Agenda Item C.6.a
Attachment 3
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Evaluating Rebuilding Revision Rules for Assessing Progress Towards Rebuilding of OverFished West Coast groundfish

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1. Introduction

Eight west coast groundfish stocks have been declared overfished and rebuilding plans have been implemented to restore them to levels that can support productive, sustainable fisheries. These stocks are: bocaccio (*Sebastes paucispinis*), cowcod (*S. levis*), canary rockfish (*S. pinniger*), darkblotched rockfish (*S. crameri*), Pacific ocean perch (*S. alutus*), widow rockfish (*S. entomelas*), yelloweye rockfish (*S. ruberrimus*) and lingcod (*Ophiodon elongatus*)[4].

The Pacific Fishery Management Council (PFMC) adopted rebuilding plans for these species in 2004 in the form of Amendments 16-2 and 16-3 to the groundfish FMP, which were approved by NMFS. All these stocks are currently being managed under very restrictive harvest guidelines that have severely constrained the entire west coast groundfish fishery. Moreover, each of these eight stocks will be re-assessed during 2005 and, as a consequence, there will be an opportunity to determine whether or not they have responded to recovery efforts and are on track to rebuild as previously projected.

In developing the rebuilding plans, rebuilding analyses were conducted that were designed to meet the requirements of the NOAA Fisheries National Standard 1 (NS1) guidelines for implementing the 1996 Sustainable Fisheries Act. Specifically, these analyses determined the relationship between a rebuilding fishing mortality rate (F) and the probability (P_0) that a stock would recover to the spawning output capable supporting Maximum Sustainable Yield (SB_{MSY}) within the maximum time allowable (T_{MAX}). Under the NS1 Guidelines, for stocks that cannot rebuild within 10 years, T_{MAX} has been defined to be equal to T_{MIN} plus one mean generation time, where T_{MIN} is the minimum amount of time a stock needs to rebuild (i.e. if fishing mortality were reduced to zero). Moreover, the Council adopted a value of $SB_{40\%}$, equal to 40% of the spawning output that would be expected to occur if there were no fishing, as a proxy for SB_{MSY} based upon Amendment 11 to the groundfish FMP.

It is to be expected that the results of the 2005 groundfish assessments will not conform exactly with the results expected based on the previous assessments (e.g. due to recruitment not being equal to that expected, the consequences of changes to parameter values, and the impact of new data). The question that arises then is whether the fishing mortality rate used to set harvest guidelines specified as part of the 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

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[4] A ninth stock, Pacific whiting (*Merluccius productus*), also declined into an overfished state, then quickly recovered

steepness have changed markedly). Although guidelines exist regarding how rebuilding analyses are to be conducted (PFMC, 2001), there no guidelines to determine whether (and to what extent) rebuilding plans are to be updated given new information.

The objectives of this document are to outline: a) a set of possible "rebuilding revision rules" which could be used to measure progress towards rebuilding (and make appropriate adjustments to rebuilding plans as needed), and b) a framework (often referred to as Management Strategy Evaluation or MSE – Smith (1994)) which uses simulation to provide a quantitative means to compare various rebuilding revision rules in terms of their effectiveness at correctly (and adequately) making adjustments to rebuilding plans. The focus of this work is on the consequences of changes to assessments caused by the addition of new data; it being taken for granted that major changes to the assessment (e.g. a change to the stock structure assumption underlying the assessment) will lead to the need for revision to the rebuilding plan.

2. Methods

2.1 Measures of fishing mortality

For ease of comparison among stocks, and to standardize the basis of rebuilding calculations, it is useful to express any specific fishing mortality rate in terms of its effect on Spawning Potential Ratio (SPR = spawning output-per-recruit relative to that in an unfished state), as is being done for the stock assessments to be conducted during 2005. Given fishery selectivity patterns and basic life history parameters, there is a direct inverse relationship between F and SPR. When there is no fishing, each new female recruit is expected to achieve 100% of its spawning potential. As fishing intensity increases, expected lifetime reproduction declines due to this added source of mortality. Conversion of F into the equivalent SPR has the benefit of standardizing for differences in growth, maturity, fecundity, natural mortality, and fishery selectivity patterns.

2.1 The Simulation Protocol

The performances of the various rebuilding revision rules are evaluated by means of simulation. The basic situation being modeled is outlined in Figure 1. A resource is declared overfished based on the results of a stock assessment. As a result, there is a need to develop a Rebuilding Plan based on the results of the assessment[5] and input from the Council (the latter in the form of a value for P_0, the probability of rebuilding to 0.4 SB_0 by T_{MAX}), which, if P_0 is greater than 0.5, is equivalent to choosing a target year to rebuild that is sooner than T_{MAX}.

The stock assessment is updated / revised at some time in the future to include new information. The results of this updated assessment form the input to rules that determine whether progress is adequate. The possible outcomes from these rules are: a) progress is adequate so the harvest guidelines for the forthcoming years can be set based on the SPR in the latest version of the rebuilding plan (it is possible that the SPR was revised between when the rebuilding plan was originally developed and when the current assessment is being undertaken), and b) progress is inadequate. If progress is inadequate, it may be possible to still achieve rebuilding by T_{MAX} with probability of at least 0.5 by adjusting the SPR upwards (F downwards). As stated earlier, if the assessment had led to a major revision to the understanding of the dynamics of the stock, the status of the stock relative to 40% of SB_0, or the productivity of the resource, it may be necessary to revise the Rebuilding Plan completely (including, for example, changing T_{MIN} and T_{MAX}).

[5] The Rebuilding Plan developed when the stock was first declared overfished is referred to as the "original" Rebuilding Plan.

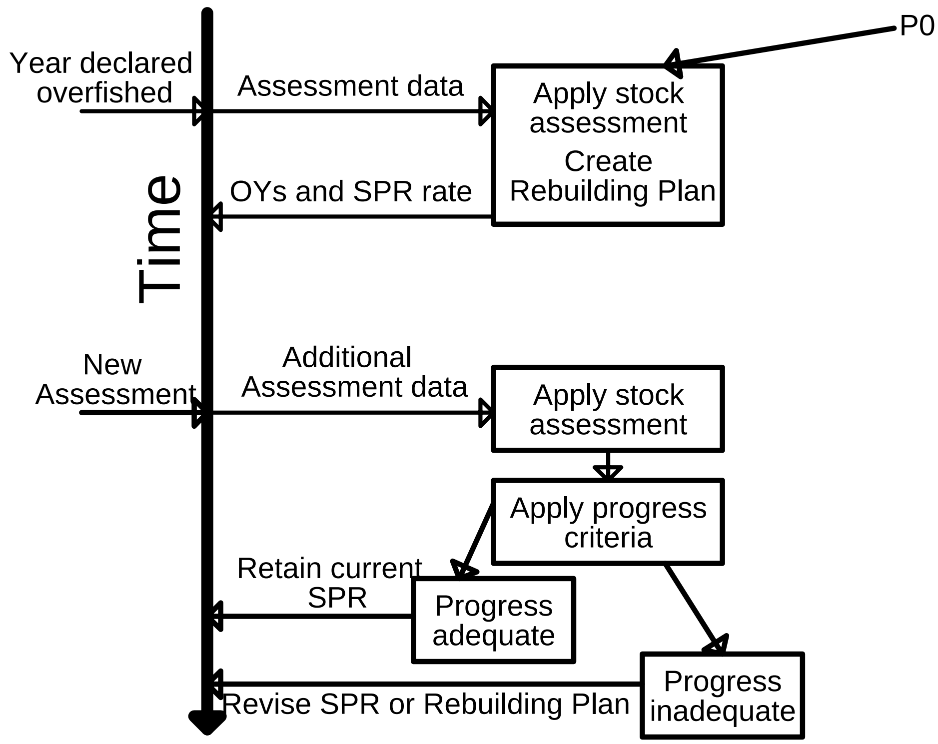


Figure 1. The conceptual basis for the simulations.

The conceptual schema in Figure 1 can be captured within a "Management Strategy Evaluation" (MSE) framework. The MSE framework considered for the analyses of this document is similar to that of Punt (2003). It consists of two components: a) an "operating model" (which mimics the "true" dynamics of the resource and generates the data available for assessment purposes) and b) a "management strategy" which includes how data are used to conduct a stock assessment, how rebuilding analyses are conducted, and the rules used to evaluate progress.

The annual steps when using the MSE approach to evaluate a management strategy are:

a. Generation of the data available for assessment purposes using the operating model.
b. Application of a method of stock assessment to the generated data to determine key assessment-related quantities (e.g. current age-structure, spawning output relative to target and limit levels, historical trends in recruitment) and any other model outputs needed to determine harvest guidelines.
c. Application of the rebuilding revision rules to determine whether it is necessary to revise the rebuilding plan, and to determine a harvest guideline.
d. Determination of the biological implications of this harvest guideline by setting the catch for the 'true' population represented in the operating model based on it. It is assumed that the catch equals the harvest guideline for the purposes of this study.

The operating model used for the analyses of this document is essentially identical to that used by Punt (2003). It includes an age- and sex-structured population dynamics model in which recruitment is governed by a Beverton-Holt stock-recruitment relationship with lognormal deviations ($\sigma_R = 0.6$), natural mortality is independent of age and equal to 0.15yr^{-1}, there is a single fishery, and selectivity is time-invariant and domed shaped. The values for the biological and technological parameters are based (somewhat loosely) on the situation for widow rockfish off the west coast of the U.S. (Williams *et al*., 2000). Figure 2 summarizes selectivity-, weightand fecundity-at-age and the catches for the years prior to when the stock is first declared overfished and the original Rebuilding Plan is developed.

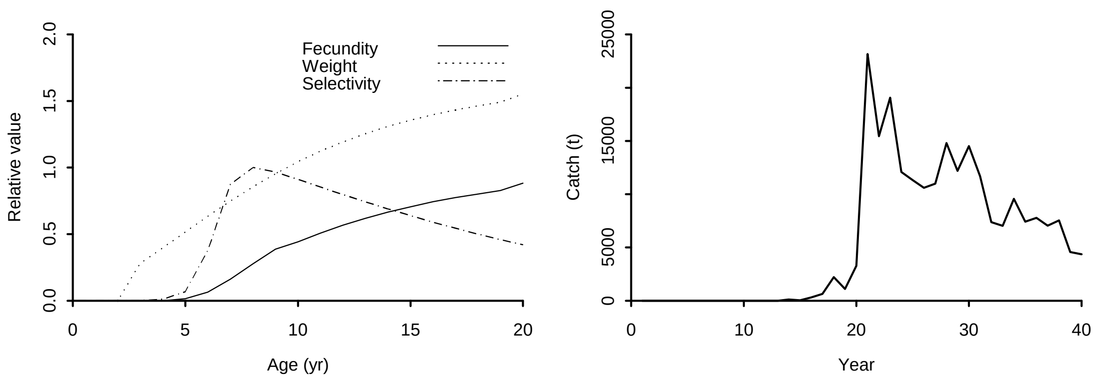


Figure 2 : The biological parameters (left panel) and catch history (right panel) in the operating model.

The data available for assessment purposes are the catches and weight- and fecundity-at-age (assumed known exactly), natural mortality (assumed known exactly for the bulk of the analyses), catch-rate-based indices of abundance, survey indices of abundance, catch age-composition data, and survey age-composition data. The surveys are assumed to be available tri-annually from year 13 (survey CV = 0.5; effective sample size for survey age-composition data = 100) while the catch-rate indices and the catch age-composition data are assumed to be available for all years for which the catch is non-zero. The coefficient of variation for the catch-rate indices is set to 0.4 and the effective sample size for the catch age-composition data is set to 100. These specifications correspond to a “data rich” stock.

Table 1 summarizes the six scenarios related to the values for the parameters of the operating model. These scenarios are based on specifying the depletion when the Rebuilding Plan is first developed (year 41 – either 0.1 SB_0, 0.15 SB_0 or 0.2 SB_0), the steepness of the stock-recruitment relationship (h=0.4 or h=0.7), whether recruitment is auto-correlated or not, and the value of M on which stock assessments prior to year 70 are based.

The harvest guideline is not updated every year in the simulations of this document, but rather every 4th year. This reflects a realistic frequency with which regular assessments for West Coast groundfish species are likely to be conducted. The frequency with which assessments are updated is another factor that could be considered within the framework of an MSE. Each simulation trial (i.e. each combination of an operating model variant and candidate management strategy) involves 10 simulations of an 80-year management period.

2.2 The stock assessment

The method of stock assessment is a statistical catch-at-age analysis (e.g. Fournier and Archibald (1982)). The underlying population dynamics model is essentially identical to the biological component of the operating model. The estimable parameters of the stock assessment model are the annual recruitments, and the parameters of the selectivity function. The values for these parameters 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.

2.3 The Rebuilding Revision Rules

Several sets of rules ("options") have been identified based on the intent of a rebuilding plan, as outlined in Section 1. All of the options are based on a value for P_0 (the target probability of rebuilding by $T_{\max}$). Furthermore, it is assumed that a formal stock assessment (see Section 2.2) is conducted every fourth year and forms the basis for the application of the rules. The outcomes from the stock assessment are: a) an estimate of the ratio of the spawning output at the start of year *n*+1 divided by the pre-fishery spawning output, SB_{n+1}/SB_0, where *n* is the last year for which catch data are available, and estimates of the spawning output and recruitment time-series. For the purposes of this document, the estimate of SB_{n+1}/SB_0 forms the basis for the harvest guidelines for year *n*+1 and beyond. In reality, there is a longer time lag between the last year for which data are available and the first year in which the harvest guideline would be changed.

It is assumed that a rebuilding plan was developed in year 41 which led to values for P_0, T_{MAX}, T_{MIN}, and the target SPR (denoted T_{MAX} (current), T_{MIN} (current) and $SPR_{current}$) on which harvest guidelines were based. For the purposes of the analyses of this document, T_{MAX} is defined as T_{MIN} + one mean generation time irrespective of whether T_{MIN} is estimated to be less than ten years or not.

The rebuilding revision rules in Table 2 are variants of a "reference" rebuilding revision rule. The reference rule attempts to capture the idea that performance is adequate as long as the probability of rebuilding to T_{MAX} remains above 0.5 and that there is a need to revise the entire rebuilding plan if there is no SPR for which the probability of rebuilding to T_{MAX} is at least 0.5. The value of P_0 is 0.6 for the "reference" rule. The rule operates as follows (the algorithm is based on an update to the stock assessment in year *n*+*v*).

a. If $SB_{n+v}/SB_0 > 0.4$, the resource has rebuilt so rebuilding is completed[6].
b. Project the population from year *n*+*v* until T_{MAX}(current) using $SPR_{current}$ to determine future harvest guidelines and to compute the probability, P_{rec}, that the spawning output will rebuild to $0.4SB_0$ at least once by T_{MAX}(current).
c. If P_{rec} is larger than a critical value, $P_{critical}$, progress is considered to be adequate and the harvest guidelines for the next four years are based on $SPR_{current}$. The value of $P_{critical}$ will always lie between 0.5 and P_0.
d. If P_{rec} is less than $P_{critical}$, progress is inadequate and some measures need to be taken to reduce fishing mortality to improve the chances of achieving the recovery objective. The following represents the specific rules considered in the "reference" rule:
    1. Determine the SPR so that the probability of rebuilding to $0.4SB_0$ from the current state of the stock by T_{MAX}(current) is $P_{critical}$ (this SPR is denoted SPR_1).
    2. If $SPR_1 < 1$ then set $SPR_{current}$ to SPR_1 and base the harvest guidelines for the next four years on SPR_1.
    3. If there is no SPR so that the probability of recovery to $0.4SB_0$ from the current state of the stock by T_{MAX}(current) is at least $P_{critical}$, a new rebuilding plan is needed. This involves redefining T_{MIN} and T_{MAX} and hence $SPR_{current}$ based on starting the new rebuilding plan from the stock size in year *n*+*v* with a probability of rebuilding by the revised T_{MAX} of P_0. If the new $SPR_{current}$ is less than the previous one (so that the fishing mortality would be higher), $SPR_{current}$ is left unchanged.

[6] Note that because this appraisal is based on the results of a stock assessment, the "true" resource may or may not have rebuilt to $0.4SB_0$.

The seven options (Table 2) are constructed from the “reference” rule as follows:

1. “No change”. This option involves not revising the rebuilding plan but rather sticking with the SPR set when the original rebuilding analysis was conducted. While not necessarily a viable rebuilding revision rule, it sets a standard against which the other options can be compared.
2. “At least P_0”. This option involves setting $P_{critical}$ equal to P_0, i.e. the SPR on which future harvest guidelines are based is increased if the probability of rebuilding drops below P_0 (rather than 0.5).
3. “Attain P_0”. This option involves adjusting the SPR every time a new assessment is conducted so that the probability of rebuilding is always estimated to be P_0. This option differs from the “At least P_0” option because the SPR can be decreased if the probability of rebuilding exceeds P_0 (P_{high} in Table 2)
4. “MAX-SPR-1”. This option involves determining the SPR so that the probability of rebuilding to $0.4SB_0$ by T_{MAX}(current) from the state of the stock in the year the current rebuilding plan started is P_{floor} (this SPR is denoted SPR_{floor}). SPR_{floor} is therefore the SPR which would have been set when the rebuilding plan was originally developed had the information available in year $n+v$ been available in year n). Calculate $SPR_{MAX} = SPR(P_{floor}) + \phi[1-SPR(P_{floor})]$. If $SPR_1 > SPR_{MAX}$ then recovery is highly unlikely. In this case, a new rebuilding plan is needed. Note that the “reference” option corresponds to $\phi=1$.
5. “MAX-SPR-2”. This option involves not allowing the SPR to be increased to more than $0.5+0.5\ SPR_{current}$ (i.e. halfway between $SPR_{current}$ and 1). If the probability of rebuilding corresponding to $0.5+0.5SPR_{current}$ is less than $P_{critical}$ a new rebuilding plan is needed.
6. “$P_0=0.8$”. This option is identical to the “reference” option, except that $P_0=0.8$.
7. “With phase”. This option involves not revising a rebuilding plan between years $T_{MAX}-\tau$ and T_{MAX} to avoid making large changes to SPR (and hence catches) when a stock is believed to be close to the target level.

At present, these seven options and the “reference” option are simply technical constructions. They have not been evaluated in terms of their conformance with the current NS1 Guidelines or the draft revisions circulated in 2004.

2.4 Summarizing performance

Three plots (*sensu* Figures 3, 4 and 5) have been developed to summarize the results of a set of simulations.

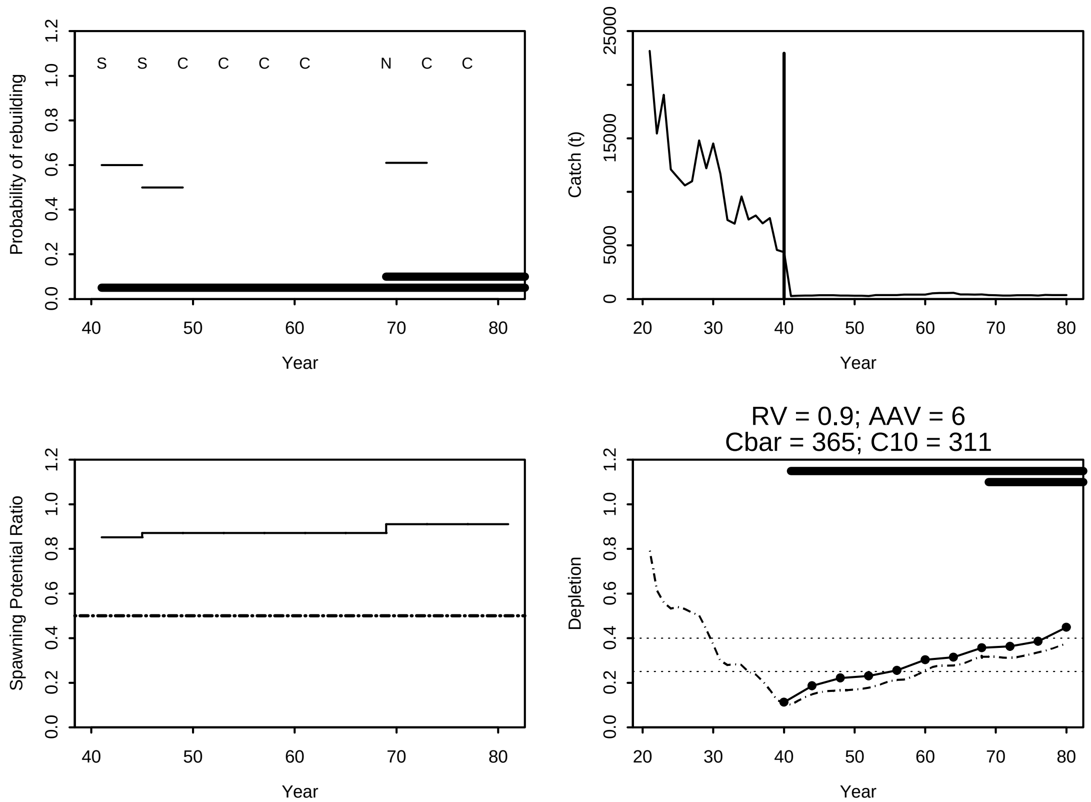


Figure 3. Plot summarizing the detailed results of a single simulation.

A 'detailed plot' (e.g. Figure 3) consists of four panels:

Upper left. The behavior of the rebuilding revision rule.

- The wide horizontal bars indicate the duration of the rebuilding plan(s). There may be multiple wide horizontal bars if the original rebuilding plan needed to be revised during the time period considered.
- The narrow horizontal lines indicate the probability of rebuilding each time it is necessary to change the SPR on which the harvest guideline is based (this will occur when the resource is first declared overfished, if it is necessary to change the SPR because the probability of rebuilding by T_{max} is less than P_{critical}, or if rebuilding is assessed to be highly unlikely and a new rebuilding plan is required). The gaps between these lines are the years when progress appears satisfactorily.
- An "S" at the top of the panel indicates that the **S**PR needed to be increased to achieve a probability of rebuilding of at least P_{critical}.
- A "N" at the top of the panel indicates that a **N**ew rebuilding plan was needed.
- A "C" at the top of the panel indicates that progress was evaluated and found to be adequate. The SPR used to set future harvest guidelines is **C**ontinued at $\text{SPR}_{\text{current}}$.

Upper right. Catches over time. The vertical line indicates when the stock was declared overfished and the first rebuilding analysis (based on P_0) was conducted.

Lower left. This panel shows the SPRs on which the annual harvest guidelines are based. The dashed line indicates the overfishing level for rockfish species of SPR=50%.

Lower right. The "true" depletion of the population over time (dot-dashed line) and the estimate of the depletion of the resource (as perceived from an assessment conducted every four years) (solid line with dots). The rebuilding revision rule is, of course, based on perceived reality. The two horizontal dotted lines are the overfishing level (0.25) and the target level (0.40). The wide horizontal bars again indicate the duration of the rebuilding plan(s).

The numbers in the title summarize various aspects of the results:

1. RV - the ratio of the number of years before the stock was assessed to have rebuilt divided by the number of years that it was expected that rebuilding would take based on the original rebuilding plan.
2. AAV - a measure of the variability of the catches, defined as:

$$AAV = \frac{\sum_y \left| C_y - C_{y+1} \right|}{\sum_y C_y} \tag{1}$$

   where C_y is the catch during year *y*.

3. Cbar - the average catch during the years when the resource was under a rebuilding plan.
4. C10 - the average catch during the first ten years of the period during which the resource was under a rebuilding plan

The x-axis in each of the panels is limited to the years that the resource is considered to be under rebuilding (i.e. the years during which the assessment indicates that the spawning biomass is less than $0.4B_0$).

A 'summary plot' (e.g. Figure 4) consists of 16 panels. The 1st and 2nd rows show the time-trajectories of SPR and the 3rd and 4th rows show the bottom right plots from a detailed plot. These plots provide the results for the eight rebuilding revision rules when they are applied to one simulation (i.e. the "true" situation as represented in the operating model is the same for all eight option).

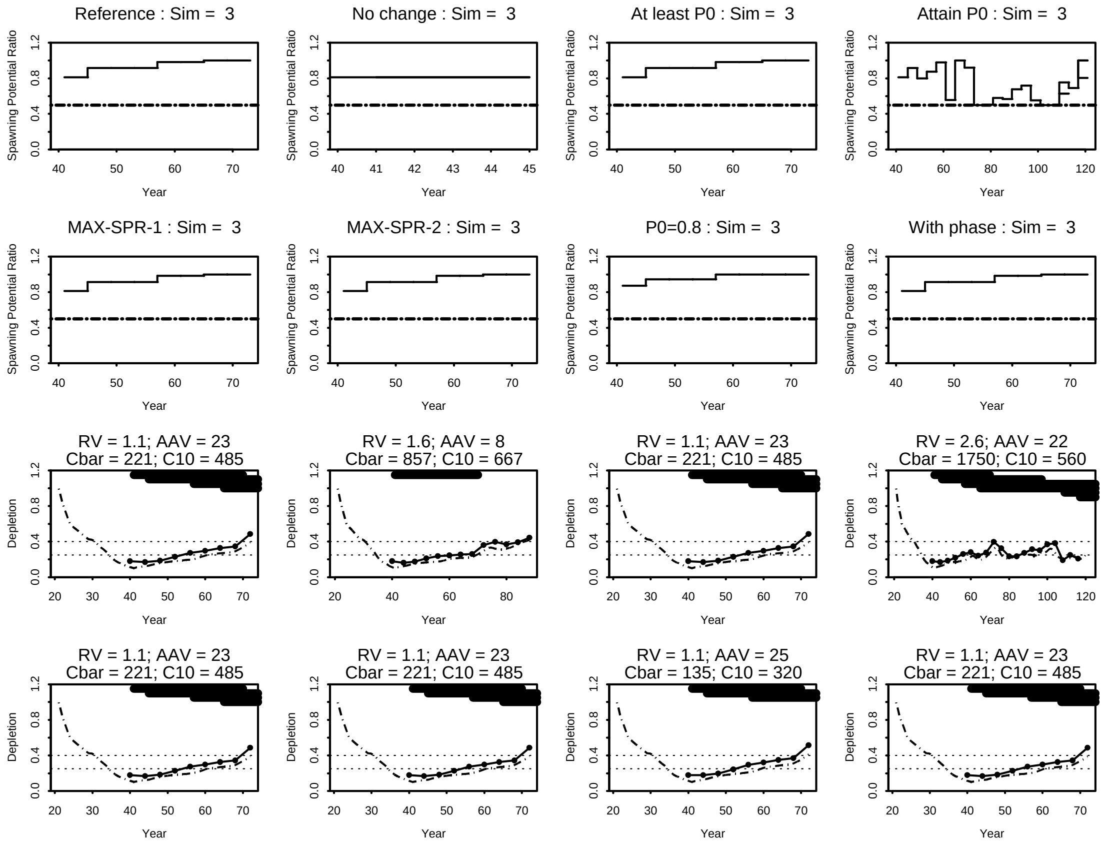


Figure 4. Summary plot for one simulation for operating model A.

The final type of plot (e.g. Figure 5) attempts to summarize the performance of the rebuilding revision rules across all the simulations in terms of three statistics:

- The average catch during the years when the resource was under a rebuilding plan.
- The ratio of the number of years before the stock was assessed to have rebuilt divided by the number of years that it was expected that rebuilding would take based on the original rebuilding plan (solid dots).
- The number of times that the SPR had to be altered during the rebuilding period (open dots; for improved clarity values larger than eight are set to eight and represented in the form of open triangles).

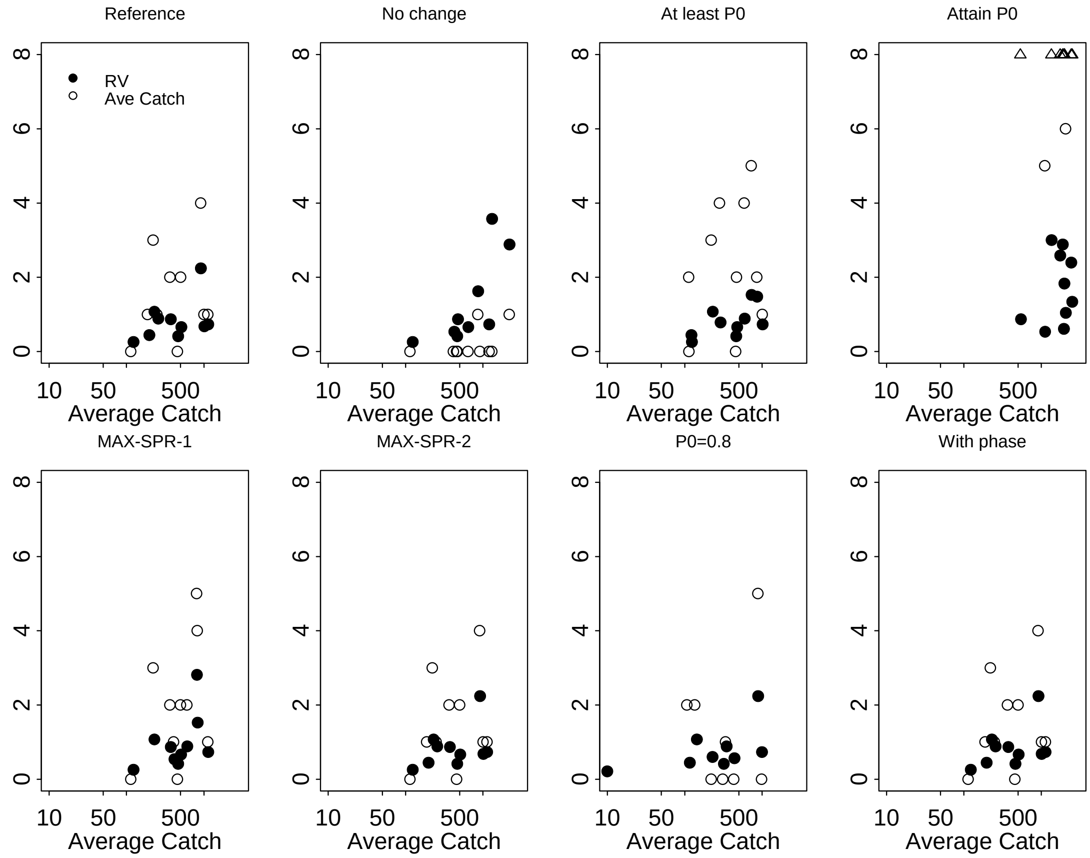


Figure 5. Comparison of the performances of the eight rebuilding revision rules for operating model A.

3. Results and discussion
3.1 Interpreting the plots
The properties of an ideal rebuilding revision rule are that: a) the spawning output rebuilds to $0.4B_0$ in as short a time as possible (the exact rate of rebuilding will depend on the productivity of the resource and the value assumed for P_0), b) catches are relatively stable (or increasing steadily) during the rebuilding period, c) the SPRs on which future harvest guidelines are based are stable, and d) the probability of needing to revise the entire rebuilding plan during the rebuilding period is low.

3.2 Results for the “base case” operating model
Figure 5 provides a summary of the overall performances of the eight rebuilding revision rules for the “base case” operating model while Figure 6 shows summary plots for two of the ten simulations for this operating model.

The “reference” option is able to recover the resource faster than anticipated when the first rebuilding analysis is conducted (the time to rebuild the resource to 0.4 SB_0 is 70% of that anticipated when the first rebuilding analysis is conducted). The median (across simulations) average catch during the rebuilding period is 365t (8.3% of the catch for the year prior to the resource being declared overfished) for this option and the median value of the AAV statistic across simulations is 10%. There is no need to change the SPR determined from the original rebuilding analysis in two of the simulations (e.g. simulation six – Figure 6a), but the number of changes in SPR can be far higher (e.g. simulation one – Figure 6b).

Not modifying the SPR no matter what the monitoring data indicate (the “no change” option) leads (as expected) to longer rebuilding times than those for the “reference” option. However, catches are higher and less variable, and recovery for the “no change” option can occasionally occur as fast as for the “reference” option (e.g. simulation 6). The “at least P_0” option leads, as expected, to shorter rebuilding times (e.g. for simulation 1), but at the expense of the need for more revisions to the SPR on which harvest guidelines are based compared to the “reference” option (Figure 5).

Modifying the SPR each time a new assessment is conducted so that there is always a perceived probability of rebuilding by T_{MAX} of P_0 (the “attain P_0” option) leads to higher average catches, but much more frequent changes to the SPR. This variability in SPR is perhaps most evident for the cases in which sticking to the original SPR would allow rebuilding by T_{MAX} (e.g. simulation 6 in Figure 6). Apart from the administrative disruption caused by changing the SPR every fourth year, the “attain P_0” option would also lead to large inter-annual variation in harvest guidelines (18% compared to 10% for the “reference” option).

The two MAX-SPR options are qualitatively similar, although the “MAX-SPR-1” option leads to more frequent changes to the SPR used to set harvest guidelines. Increasing P_0 from 0.6 to 0.8 leads to shorter rebuilding times, fewer changes to SPR values (because there is a larger “buffer” between the original probability of rebuilding of 0.8 and the “critical” value of 0.5), but lower catches (the median average catch for the “P_0=0.8” option is 85% of that for the “reference” option).

The results for “with phase” option are identical to those for the “reference” option. This result should be considered fortuitous. This would not have been the case had the idea of not changing the SPR when the resource is close to $0.4SB_0$ been combined with, say, the “attain P_0” option.

3.3 Sensitivity to alternative operating model parameters values

Figures 7 - 10 summarize the results for operating models C – G (Table 1). Results are not shown for operating model B because the resource is correctly detected to be depleted to below 0.25 SB_0 (and rebuilding initiated) in only a few simulations when the true spawning output is 20% of SB_0. This is a consequence of the structure of the assessment procedure selected (and the uncertainty associated with the data) and not of the form of the rebuilding revision rules.

The performance of all eight options is generally “better” (fewer changes in SPR, more rapid rebuild and larger average catches) if steepness is 0.7 (rather than 0.4 as is the case for the “base case” operating model) (Figure 7). The “attain P_0” option is again very variable. Unlike the case for “base case” operating model, even the “no change” option always allows rebuilding to occur when steepness is 0.7.

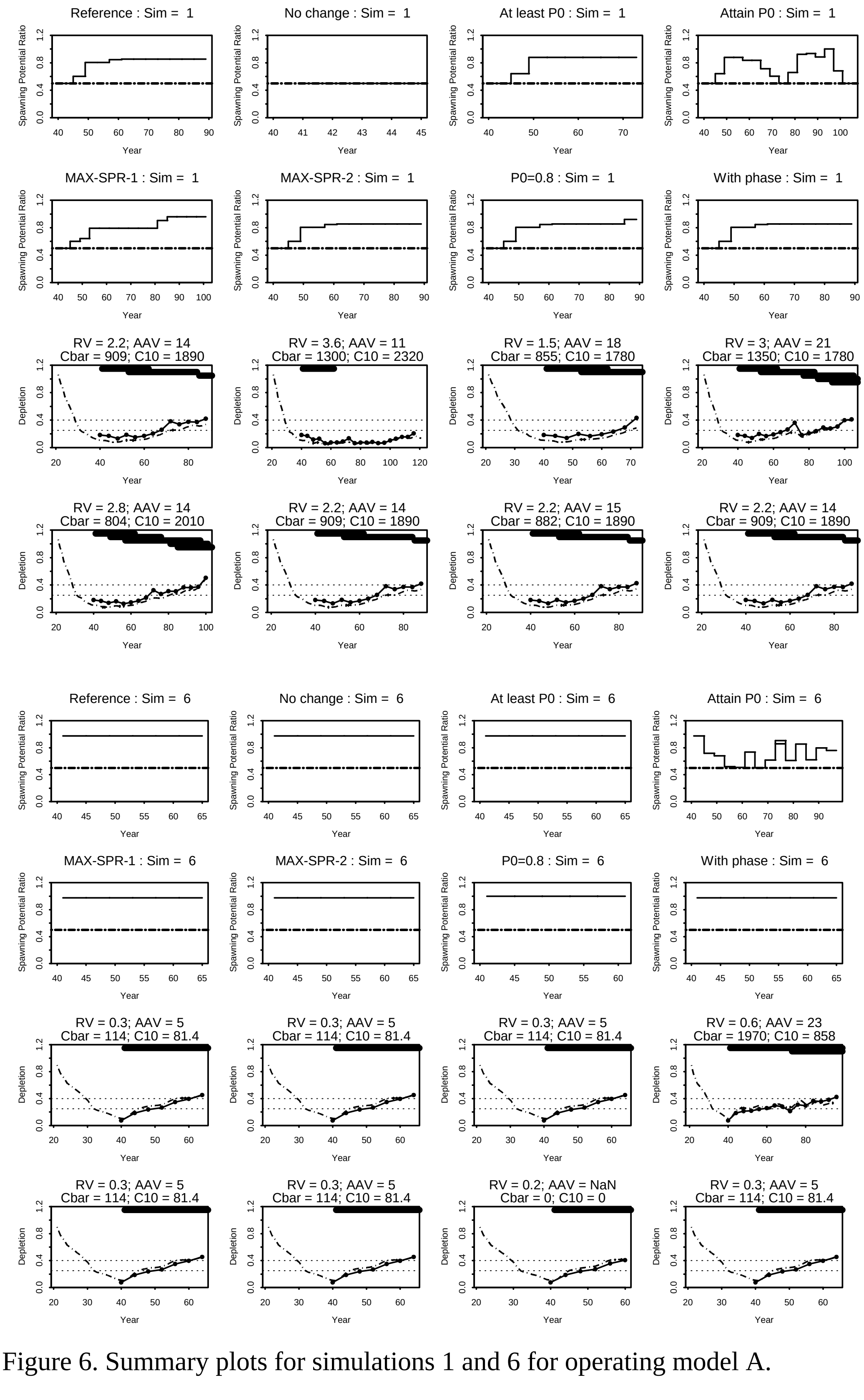


Figure 6. Summary plots for simulations 1 and 6 for operating model A.

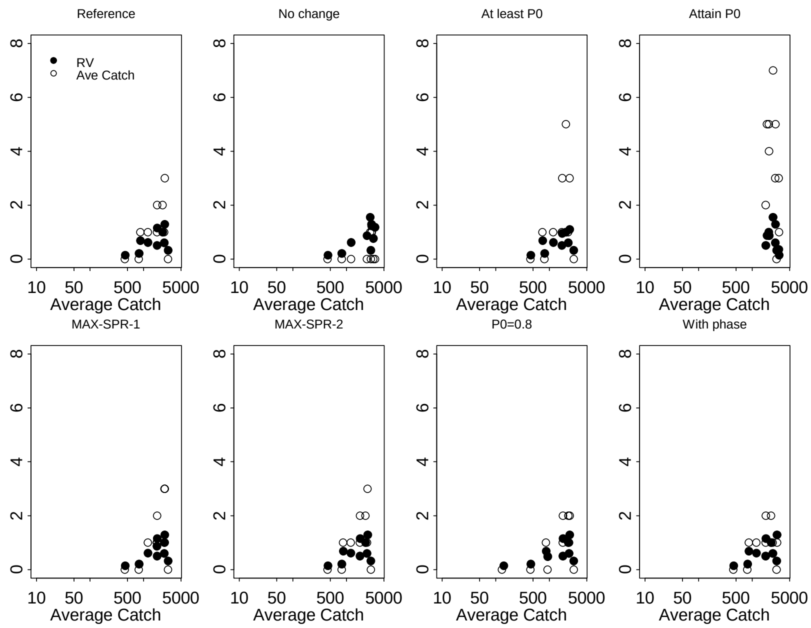


Figure 7. Comparison of the performances of the eight rebuilding revision rules for operating model C.

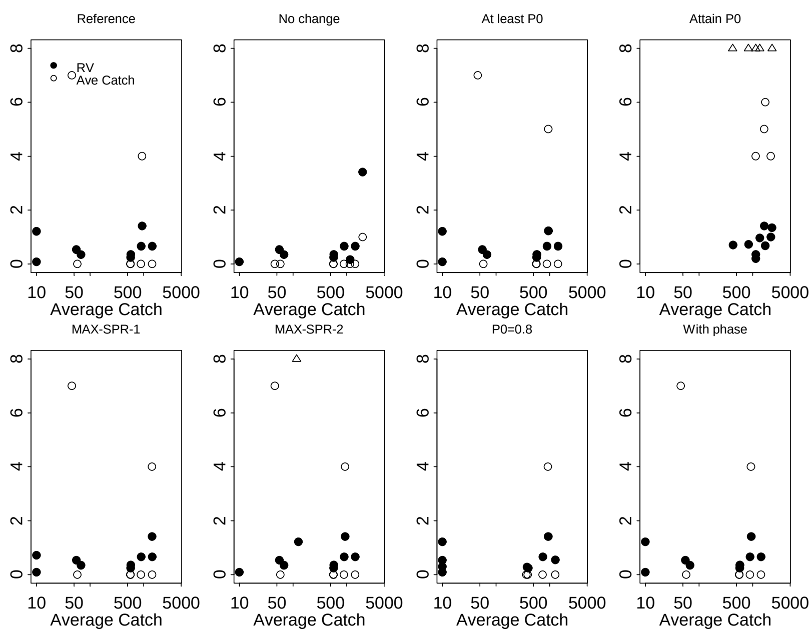


Figure 8. Comparison of the performances of the eight rebuilding revision rules for operating model D.

Allowing for temporal auto-correlation in recruitment (operating model D; Figure 8) increases the time to rebuild (compared to that expected when the original rebuilding analysis was conducted) in a sub-set of the simulations. This results in a substantial increase to the number of times the SPR needs to be adjusted in these simulations. Unfortunately, this problem affects almost all the options equally; a noteworthy exception is the "P_0=0.8" option, presumably because the "buffer" between P_0 and P_{critical} created by selecting a high P_0 increases the robustness to auto-correlation in recruitment. However, the "P_0=0.8" option leads to near zero (<10t) average catches for this operating model for several simulations.

The results for the operating models in which the value of *M* on which assessments are based is wrong during years 41-70 (operating models E and F; Figure 9), while substantially different from those for the "base case" operating model do not perhaps behave as expected. Specifically, major changes to the rebuilding plan often do not occur in year 70. This is because: a) the resource may have rebuilt by then anyway, and b) the probability of being rebuilt by T_{MAX} for $\text{SPR}_{\text{current}}$ may still be larger than P_{critical} even with the change to *M* (this is supported by the fact that the SPR was changed eight or more times in almost all simulations for the "attain P_0" option).

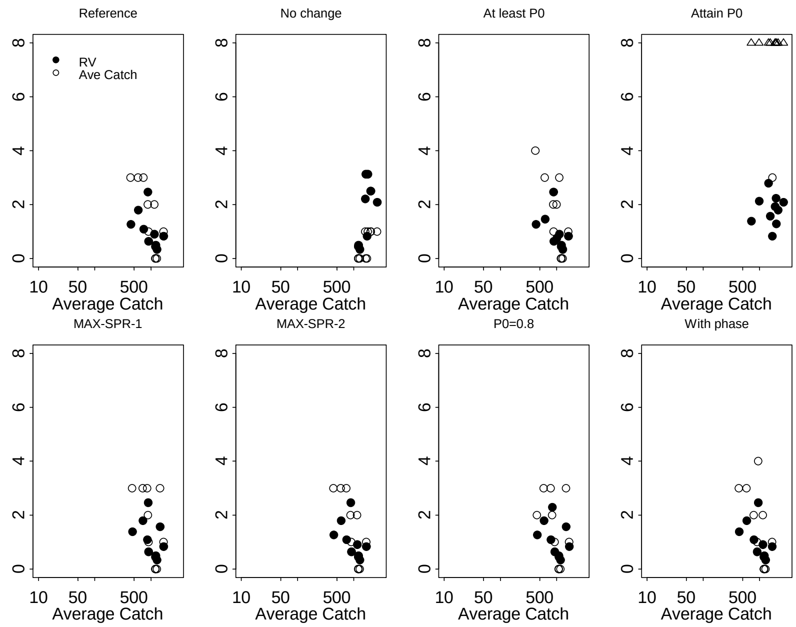
The results for the operating model in which the resource is depleted to 15% of SB_0 (Figure 10) are not noticeably different from those for the "base case" operating model.

3.4. Conclusions / observations

The selection among the options is clearly a policy decision. However, there are some factors which should be taken into account when selecting among the options:

- The structure and viability of the options depends on how NS-1 will be revised. The final wording of NS-1 (and the interpretation of the wording) is not yet final. Changes to NS-1 may preclude some of the options considered in this document.
- Results are only shown for situations in which the "true" status of the stock in year 41 is 0.15 SB_0 or less. This is primarily because the assessment procedure considered in this study was often unable to correctly detect that a stock depleted to (say) 0.2 SB_0 was actually depleted to below 0.25 SB_0. This is almost certainly a consequence of the structure of the assessment procedure selected for this work. This study also did not consider scenarios involving "false positives" (i.e. the stock is assessed to overfished when it isn't).
- The options are all variants of the "reference" option – it is possible that changes to the "reference" option may lead to the performances of the options changing in ways that cannot necessarily be predicted well from the results presented in Figures 5-10.
- Changes to SPR (and revisions to entire rebuilding plans) are likely to be frequent during the rebuilding period – such changes are needed to ensure rebuilding proceeds at a reasonable rate.

(a) M=0.1 yr^{-1} for years 41-70



(b) M=0.2 yr^{-1} for years 41-70

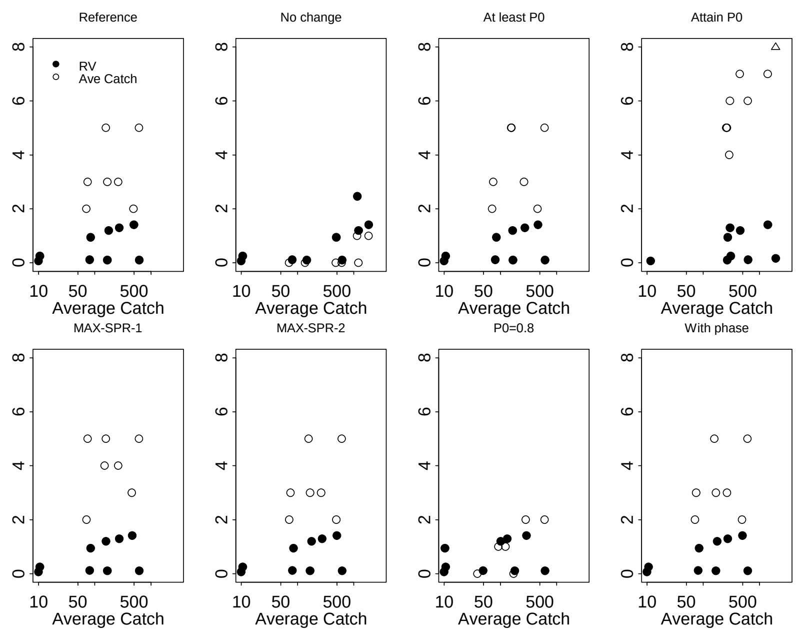


Figure 9. Comparison of the performances of the eight rebuilding revision rules for operating models E and F (upper and lower panels respectively).

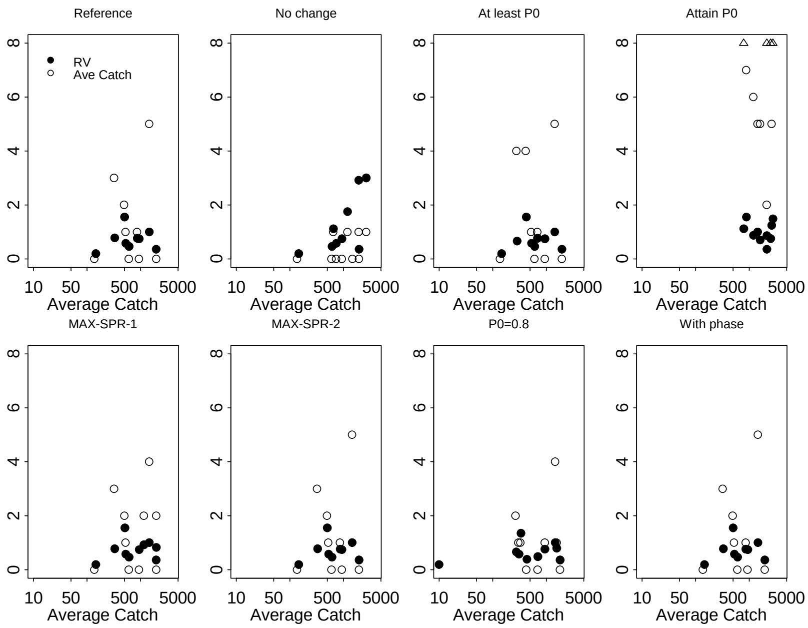


Figure 10. Comparison of the performances of the eight rebuilding revision rules for operating model G.

- The “attain P_0” option tends to follow noise rather than signal, and leads to frequent changes to SPR and hence harvest guidelines. Although average catches are larger for this option, the resource tends to be under rebuilding for longer.
- There were no notable benefits associated with the two SPR-MAX options even though these were more complicated than the “reference” option.
- Setting a “high” P_0 when developing a rebuilding plan can mitigate against uncertainty because there is then a “buffer” between P_0 and the minimum probability of rebuilding to T_{MAX} (P_{critical}=0.5).

4. References

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Table 1. The specifications that define the alternative "true" scenarios considered in the simulations.

Scenario	True biomass in year 41	Steepness	Auto-correlation in recruitment	*M* for years 1-70 used in assessments
A – Base case	0.1 SB_0	0.4	0	0.15yr^{-1}
B – Less depletion	0.2 SB_0	0.4	0	0.15yr^{-1}
C – Higher steepness	0.1 SB_0	0.7	0	0.15yr^{-1}
D – With auto-correlation	0.1 SB_0	0.4	0.707	0.15yr^{-1}
E – Low *M* in assessment	0.1 SB_0	0.4	0	0.10yr^{-1}
F – High *M* in assessment	0.1 SB_0	0.4	0	0.20yr^{-1}
G – Less depletion	0.15 SB_0	0.4	0	0.15yr^{-1}

Table 2. The specifications of the eight rebuilding revision rules.

Abbreviation	P_0	$P_{critical}$	P_{floor} / ϕ	P_{high}	Impose Max SPR	τ
0 – Reference	0.6	0.5	N/A	N/A	No	0
1 – No change	0.6	N/A	N/A	N/A	No	0
2 – At least P_0	0.6	0.6	N/A	N/A	No	0
3 – Attain P_0	0.6	0.6	N/A	0.6	No	0
4 – MAX-SPR-1	0.6	0.5	0.5 / 0.5	N/A	No	0
5 – MAX-SPR-2	0.6	0.5	N/A	N/A	Yes	0
6 – P_0=0.8	0.8	0.5	N/A	N/A	No	0
7 – With phase	0.6	0.5	N/A	N/A	No	5