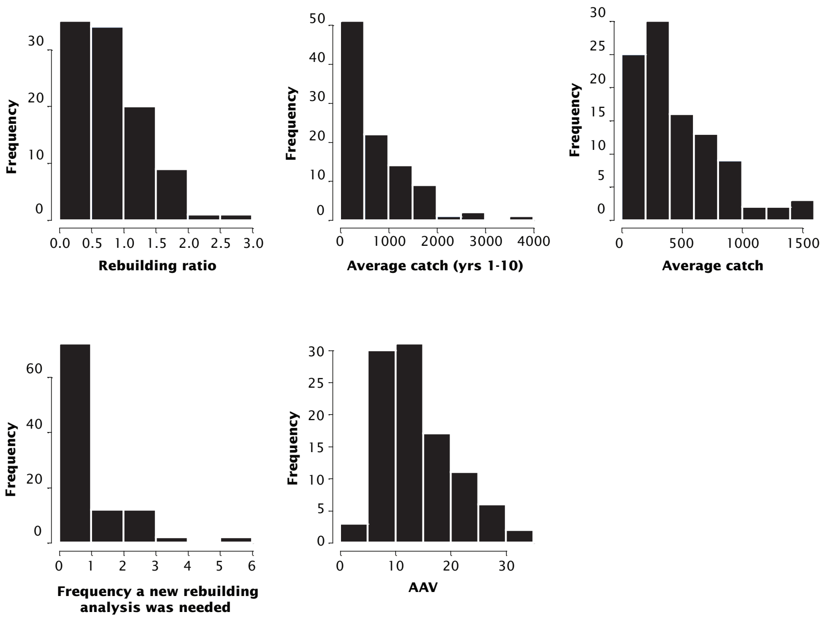

Figure 4. Summary of the five performance measures for 100 simulations for the reference management strategy and the "base case" operating model.

An ideal management strategy would lead to an "S" in year 41 (the year in which the management strategy is first applied) and "C"s for all years thereafter because this would imply that there was no need to adjust the plan during the rebuild period. In contrast to the ideal, it is frequently necessary to both revise SPR^{curr} and implement a new Rebuilding Plan. It is particularly noteworthy that new Rebuilding Plans can be required early during the rebuild period (12 and 4 years after the Rebuilding Plan is first implemented in Fig. 3) and right at the end of rebuild period (the simulation in the upper panel).

The center panels of Fig. 3 show the time-trajectories of catch. The vertical line indicates the first year in which the management strategy is used to set the harvest guideline. In both simulations, the catch is not reduced sufficiently during the first few years of the rebuild period, which is one reason for the marked reductions thereafter. Interannual catch variability, as quantified by the AAV statistic, is 14% and 15% for the two simulations in Fig. 3. The right panels in Fig. 3 show the true (solid lines) and assessment model-based estimates of depletion along with the thresholds that define the proxy for B_{MSY} ($0.4B_0$) and the minimum stock size threshold (MSST) ($0.25B_0$). The stock assessment tends to overestimate relative stock size for the simulation in the upper panel, and consequently indicates that recovery has occurred even though the true stock size is still appreciably below the $0.4B_0$.

The method used to generate future recruitments when conducting rebuilding analyses is one cause for the need to redefine a Rebuilding Plan. For example, if recent recruits-per-spawning output ratios are used as the basis for projections, the rate of recovery will tend to be overestimated because this method assumes that there is no change in the distribution of recruits-per-spawning output ratios as the stock recovers. However, if the recruits-per-spawning output ratios are based on a period when the stock is low (and density-dependence is high), the central tendency of the distribution of recruits-per-spawning output ratios would be expected to drop over time.

Figure 4 summarizes the results of 100 simulations for the five performance measures for the "base case" operating model and the reference management strategy. The data in this figure were selected from a slightly larger sample because cases in which the stock was incorrectly assessed not to be overfished at the start of year 41 were excluded. In general, the stock assessment indicates that recovery occurs regularly before the initial T_{MAX} selected (62 of the 100 simulations have a rebuilding ratio of 1 or less), although there are cases in which recovery occurs well after that. Given that P_{MAX} is 0.6 for the reference management strategy, it would be expected that recovery should occur before T_{MAX} more often than not. Note also that the range for the average catch over years 1-10 is much wider than that of the average catch over the entire rebuild period, primarily because the feedback nature of the management strategy corrects for large initial catches by lowering catches as the stock assessment detects that recovery is proceeding too slowly. The interannual variation in catches ranges between 5 and 30% per annum. There is no need to replace the Rebuilding Plan in 33 of the 100 simulations, but the incidence of simulations wherein two or more revisions are required is not small.

Implications of different management strategies

Figure 5 summarizes the results of the six management strategies (the reference strategy and the five alternatives) in terms of plots of the rebuilding ratio versus the average catch, the number of times the Rebuilding Plan is redefined versus the average catch, and the AAV versus the average catch. The results in Fig. 5 are based on 20 simulations using the "base case" operating model.

The results for the reference management strategy are essentially identical to those for the "With phase" strategy, suggesting that the impact of not modifying the Rebuilding Plan at the end of the rebuild period has little adverse effect on the performance measures, but little

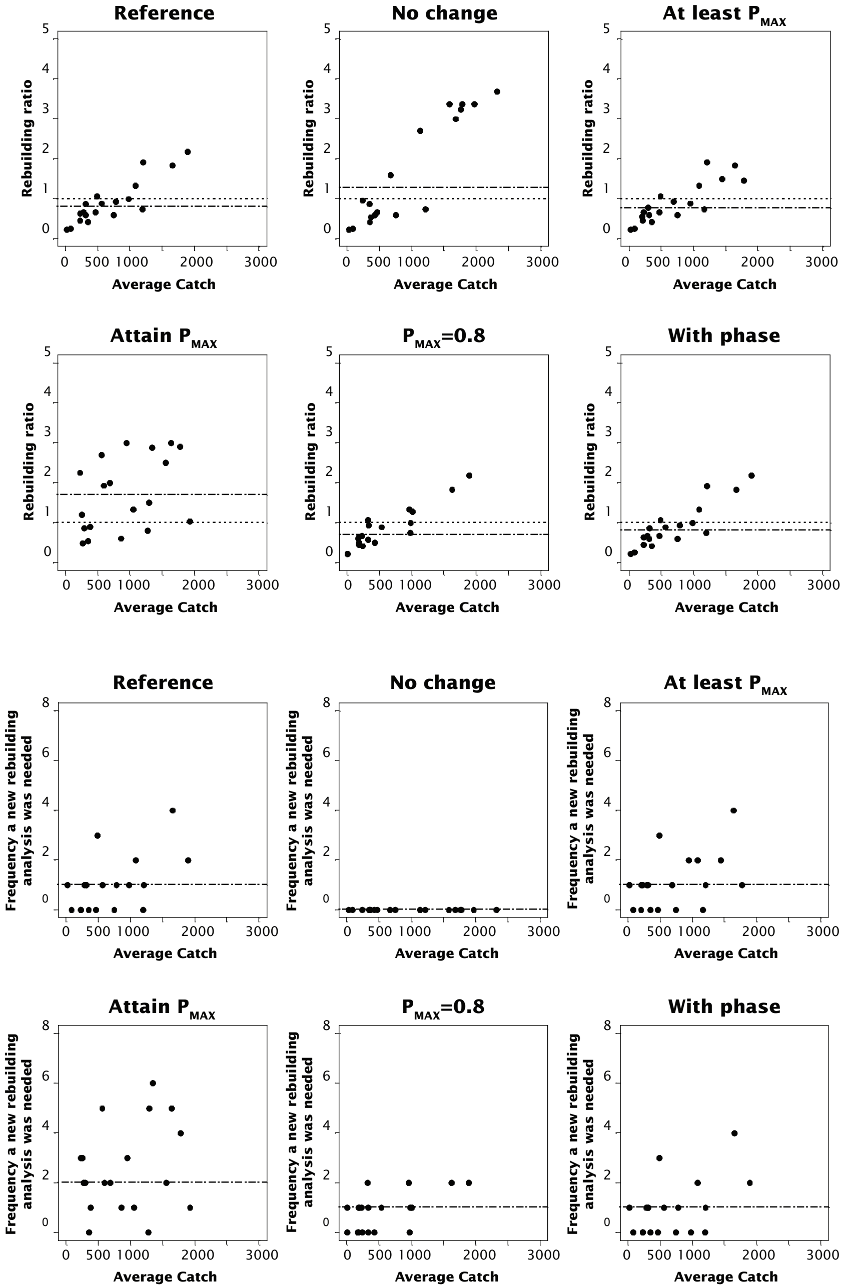

Figure 5. Performance measures (see text for details) for six management strategies for the "base case" operating model. The horizontal dashed line in each panel indicates the median of the performance measure represented on the y-axis.

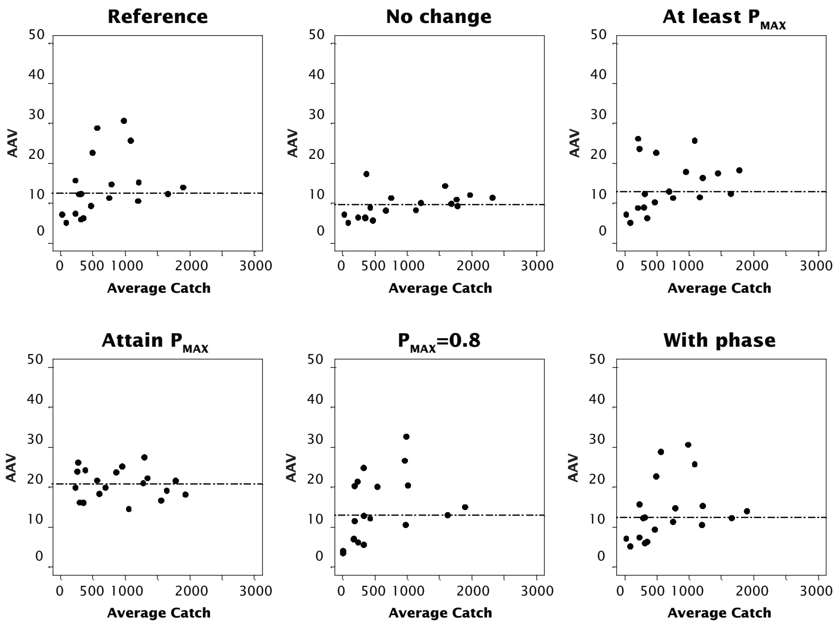

Figure 5. (Continued.)

beneficial effect either. The "No change" strategy, wherein the initial SPR selected when the stock was declared overfished is maintained, leads to much longer times to recovery in some instances. One consequence of not updating SPR^{curr} every fourth year is a lesser chance of high interannual variation in catches and a higher probability of larger average catches during the rebuild period.

The "At least P_{MAX}" management strategy leads to slightly shorter recovery times, but consequently to a slightly higher chance of needing to redefine T_{MAX} during the rebuild period. There is an obvious (and expected) relationship between the rebuilding ratio and the average catch in Fig. 5, except for the "Attain P_{MAX}" strategy because this strategy increases fishing mortality when progress is faster than anticipated and vice versa. Apart from longer times to recover, the "Attain P_{MAX}" management strategy also leads to frequent redefinitions of Rebuilding Plans and to increased interannual variation in catches (see Fig. 6, which shows detailed results for the simulations illustrated in Fig. 5). One reason for the latter result is that this strategy permits a decrease in SPR^{curr} if progress is faster than expected, unlike the reference strategy. Increasing P_{MAX} from 0.6 to 0.8 increases the buffer between P_{MAX} and $P_{critical}$. Consequently, not only are rebuilding times shorter for $P_{MAX} = 0.8$,

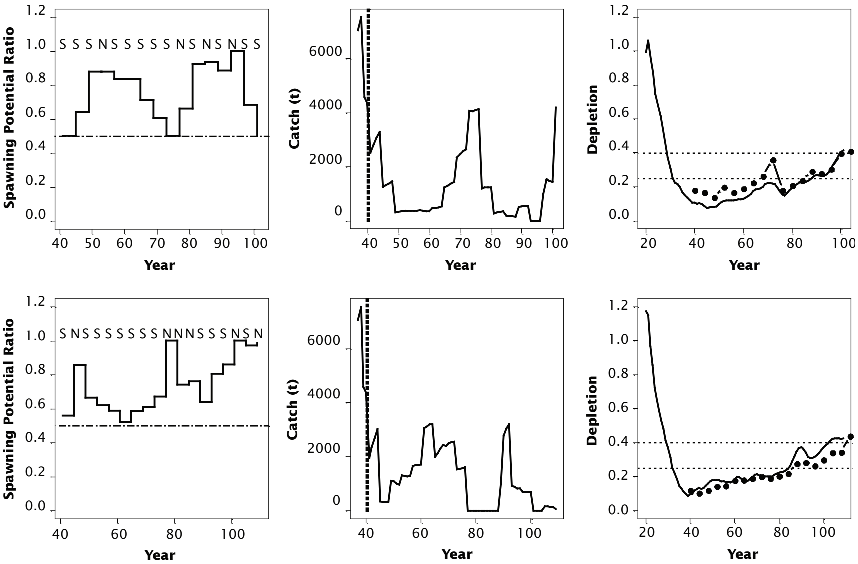

Figure 6. Results of two illustrative simulations for the "Attain P_{MAX}" management strategy and the "base case" operating model. The left panels summarize the decisions arising from the management strategy: the solid line indicates SPR^{curr} and dashed horizontal line is the spawning potential ratio (SPR) proxy for F_{MSY}. The letters in the upper parts of the left panels indicate whether SPR is increased ("S"), whether the SPR is unchanged from its previous value ("C"), or whether it is necessary to implement a new Rebuilding Plan ("N"). The center panels show the time-trajectories of catch. The vertical lines in these panels indicate the first year in which the management strategy is used to set the harvest guideline. The right panels show the true (solid lines) and assessment model-based estimates of depletion (solid dots) along with the thresholds that define the proxy for B_{MSY} and the MSST.

but there is also a lower likelihood of needing to redefine T_{MAX}, which are both desirable features from a conservation perspective.

In summary then, the "No change" and "Attain P_{MAX}" management strategies lead to the highest average catches, but also to the longest recovery times and, for "Attain P_{MAX}," to frequent redefinitions of the Rebuilding Plan. In contrast, the "$P_{MAX} = 0.8$" management strategy leads to the lowest average catches, the shortest rebuilding times, and the lowest probability of needing to redefine the Rebuilding Plan.

Implications of changes to the operating model

Figure 7 summarizes the results of the reference management strategy for the six alternative operating models outlined in Table 2. Results are presented using the same format as Fig. 5. The patterns in Fig. 7 are quite similar to those in Fig. 5, although there are some noteworthy differences. For example, average catches are higher and the rebuilding ratio lower if the stock is initially less depleted or if steepness is higher than in the "base case." Neither of these findings is unexpected. Somewhat surprisingly perhaps, the rebuilding ratio is not much higher when recruitment is temporally autocorrelated. This is probably because the reference management strategy makes more frequent changes to the Rebuilding Plan in this case, i.e., its feedback nature allows the reference management strategy to correct for sequences of poorer-than-average recruitment by decreasing the SPR used to determine the harvest guidelines. Also, interannual variation in catch is increased if recruitment variation is increased, but there is relatively little impact on the rebuilding ratio and the frequency of the need to construct a new rebuilding plan.

Conclusions

The results of the simulations of this paper only consider a limited set of possible Rebuilding Revision Rules and a narrow range of operating models. However, it is possible to draw some general conclusions from our findings that are likely to be robust to a broader set of Rebuilding Revision Rules and operating models.

- There is clearly a need for Rebuilding Revision Rules; the "No change" management strategy, which fixes the SPR equal to that when the stock was declared overfished, leads to occasional very long rebuilding times compared to those expected when the stock was declared overfished.
- It should be expected that there will be both frequent revisions to the SPR and occasionally to T_{MAX}.
- The management strategies considered in this paper tend to allow recovery to occur before T_{MAX}; the extent to which this occurs depends on P_{MAX}.

The PFMC has not adopted any set of Rebuilding Revision Rules. However, past practice is most similar to the "Attain P_{MAX}" management strategy. Unfortunately, this management strategy leads to high interannual variation in catches and frequent changes to the Rebuilding Plan (e.g., Fig. 6). This management strategy adjusts the SPR every time new data become available and is very susceptible to following noise rather than signal. For these reasons we recommend that this particular strategy be given less consideration when alternative policies are evaluated.

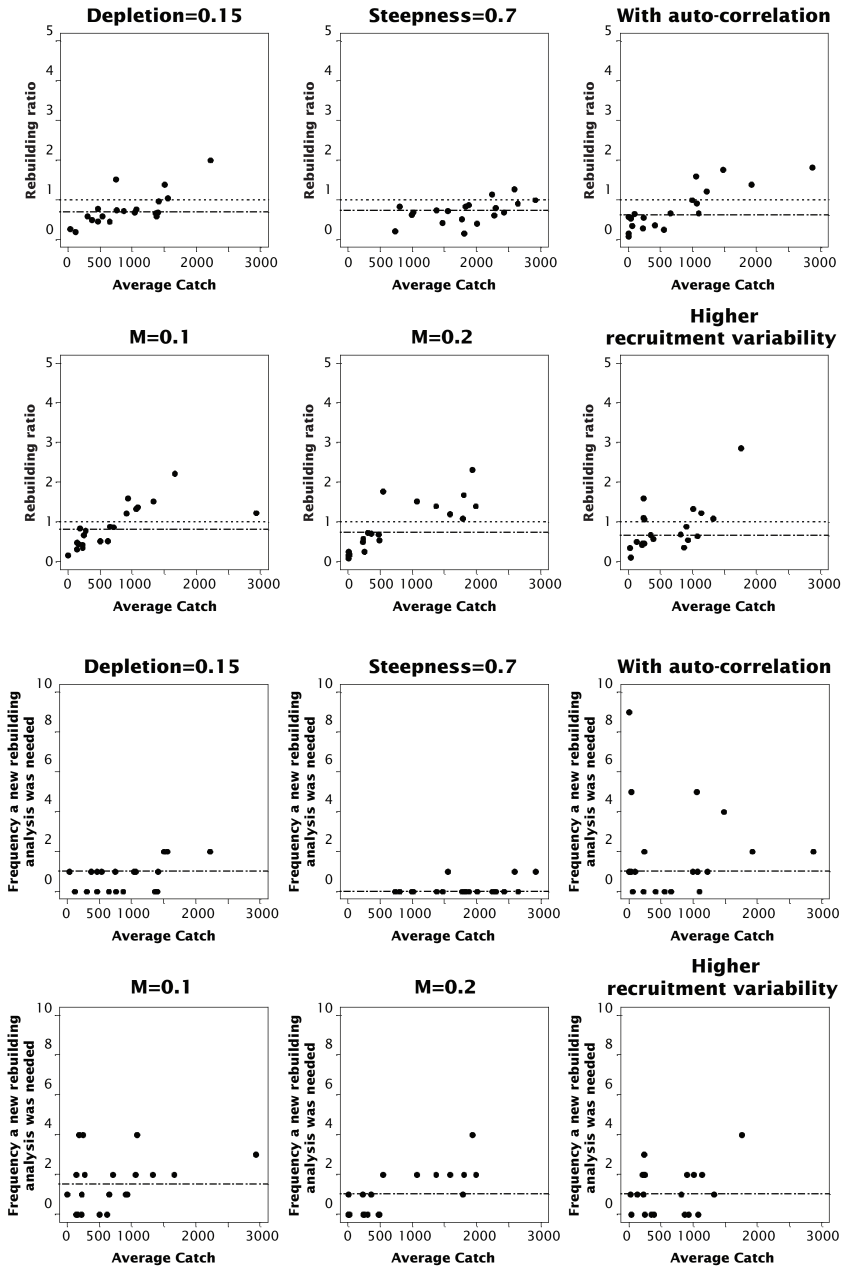

Figure 7. Performance measures (see text for details) for the reference management strategy for six alternative operating models. The horizontal dashed line in each panel indicates the median of the performance measure represented on the y-axis.

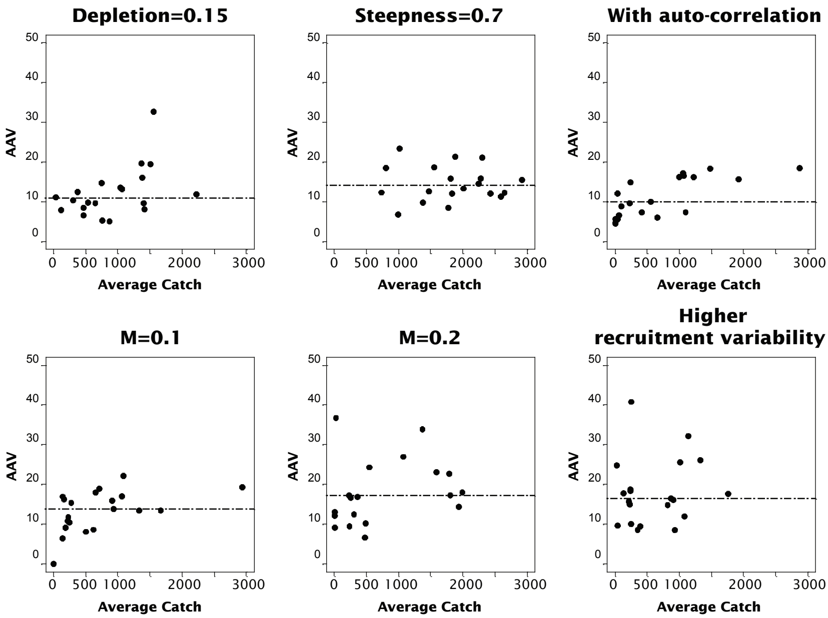

Figure 7. (Continued.)

The analyses of this paper only consider a subset of the possible sources of uncertainty. In particular, the only reasons for failing to recover with the intended probability relate to unforeseeable events such as a random occurrence of a string of poor recruitments and changes in assessment results due to additional data. There are several other reasons why failure to recover with the intended probability could occur, such as catches exceeding harvest guidelines and low-frequency changes in ocean productivity. Future analyses along the lines developed in this paper could explore the consequences of such effects.

The analyses of this paper are based on changes to assessments owing primarily to the acquisition of new data. However, there are other, more philosophical, reasons why the results of assessments may change over time. For example, the assessment scientists who conduct the assessments and rebuilding analyses for overfished species are apt to change over time. Different assessment authors have different backgrounds and attitudes to modeling; for example, whether all possible, or just the best, data sources should be included in an assessment. Thus, it may be that one assessment scientist will use commercial catch rate data in an assessment, but the next would not. Such decisions could strongly impact estimates of stock status and productivity. Similarly, there are philosophical differences among assessment scientists in how uncertainty should be quantified. For example, Punt et al. (2003) conducted rebuilding analyses for Pacific ocean perch starting from the best estimates of current stock size and taking account of uncertainty through a Bayesian posterior. Notably, they found major differences in the resulting harvest guidelines.

The analyses of this paper assume that assessment methods and P_{MAX} do not change over time, primarily because of computational constraints. In contrast, it seems likely that rebuilding analyses will eventually be based on the results of fitted stock-recruitment relationships rather than by sampling recruitments or recruits-per-spawner ratios (this approach is already being used for some stocks). Also, P_{MAX} for overfished species may increase with time as management moves to a more ecosystem-orientated approach to management.

Finally, the analyses of this paper focus only on management strategies during the rebuilding period and do not consider the implications of what happens after rebuilding is perceived to have occurred. Future MSE analyses need to consider not just rebuilding considerations, but the entire harvest policy and management system.

Acknowledgments

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