EVALUATION OF THE INTERNATIONAL WHALING COMMISSION'S REVISED MANAGEMENT PROCEDURE FOR USE IN GROUNDFISH FISHERIES

by

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Abstract

Developed for the International Whaling Commission (IWC) to manage a baleen whale fishery, the Revised Management Procedure (RMP) uses catch and abundance estimates to fit a simple population model and produces a target catch consistent with an acceptable probability level. When applied to a long-lived simulated groundfish species with low productivity, the RMP performed well once the no fishing benchmark was adjusted to a value more appropriate for a population with occasional, high recruitment. When compared to a simplified 40-10 strategy, the RMP closed the fishery much less frequently with similar average catches without depleting the population. When the population began at 20% of carrying capacity (K), it allowed rebuilding without closing the fishery. The RMP appears to be robust to changes in survey variability up to a CV of 90%, positive and negative survey bias, infrequent surveys, and changes in carrying capacity.

Keywords: Revised Management Procedure; data-limited; Fish++

Executive Summary

Fisheries management in many jurisdictions requires the implementation of a precautionary approach to provide economic benefits to society while maintaining the ability of the resource to provide those benefits in perpetuity. One of the methods used to judge whether management meets the "precautionary" standard is to use management strategy evaluation (MSE) to estimate the probability of the management plan achieving the stated objectives. MSE is also used more broadly to improve management through the development and objective evaluation of alternative management strategies by groups with an interest in a resource. Using methods and performance measures developed by the group can improve acceptance of the management strategy if there is evidence that one strategy, or even type of strategy, is clearly superior over a reasonable range of scenarios. This broader form of MSE was used by the International Whaling Commission (IWC) to develop their Revised Management Procedure (RMP). A wide variety of management strategies were proposed and evaluated to try to improve whale harvest management. That situation is similar to groundfish in the limited availability of data, differs in the ability of groundfish to produce a large number of offspring given favourable conditions. I applied the output of that process, the RMP, to the management of a long-lived, low productivity species in a variety of scenarios to assess how it coped with data and biological problems. For comparison, I also built several simple alternative management procedures. To make them true competitors and compensate for their simplicity, they had direct access to information about the "true" population whereas the RMP received only abundance estimates from an observation model. These procedures included a simplified 40-10 rule that used a linear regression of the estimates from the observation

model to assess the current population size, and harvested the population at h_{MSY} when the population estimate is above 40% of the carrying capacity and reduces it linearly to zero as the population estimate declines to 10% of the carrying capacity. A fixed escapement rule, that harvested all biomass above B_{MSY}, and an h_{MSY}-based rule, that applies h_{MSY} above B_{MSY} and scales the harvest rate based on the ratio of the current biomass to the carrying capacity. Ultimately, I was able to tune the RMP parameters to manage a low productivity fishery better than the simplified version of a 40-10 rule and nearly as well as two strategies that had perfect information.

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Chapter 1 Project Overview

Fisheries management is subject to considerable biological and technical complexity and is thus prone to error and uncertainty. Current fisheries management attempts to implement a precautionary approach in response to this error and uncertainty. There are several definitions of the Precautionary Approach, some very similar to the Precautionary Principle (Garcia 1996). The following definition comes from the FAO (Food and Agriculture Organisation) expert consultation on the Precautionary Approach to Fisheries Management (FAO 1996, p. 6):

> The precautionary approach involves the application of prudent foresight. Taking account of the uncertainties in fisheries systems and the need to take action with incomplete knowledge, it requires, *inter alia*: (*a*) consideration of the needs of future generations and avoidance of changes that are not potentially reversible; (*b*) prior identification of undesirable outcomes and of measures that will avoid them or correct them promptly; (*c*) that any necessary corrective measures are initiated without delay […]; (*d*) that where the likely impact of resource use is uncertain, priority should be given to conserving the productive capacity of the resource; (*e*) that harvesting and processing capacity should be commensurate with estimated sustainable levels of resource […]; (*f*) all fishing activities must have prior management authorization and be subject to periodic review; (*g*) an established legal and institutional framework for fisheries management, within which management plans that implement the above points are instituted for each fishery; and (*h*) appropriate placement of burden of proof by adhering to the requirements above.

Quantifying uncertainty, defining reference points, and using pre-agreed harvest control rules are all necessary parts of implementing a precautionary approach (Hilborn et al. 2001). A management strategy is an algorithm to provide a management decision, such as a Total Allowable Catch (TAC) where the inputs are pre-specified. A

Management Strategy Evaluation (MSE) takes a proposed management strategy and uses simulation to determine whether it has a reasonable chance of achieving its stated objectives when based on data with a realistic error distribution. A strategy developed using MSE is compatible with the precautionary approach, because it takes into account a realistic amount of scientific uncertainty. Management strategy evaluation can be used to design, evaluate, and support processes to achieve consensus for robust, precautionary management in data-limited situations (Butterworth 2007).

Understanding the entire management system is integral to successful implementation of the precautionary approach, the ecosystem approach, adaptive management, and harvest control rules. Such an exercise requires a much broader understanding of species and ecosystem biology, fish harvester behaviour, and the management system than previously needed when fitting a stock-recruitment or yield curve was the biological basis for fisheries management. It requires a great deal of modelling and simulation to include all of the identifiable sources of uncertainty (Rice and Connolly 2007).

The International Whaling Commission (IWC) conducted a management strategy evaluation to improve their management system. Multiple management strategies were developed and tested. The strategy that performed the best across the range of test scenarios, in terms of minimising the probability of the stock being depleted, while allowing an acceptable catch distribution, became the Revised Management Procedure (RMP) (Kirkwood 1992; IWC 1992; IWC 1994). The purpose of this project was to determine if a straight forward application of the IWC's RMP would perform well in the context of a typical data-limited groundfish fishery. The objectives were to develop a model framework, tune the management procedure, develop alternative procedures, and test the suite of procedures against various biological and data-availability scenarios.

Chapter 2 Literature Review

Introduction

Management strategy evaluation (MSE) is a method of determining whether a particular management strategy is likely to achieve the management objectives associated with the precautionary approach (Cooke 1999; Smith et al. 1999). These objectives generally include sustainable benefits from the fishery with an acceptable probability of population decline below lower biomass benchmarks. Here I will review the design and evaluation of strategies consistent with the precautionary approach. I hope to provide an overview of management strategy evaluation as a tool for improving management outcomes. In Chapter 3 I will describe the RMP, apply a version of the RMP to groundfish management, and evaluate its performance relative to three alternative management strategies.

Precautionary Approach

Legislation and government policies in many jurisdictions requires management to result in sustainable harvests, based on a precautionary approach (UN Food and Agriculture Organization (FAO) Code of Conduct for Responsible Fisheries 1995; US Sustainability Act 1996; Canada's Policy for Conservation of Wild Pacific Salmon 2005; Australia's Harvest Strategy Policy for Commonwealth Fisheries 2007). Evaluating and managing risk is an important part of implementing a precautionary approach (Francis and Shotton 1997). One way to evaluate and manage risk is to use harvest control rules

(Punt et al. 2008). Harvest control rules, also known as decision rules, specify how the results of population data analyses are translated into management actions (Sainsbury et al. 2000). Building a management system with pre-specified management responses triggered by agreed upon decision rules is an essential part of implementing the precautionary approach (Cooke 1999; Logan et al. 2005; Butterworth 2007; Schnute et al. 2007). MSE can be used to determine if the methods used to estimate relevant population parameters are likely to compromise management objectives when used in a management system, evaluating whether such management systems are likely to achieve its stated objectives rather than focusing on estimating particular parameters of interest is a current trend in resource management (Plaganyi et al. 2007).

Harvest Control Rule Design

Designing a precautionary management strategy requires the selection of a harvest control rule that has a reasonable chance of achieving management objectives given the dynamics of the fish population and fishery, as well as the quantity and quality of stock assessment data. A wide range of harvest strategies have been proposed, including constant catch, constant proportional harvest rate, and fixed escapement (Getz and Haight 1989; Restrepo and Powers 1999). But all of these strategies have been shown to have both advantages and disadvantages when implemented (Zheng et al. 1993). For example, constant catch, harvesting the same amount every year, provides for a stable yield, but the harvest level must be kept relatively low to keep it sustainable. If the number of mature members of the harvested population were to drop below the number required to support the specified harvest for any reason, the population would not recover. The 'constant fishing proportion' provides a balance between the average catch and catch variation

(Walters 1986), but it may inhibit recovery if the population drops to a very low level. ‘Fixed escapement’ provides for the maximum yield, but catches are also the most variable of the three strategies (Reed 1979; Getz and Haight 1989).

To provide a balance between average catch and catch variation and allow the population to recover to target levels in cases of depletion (Punt et al. 2008), several jurisdictions have shifted to some form of threshold management strategy; (e.g. Dichmont et al. 2006; PFMC 2006; Dowling et al. 2008). Threshold strategies are based on aiming for, or avoiding pre-determined levels of abundance (or in the case of salmon, escapement). The parameters of a threshold strategy are the target abundance, the harvest rate above the target abundance, the limit abundance, and the way harvest is reduced when the population is between the target and limit abundance levels (Figure 1). The values of these parameters are typically based on broad policy objectives rather than to achieve specific conservation or yield targets with an acceptable probability derived from an analysis of the relevant uncertainties (Butterworth and Best 1994). The target can also be set relative to the maximum sustainable or economic yield (MSY or MEY) (PFMC 2006; IWC 2005; Dowling et al. 2008).

Stock Status Indicator Type

Inputs to harvest control rules can be based on either directly measured indicators (catch, average length or age, abundance index measured in a particular way, etc.) or indicators that are measured relative to theoretical, and therefore unobservable constructs such as maximum sustainable yield (MSY), carrying capacity or unfished abundance (*K*), the optimal fishing mortality rate (F_{MSY}), etc. Using values that cannot be directly measured as inputs to a harvest control rules can cause problems if there are insufficient resources to generate and maintain estimates of relevant reference points and population status in relation to those reference points (Cadrin and Pastoors 2008). Additionally, when rules are based on quantities not directly observable, there can be difficulty in deciding which method and estimate should be used because methods to estimate them continue to be developed and improved. Between development and wide-spread acceptance of a new method, there can be debate about which method is the most appropriate. Once the "best" estimate is agreed upon, there can be further debate as to the proper way to incorporate the uncertainty around the estimate (Schnute and Haigh 2006; Butterworth 2007). Such debates complicate implementing the management plan and possibly reduce the transparency of the management system.

Traditional Approach

The traditional approach to providing scientific management advice in support of fisheries management has historically involved producing a "best" estimate of the status of the resource and then basing harvest advice solely on this estimate. A common criticism of this approach is that it ignores uncertainty in estimates of stock status and thereby, does not communicate to managers the magnitude of uncertainty in the resulting harvest advice. Fisheries management is subject to error and uncertainty from a multitude of sources. Some of the more important of these are process and observation error, insufficient and/or imprecise data, misspecification of assessment models, error when implementing management actions and enforcing fisheries regulations, changes in the ecosystem, multi-species interactions, environmental variability, and regime shifts. The major disadvantage of the traditional approach is that it is not known whether the management actions will achieve the management objectives, or even the extent to which it is likely. This is because the methods used to generate the advice, as well as the management actions themselves, have not been tested over the range of plausible uncertainties (Punt 2006; Butterworth 2007).

Improvement on the Traditional Approach

Simulation testing can be used to test the ability of models to estimate parameters of interest, and the effectiveness of alternative management strategies. Specifically, one can compare the values for quantities of management interest estimated from simulated data with the "true" values used to generate those data for various scenarios to determine the performance of alternative assessment methods and how robust those methods are to uncertainty. The ability to achieve management objectives can be evaluated by projecting simulated populations in a variety of scenarios and applying the management strategy. The results can inform data collection and research funding decisions (Butterworth 2007). The results can also be used to identify which alternative modeling approaches, decision rules, and management actions are most likely to achieve a desirable tradeoff among the management objectives.

Once the uncertainty, and the effect of the uncertainty, has been assessed, it needs to be communicated to decision-makers. The most common ways of communicating that uncertainty are sensitivity analyses and Bayes posterior distributions (SK forecast) (Francis and Shotton 1997; Hilborn 2003). The RMP goes a step further, trying to find the best way to use such posterior distributions in management rather than leaving the selection of the probability level to managers, without providing them with an evaluation of what the result of their selection (for example, defaulting to the median of the distribution) could mean over the long term.

Strategy Design and Evaluation

To explore the possible consequences of the selection of a probability level, a management system that can be evaluated is required. "Adaptive management" (Walters and Hilborn 1978), and "comprehensive assessment and management procedure evaluation" developed by the IWC (Sainsbury et al. 2000) have both been developed as methods to evaluate and refine fishery management strategies. When designing such a management system, one should try to make each part of the management system robust to errors in the other parts of the system, including assessment bias, implementation error, or changes in the resources available for monitoring (Rice and Connolly 2007). A management strategy that can be evaluated is a completely specified procedure for managing a fishery so as to meet measurable objectives. A fully specified strategy includes the methods used to collect population and fishery information, the translation of that information to an assessment of stock status, and the development and implementation of management actions.

Management strategy evaluation (MSE; Smith et al. 1999) was developed to explore the consequences of various management strategies, and clearly show the trade-offs of alternative management choices across a range of performance measures. The use of simulations to evaluate alternative management strategies began in the late 1960s and 1970s (Southward 1968; Hilborn 1979). Practical applications began in the late 1990s with the use of simulation-tested management strategies (operational management procedures, OMPs) in South Africa (Butterworth and Bergh 1993; Plaganyi et al. 2007; Rademeyer et al. 2007) and the development of the Revised Management Procedure by the IWC (de la Mare 1996; Cooke 1999).

Current MSE

Management strategy evaluation is most commonly used as a tool for designing strategies in a manner consistent with the precautionary approach (Sainsbury et al. 2000; Butterworth 2007). Recent applications include evaluating threshold management strategies for US West Coast groundfish fisheries (Punt et al. 2008), evaluating practical sablefish harvest rules in BC (Cox and Kronlund 2008), and setting up precautionary management systems for low-value or data-limited fisheries in Australia (Dowling et al. 2008). MSE does not guarantee an optimal strategy, but it does help to eliminate proposed strategies that are not robust to expected levels of uncertainty, or fail to meet minimum objectives even under the ideal conditions of a simulation model. MSE also allows identification of the key uncertainties that are most likely to affect management outcomes so that research and data collection can be prioritised (Basson 2002).

Current Groundfish Management

The Pacific Fisheries Management Council (PFMC) manages fisheries off the West Coast of the US. It uses a threshold harvest control rule when populations are assessed to be above the lower abundance benchmark, and requires a recovery plan be developed for stocks below the benchmark (Punt et al. 2008). In 2005 there was enough stock information to apply the PFMC's harvest control rule to only 22 of the 80 species for which catch is managed under the PFMC Groundfish Management Plan (Punt and Donovan 2007). Therefore, a management strategy with fewer data requirements might prove useful.

Fisheries and Oceans Canada has recently developed a "fisheries decision-making framework incorporating the precautionary approach", which specifies a candidate harvest control rule for managing Canadian fisheries (DFO 2009). MSE has been identified as a useful tool for evaluating the harvest control rule (Shelton and Sinclair 2008), but this has not yet been done.

RMP Innovations

The RMP departs from general management strategy practice in two ways. First, the parameter of interest that is estimated is an acceptable total allowable catch (TAC) rather than a population parameter (abundance, depletion, MSY, etc). The RMP was designed to be a simple way of generating catch limits. By directly estimating a posterior distribution for a TAC rather than deriving one from estimated population parameters, the full range of uncertainty in estimated parameters gets integrated into this one value. Second, the percentile of the posterior TAC distribution that is used as a basis for a harvest decision (Pprob) is selected based on its ability to meet management objectives rather than defaulting to either the posterior median or the mode. The percentile of the TAC distribution that is used for management is one of the tuneable parameters within the RMP. Initially, the median of the TAC distribution was used. However, when the IWC was tuning the procedure to meet their one of their conservation objectives, they found that reducing the percentile was an effective way to meet that objective (IWC 1994).

Conclusions

To provide scientific advice in support of management consistent with the precautionary approach, fisheries science has begun to shift from giving point estimates to helping to design management systems and providing performance evaluations of current and proposed management systems. The precautionary approach requires that harvest strategies be biologically conservative when the consequences to the stocks affected by the harvest strategy are uncertain. To operationalise such requirements, quantifiable objectives and fully specified management strategies that can be evaluated are needed.

Chapter 3 Evaluation of an RMP-based Management Strategy

Introduction

The RMP is made up of three elements, data collection, population assessment, and a harvest control rule. The data collection element is quite simple and requires a series estimated population sizes and the lower 95th percentile of the population estimate. The population assessment model uses the estimated population sizes and the prior distributions of the population parameters to generate a distribution of TACs by applying the harvest control rule.

The population assessment model used in the RMP to estimate the current depletion and productivity parameters is a simple discrete time Pella-Tomlinson model fitted to the catch and abundance index time series. Depletion is the current abundance as a proportion of the carrying capacity. For example, depletion equal to 0.75 and a carrying capacity of 10,000 means a current abundance of 7,500. A unique aspect of the RMP is that Bayesian methods are used to generate a distribution of recommended catch limits (i.e., TAC) rather than population parameters. A second unique aspect is that the percentile of the estimated posterior TAC used to select the catch target is evaluated and tuned to achieve management objectives rather than using either the most likely or the median value.

By fitting the model to the data, estimates of the current abundance, maximum sustainable exploitation rate, and depletion relative to the unexploited biomass are generated. Nominal catch limits are related to these estimates by a simple harvest rule. The nominal catch limits are not directly used as actual catch limits. The uncertainty in the input data and parameter estimates translates into uncertainty in the catch limit. A range of nominal catch limits is calculated, along with the probability of each value. The chosen percentile of the distribution (Pprob) becomes the catch limit. The probability associated with each catch limit depends on both how well it fits the data, and on prior assumptions built into the procedure (Kirkwood 1992).

During the original selection of this algorithm by the IWC, the strategy was compared to a number of competing algorithms to manage a simulated fishery over a broad range of scenarios about how populations respond to fishing in the presence of disease outbreaks, shifting carrying capacities, data bias, and variability. The RMP provided the best trade-off between biological and catch objectives across the tested scenarios (IWC 1994; de la Mare 1996; Cooke 1999).

Simulation testing by the IWC during the development of the RMP focused specifically on baleen whales. While it seems likely that performance would be comparable for long-lived fish species, to my knowledge, this application has never been formally tested. For this project, I applied the RMP to a long-lived fish population with lognormal recruitment. For comparison, I also considered three additional management strategies using simple management rules that had an advantage over the RMP. The alternative strategies used data directly from the true population model, rather than observing the true population only through the observation model. To test the relative robustness of each strategy, they were challenged with two sets of problems. The first set dealt with data challenges (survey bias and variability), and the second set concerned biological challenges (changes in the carrying capacity and population depletion).

Material and Methods

Simulation Framework

I constructed an operating model of the "true" fish population using Fish++ (Logan et al. 2005, Appendix F), which is an open-source software package developed by Dr. Bill de la Mare. For the management component of the operating model, I developed a version of the IWC's revised management procedure (Cooke (1999)) for application to a long-lived fish, described in more detail below. The most recent published version of the RMP is in IWC (1999), but at IWC's annual meeting in Agadir, Morocco in June 2010 the Scientific Committee recommended that a consolidated revised version be published in full in the next supplement to the Journal of Cetacean Research and Management.

I simulated each combination of operating model scenario and management procedure 500 times where each trial ran for 200 years. The management period was only 135 years because one of the inputs to the management procedure is catch data, and the model generated the necessary data in the first 65 years of the run. For the first 30 years, the fishery was closed. In the following 35 years, a low fixed annual harvest resulted in a population near the carrying capacity (*K*) at the beginning of the management period. When I needed to examine how the strategies dealt with heavily exploited populations, I simply substituted a larger annual harvest during pre-management. The data that came from the true population model were biomass estimates ($\hat{B}_t$) via a survey algorithm once every five years and annual catch numbers (C_t).

Operating model

Fish ++ is a C++ library of fisheries model functions and procedures that allows modelling of populations based on simple or complex biological and management scenarios (Logan et al. 2005, Appendix F). I used Fish ++ to simulate an age-structured "true" population, using the following recruitment model (Figure 2):

$$S = e^{-M} \quad (1)$$

$$f = 1 - S \quad (2)$$

$$R_t = f * B_{t-1} * (1 + c(1 - \frac{B_{t-1}}{K})) \quad (3)$$

Where:

S is the survival rate;
M is the mortality rate;
f is the fecundity;
R_t is recruitment in year t;
B_{t-1} is the mature biomass in year t-1;
c is the compensation factor;
and K is the carrying capacity.

Interannual variation in recruitment was lognormally distributed and not auto-correlated. Recruitment compensation was equal to 2 and the recruitment variance was +1.

My evaluation of management methods was independent of the inner-workings of both the "true" population model and the RMP. I wrote the code that allowed the two models to pass catch targets and indices of abundance between them and the observation model. The management procedure and the population model interacted in only two places. Annual catch is delivered from the management procedure to the "true" population which returns a population estimate and the 95th percentile of the survey at specified intervals. The two models were kept separate to protect the integrity of the management procedure evaluation (Figure 3).

Observation Model

The survey data are generated from the operating model with a specified bias and coefficient of variation that along with the sample size yields a survey estimate and 95th percentile using the following equations:

$$\sigma = \sqrt{e^{CV^2} - 1} \tag{4}$$

$$\mu = -0.5 \cdot \sigma^2 \tag{5}$$

$$\hat{B}_t = B_t \cdot b \cdot e^{x \cdot \sigma + \mu} \tag{6}$$

$$\hat{B}_{95,t} = \hat{B}_t \cdot e^{-1.64 \cdot \sqrt{\log(1.02 + 0/012 \cdot K / B_t) \cdot \chi^2}} \tag{7}$$

Where:

σ is the standard deviation of the survey;
CV is the survey coefficient of variation;
x is a random number from a normal distribution with a mean of zero;
$\hat{B}_t$ is the abundance estimate in year t;
B_t is the true abundance in year t;
$\hat{B}_{95,t}$ is the 95th percentile of the survey estimate in year t;

K is the true population carrying capacity;

χ^2 is a random number from a chi-squared distribution;

and *b* is the survey bias.

The baseline scenario has a true bias equal to 1 (meaning no bias). Two other bias values were included in the scenarios, 0.5 (index values equal to one half of the unbiased estimate) and 1.5 (index values equal to one and a half times the unbiased estimate).

The Revised Management Procedure (Cooke's algorithm)

The management procedure generates a TAC when given access to a time series of catch data and population estimates. For the current simulation study, catch data was available for a longer time period than the indices. The RMP algorithm uses these data sources to find a TAC with an acceptable probability of fulfilling management objectives. These objectives include minimising the time the population is less than 20% of the carrying capacity, avoiding fishery closures, and maintaining high, constant catches. The performance of the procedure can be adapted to address different management problems and priorities using the RMP parameters (Table 1).

Uncertainty about the current state of the population is taken into account by the harvest algorithm by selecting catch limits in a probabilistic way (Figure 4). All of the uncertainty in the estimates of the model parameters is expressed through the generated TAC. The algorithm uses a modified form of Bayes' theorem that down-weights the incoming data (by Pscale) to meet the inter-annual variability in the catch objective. The priors for the three parameters that determine the TAC are uniform. The range for the MSY rate (r) is from 0% to 5%. The current level of depletion ($D_T = B_T/K$) range is from

0% to100%, and the population estimate bias (b) ranges from 0% to 167% of the true value.

Instead of a single TAC, a distribution of catch limits is generated, each with its own probability. A large number of population trajectories from the model are calculated using a grid-search over the assumed ranges for the productivity, depletion and bias parameters given the catch history. The catch limit based on each trajectory and the control rule is associated with its posterior probability (Figure 5). The array of catch limits and posterior probabilities are then sorted by the catch limit. Beginning with the lowest catch limit, the posterior probabilities are accumulated until they are equal to the desired percentile. Rather than defaulting to selecting a catch based on either the median or the mode of the posterior distribution, the selected catch limit is a percentile of this posterior probability distribution (Pprob), which is selected to give a reasonable compromise between the dual management objectives of sustainability and profitability. This procedure has the property that catch limits are dependent on the precision of the abundance estimates. Imprecise abundance estimates result in lower catch limits than those obtained with more precise estimates.

Population assessment model within the RMP

The population assessment model was selected to meet management objectives, not to be a realistic representation of the population. It is a discrete time version of the Pella-Tomlinson model:

$$K = \frac{B_T}{D_T} \quad (8)$$

$$B_0 = K \quad (9)$$

$$B_{(t+1)} = B_t - C_t + 1.4184 \cdot r \cdot B_t \left(1 - \left(\frac{B_t}{K}\right)^2\right) \quad (0 \le t < T) \qquad (10)$$

Where:

K is the carrying capacity;

B_t is the population size in numbers at the beginning of year t;

D_T is the ratio of the population size at the beginning of year T to the population's carrying capacity, known as the stock depletion;

Year T is the year for which a catch limit is to be calculated;

Year 0 is the first year of the catch series used in the catch limit calculation;

C_t is the catch in numbers in year t;

and r is a productivity parameter.

The population dynamics model is fully determined when the catch series and the values of D_T and r are specified. Beginning with the population at carrying capacity, the model subtracts known catch and adds recruitment until it reaches the present. When fitting the model to the data, the abundance estimates are assumed to be consistently biased.

Harvest Control Rule

The RMP was designed to meet management objectives across the range of uncertainties built into the scenarios included in the evaluation rather than to be realistic. For this reason, the parameters and priors used in the procedure are not necessarily the best estimates of the true population parameters. They are all tuned to improve performance (Cooke 1999). The control rule determines the target harvest based on the current depletion level relative to the protection level (Plevel) and the productivity of the population (Figure 6).

$$h = Pslope \cdot r\left(\frac{B_T}{K} - Plevel\right) \quad (11)$$

$$TAC = h \cdot B_T \quad (12)$$

Where:

h is the harvest rate;
Pslope is the slope of the control rule;
r is the given population productivity;
and Plevel is the no fishing point for the control rule.

The Pslope and Plevel are tuneable parameters set at the beginning of each scenario. The r and depletion (B_T/K) are pulled from their prior distributions. The current biomass estimate (B_T) comes from the population model with the r and depletion values as inputs. Once the TAC is selected, it is removed from the operating model annually until a new abundance estimate is available or until number of years since the last survey is greater than the maximum number of year between surveys (Ptmout). In the latter case, the TAC is reduced by 20% each year until another survey is conducted or the fishery is closed.

To reduce the effect of the survey information, the coefficient of variation (CV) of the incoming survey data is increased by Pscale. The use of Pscale to reduce the effect of the incoming data versus the prior is a deviation from a strictly Bayesian approach. In the initial IWC tests of the RMP, a scaling factor of one, consistent with a strictly Bayesian approach, resulted in unacceptably high variability in the TAC. The priors are fixed and the likelihood is data-dependent, so a scalar greater than one, reducing the effect of the incoming data on the posterior, reduces TAC variability (Cooke 1999).

Fitting the model within the RMP

The calculation of the likelihood of each TAC is internal to the RMP. The likelihood equation comes from an International Whaling Commission report (1994) detailing the RMP.

$$\text{Likelihood}(D_T, r, b) \propto e^{-\frac{1}{2}(\mathbf{a}-\mathbf{p}-\beta\mathbf{1})' H (\mathbf{a}-\mathbf{p}-\beta\mathbf{1})} \tag{13}$$

Where:

a is the vector of logarithms of annual estimates of absolute abundance; $a_t = \log(\hat{B}_t)$

p is the vector of logarithms of the modelled annual population sizes; $p_t = \log(B_t)$;

β is the logarithm of the bias parameter; $\beta = \log(b)$;

1 is a vector of ones;

D_T is depletion in year T;

r productivity;

b bias;

and H is the information matrix of the **a** vector.

If H is non-singular, $H = V^{-1}$ where V is the variance-covariance matrix of the components of **a**.

The RMP uses the following algorithm to generate annual TACs as needed:

1) Given the index time series, calculate the coefficient of variation of the indices.

2) Scale index CV using: Index CV' = Pscale*Index CV

3) Generate a distribution of TACs and associated probabilities

   a) for each combination of D_T, r, and b calculate the TAC (equations 11 and 12)

   b) calculate the probability associated with that TAC given the priors associated with the D_T, r, and b values, the Index, and the Index CV' (equation 13)

4) Find the TAC associated with the desired cumulative probability, Pprob.

Tuning RMP

The RMP contains a number of parameters that can be tuned to meet a variety of management objectives. The tuneable parameters include the prior distributions of the population assessment model; the weighting of the incoming data versus the prior information; the parameters of the harvest control rule; and the percentile of the posterior distribution of the TAC (Cooke 1999). I looked at the parameters of the algorithm individually to meet the needs of groundfish management with the most relevant presented below. Starting with the control parameters at the values used by the IWC, I changed one parameter at a time to determine the effect. The relative performance of each tuning was assessed by comparing the mean of performance measures across the 500 simulations. I then compared the performance of the tuned management procedure to the performance of alternative management strategies in a variety of scenarios testing robustness to data quality and biological challenges.

Scenarios

Baseline

The baseline scenario was meant to represent the management of a long-lived, low productivity, stable population beginning with a population size near the carrying capacity. In other words, the management strategy is applied to a new fishery during a period of stable ocean productivity. The basic scenario conducted an unbiased survey every 5 years with a survey CV of 0.3 (Table 2). The managed species had a maximum age of 50 years and an annual natural mortality rate of 0.04 (Table 3). The recruitment model parameters resulted in a stock-recruitment relationship steepness (the fraction of the unfished recruitment that occurs when the spawning stock biomass is reduced to 20% of the unfished level) of 0.52.

Data Challenges

Different amounts of survey bias and variability were examined to evaluate how the two strategies that use the index performed. Performance in the face of imprecise information was tested by applying survey CVs from 20% up to 90%. Robustness to survey inaccuracy was tested by applying a consistent 50% positive or negative bias to the assessment information.

Biological Challenges

Population response to changes in environmental conditions such as regime shifts, interactions with an unknown species, and habitat loss were approximated by adjusting the carrying capacity. To test how the strategies managed in the face of population depletion, I reduced the population to 20% of carrying capacity before the initiation of management using a fixed annual harvest during the pre-management period. By using a fixed harvest to reduce the population to the desired level, I kept my work external to the true population model. Because the response of the population to the fixed harvest depended on a series of randomly generated recruitments, every trial in this scenario had an identical population trajectory in the pre-management period to start the depletion scenario at the same abundance level. In all other scenarios, every simulation trial generated both a unique past and a unique future trajectory of population sizes.

Alternatives to the RMP

40-10 rule proxy

The 40-10 rule, as used by the PFMC to manage groundfish stocks not considered to be overfished, applies a proxy of h_{MSY} to stocks estimated to be at or above 40% of K and reduces the harvest rate linearly to zero as the abundance approaches 10% of K (Punt 2003). The first alternative strategy used the same abundance estimates as the RMP to implement a simplified version the 40-10 rule. The fishery closed when the population was estimated to be below 10% of K, allowed the harvest rate to increase linearly as the population moved from 10% of K to 40% of K, and allowed harvests at the maximum sustainable yield rate (h_{MSY}) when the population was estimated to be above 40% of K. I used the true K and h_{MSY} parameters and the survey data that was given to the tuned RMP, rather than building a module to estimate the K and h_{MSY} parameters based on the abundance estimates. Having access to the true K and h_{MSY} should have given the 40-10 proxy a major advantage over the RMP. A simple linear regression of the abundance estimates from the observation model was used to estimate the current population size and apply the control rule. When the 40-10 rule is applied by the PFMC, an assessment model is used to estimate the current population depletion, so the 40-10 proxy harvest strategy used in this project is greatly simplified. When the survey was biased, the 40-10 rule used a biased K as well (Table 4).

Fixed Escapement at B_{MSY}

I included the B_{MSY} escapement strategy to determine the maximum amount that could be harvested given perfect information about the current status of the population. If the management objective is to maximise the total annual harvest, then the ideal strategy is to reduce the population as quickly as possible to the most productive size (i.e., B_{MSY}) and harvest the annual surplus above that level. If the population should decrease below B_{MSY} for any reason, then the fishery should be immediately closed (Clark 1990). I implemented the strategy using perfect information about B_{MSY} and the current population size.

Harvest based on h_{MSY}

I built the third harvest strategy to balance the management objectives of maximising harvest while keeping the inter-annual variation in the TAC to a low level and maintaining the population near B_{MSY}. It used perfect information and an experimentally derived maximum sustainable yield harvest rate. I found the h_{MSY} by applying a fixed harvest rate over a long period (10,000 years) to a population with no recruitment variability. The long-lived, groundfish species h_{MSY} was 0.016, the B_{MSY} was 0.54358 of K. The initial design applied h_{MSY} when the population was at or above B_{MSY} and closed the fishery below B_{MSY}. The fishery was often closed, similar to the fixed escapement strategy. To improve the performance in terms of both AAV and fishery closure, I scaled the harvest rate to the ratio of the current biomass relative to B_{MSY} rather than closing the fishery.

Performance Measures

The status of both the fish population and the fishery were used to indicate whether a strategy was successful. The average depletion and the mean number of years the biomass was below 20% of the biomass at carrying capacity were the conservation performance indicators. Fishery performance was measured by average annual catch, average annual variability of the catch, and the mean frequency of fishery closure. Catch variability was summarised by the average absolute variation (AAV) in catch (Punt and Smith 1999):

$$AAV = \frac{\sum_{t=1}^{T} \left| C_t - C_{t-1} \right|}{\sum_{t=1}^{T} C_t} \tag{14}$$

Where:

T is the final year of the simulation.

The performance measures were collected for each trial and summarised by the mean across the 500 trials.

Results

Tuning the RMP

The four management parameters that had the most effect on performance were Plevel, Pslope, Pscale, and Pprob (Table 5). Tuning parameters were selected based on a combination of their average performance measures. The preferred tuning resulted in high average catch, low AAV, proportion closed, and proportion of years of biomass below 20% of K, and an average depletion at or above B_{MSY}. Lowering the protection level (Plevel) increased the catch and decreased the abundance. The effect of the Plevel appeared to be straightforward.

Reducing the Pslope increased catch stability and decreased mean catch. The lower mean catch for lower Pslope values likely stemmed from the reduced magnitude of the initial harvest surge at the beginning of management. The average depletion increased and proportion of years the population was below 20% of K decreased as the Pslope was reduced.

Reducing Pscale increased the sensitivity of TAC to the incoming information, meaning that less weight was given to prior information. It resulted in increased mean catch (because it takes advantage of high biomasses), increased the number of fishery closures (faster responses to observed declines), and increased the AAV. A high Pscale slowed response to observed changes in abundance.

Increasing Pprob caused the RMP to be less risk averse. Higher Pprob strategies selected TACs which had a greater probability of being too high given the state of the population. The mean catch, AAV, and proportion of years the abundance was less than 20% of K all increased and the average depletion decreased. A low (0.25) or high (0.55) Pprob both increased the frequency of fishery closures. This was because the low Pprob strategy was more biologically conservative in the face on uncertainty, and the high Pprob strategy allowed higher TACs which caused reductions in the abundance and closures once the abundance dropped to the Plevel. The intermediate value of 0.423 used by the IWC did not result in any fishery closures.

I used a Plevel of 0.2 as my baseline because 20% of the estimated carrying capacity has been a commonly adopted "overfishing threshold" in the fisheries literature (Beddingtion and Cooke 1983; Getz and Haight 1989; Meyers et al. 1994). I found that a protection level of 0.2 fulfilled all of the requirements of "good enough" management. The mean catch was comparable to the mean catch of the h_{MSY}-based rule, the AAV was less than 0.05, the fishery was never closed, the average depletion was above B_{MSY}, and the population spent less than 0.25% of years below 20% of K. Altering the other tunable parameters did not provide simultaneous improvement of the selected performance measures, so the rest of the parameters were left unchanged from the IWC baseline values.

Baseline Performance

When used to manage a new fishery during a period of stable productivity, the tuned RMP generally performed well compared to all alternative strategies (Table 6). The mean catch was similar to the h_{MSY}. AAV was higher than either of the strategies using perfect information, but was 30% lower than the AAV of the 40-10 rule proxy. The average depletion was near B_{MSY}, and the population was below 20% of K on average one out of every 400 years. The 40-10 proxy strategy caught fewer fish on average, catches were more variable, the fishery was closed 15% of the time, depletion was above B_{MSY}, and the population never dropped below 20% of K. The B_{MSY} escapement alternative caught more fish on average, but the variability in the catch would likely make this strategy unacceptable even if it were possible to implement. The h_{MSY} – based strategy performed the best in terms of catch variability.

The variability in the catch using the RMP, in terms of AAV, was roughly four times the AAV of the h_{MSY}-based strategy. Considering the 0.3 CV of the abundance estimates used by the RMP, it was expected that the catch would be more variable compared to a strategy given perfect information. The avoidance of fishery closure had the consequence of a low, but measurable chance of the population dropping below 20% of K in both the RMP and h_{MSY}-based strategy.

Both the RMP (Figure 7) and the 40-10 rule (Figure 8) performed similarly to the h_{MSY} –based strategy (Figure 9). The B_{MSY} escapement alternative (Figure 10) had the highest mean catch and AAV. The RMP was able to approximate the h_{MSY}-based strategy biomass and mean catch trajectories without resorting to frequent fishery closures, unlike the 40-10 rule proxy. Biologically, the performance of all the strategies was acceptable, in that the average depletion was at or above B_{MSY}, and the proportion of years the abundance was below 20% of K was quite low (less than 0.3%). Economically, the RMP and the h_{MSY}-based strategy performed best, in that high average catches were achieved with low AAV and no fishery closures.

Two performance thresholds that have been used in other MSE studies are the probability of the population dropping below 20% of K should be less than one in ten (Francis 1993), and that the AAV of groundfish fisheries should not exceed 15-20% (Cox and Kronlund 2008). The RMP as applied in this project met both of these requirements under all scenarios as did the other strategies evaluated except for the B_{MSY}-escapement strategy (AAV: 34%).

Data Challenges

The two strategies that used the index to inform management (RMP and 40-10 proxy) were given biased and highly variable data to evaluate robustness to data-quality problems (Table 7). The RMP adapted to a consistent bias and responded to high variability in the survey by reducing harvest and only rarely closing the fishery (Figure 11). The RMP was able to detect and respond to a consistent bias. The assessment method used in the 40-10 rule proxy, a linear regression of the abundance estimates, did not include the capacity to compensate for bias, so any bias in the data translated to biased catch targets (Figure 12).

Substantial increases in the survey variability caused similar catch declines and biomass increases using either the RMP or the 40-10 rule, the contrast is in the pattern of exploitation. The 40-10 proxy proportion of years the fishery was closed increased from 15% up to roughly 55% as the survey CV increased from 30% to 90%. The RMP proportion increased from 0% to roughly 7% over the same range of survey CVs. The 40-10 rule closed the fishery much more often as the survey precision declined (Figure 13).

Biological Challenges

Variation in carrying capacity showed that the relative performance of the strategies was independent of changes in the "true" carrying capacity, and when the population began the management period at only 20% of carrying capacity, all of the alternative strategies allowed rebuilding while maintaining a modest level of harvest (Table 8). In the near term (first 10 years of management), the RMP allowed a consistent low level of harvest similar to the h_{MSY}-based strategy, the 40-10 rule generally closed the fishery. In the mid-term (year 11-21 of management) and long term (year 22-42 of management), the pattern was similar. The RMP and h_{MSY}-based strategies allowed consistent low harvests, and the 40-10 rule frequently closed the fishery. Abundance recovered faster under the 40-10 rule's frequent closures than the consistent harvests of the other two strategies (Figure 14, Figure 15). The average AAV performance measure could not be calculated for the 40-10 proxy strategy in the depletion scenario, because the scenario included many trials that did not open the fishery during the periods of interest and the AAV is the sum of the annual change divided by the total catch.

Because of the population's low productivity, the recovery of the population starting from less than 20% of *K* was slow regardless of the strategy applied. Recovery was faster under the 40-10 rule because of very frequent fishery closures (80% to 98% closed). The RMP performance was close to the performance of the h_{MSY}-based rule, except for a higher AAV, similar to the performance of the RMP relative to the h_{MSY}-based strategy in all other scenarios.

Discussion

The results in this initial application of the International Whaling Commission's Revised Management Procedure to groundfish fisheries management indicate that it can be tuned to provide performance, in terms of biological and economic objectives, on par with strategies given perfect information. This study provides a starting point for additional simulation studies considering more realistic data-availability scenarios and "true" population models.

In this study, simulated abundance data collection began when the population was near carrying capacity *K*, which is similar to the pattern of data availability off the U.S. West Coast (PFMC 2006). This type of data provides more information about *K* compared to situations in which data collection begins well into fishery development, which is more typical of groundfish fisheries in Canada. RMP performance using the long time-series abundance information was relatively insensitive to variability in the abundance estimates, which is consistent with the population parameter estimates based on fitting a population dynamics model to the same pattern of data availability (Haltuch 2008). In contrast, the fishery resources off the Northeast Coast of the U.S. have been harvested for hundreds of years and some stocks were already over fished prior to the collection of standardized catch or survey data (NMFS 2002). Given this pattern of data collection, there is less information available regarding *K*. Providing catch and abundance estimates to the RMP collected only after the population was reduced below 20% of *K* would be a useful investigation to determine how the RMP would perform managing a fishery in need of rebuilding.

Limitations of this work include a very simple application of the 40-10 rule and abundance estimates that may be unrealistically informative. The 40-10 proxy in this project used a simple linear regression of the abundance data to estimate the current biomass. Normal application of the 40-10 rule uses an assessment model such as Stock Synthesis II (Methot 2006). So the evaluation of the relative performance of the 40-10 proxy in this project is not a realistic measure of performance of a full 40-10 framework as applied to U.S. groundfish management. However, an evaluation of the 40-10 rule as implemented by the PFMC, including the use of rebuilding plans, also resulted in fishery closures (at least 5% of trials over the first 50 years) when management started with a population close to 20% of *K* (Punt 2003). At the same time, AAV was 30% after 20 years and 20% after 60 years of management (Punt 2003), which is about 4.5 times the long-term AAV in my baseline scenario using the RMP.

The abundance estimates simulated in this study are based on the true population biomass. While the observation model did add variability and bias to the data, it was ultimately representative of the true biomass. To be used in the current RMP as presented in this work, all indices must be converted to estimates of the total abundance. To evaluate the performance of the RMP in more realistic circumstances, such as management based on the results of a trawl survey biomass index or catch per hook from a long-line survey, a more realistic observation model is required.

Two useful extensions of this work include further sensitivity analysis on the effect of RMP tuning parameters, and use of more realistic operating models. Two parameters that have the potential to affect the rate of learning by the RMP assessment model are Pslope and Pscale. Increasing the Pslope (i.e., the slope of the harvest control rule) causes the applied harvest rate to be more sensitive to changes in the estimated depletion, while reducing the Pscale (i.e., increasing the weight placed on new data) causes the incoming abundance estimates to have a stronger effect on the selected TAC. These changes result in larger interannual changes in harvest as the variability in the abundance estimates increases. Therefore, either increasing Pslope or decreasing Pscale could increase the contrast in the catch and abundance data, thus potentially improving stock assessment model parameter estimates (D_T, r, and b). This is consistent with a passive adaptive management approach, which balances the current needs for stable catch with the desire for improvement in stock information. I did not investigate this aspect of the RMP in my tuning procedure, but it may prove important in future work, particularly if the RMP were to be applied to the management of a more complex stock structure.

A 40-10 harvest strategy could also be implemented using the RMP assessment model, by replacing the harvest control rule with a 40-10 rule. This would allow the evaluation of the RMP's harvest control rule relative to the 40-10 rule for the same assessment model (and resulting errors).

The RMP has been shown to generate acceptable catch targets for one low productivity species given variable and biased data, but it should be tested against a broader range of operating models that represent a cross-section of groundfish populations and more realistic observation models. Before implementing management of the harvest of any whale populations using the RMP, the IWC conducts Implementation Simulation Trials (ISTs). These consider a range of possible stock structures, methods of translating the available information into the required abundance estimates, probable ranges of the productivity parameter, and catch series to be used in the trials (IWC 2007). The guidelines for conducting ISTs include rigorous requirements to ensure that all plausible hypotheses regarding relevant factors are included. There is also a time limit on data inclusion, so that any new data can only be considered when an implementation review occurs, typically once every five years, the guidelines specify a two-year timeline for completion of the ISTs (Punt and Donovan 2007). It is likely that a similar set of trials would be required before implementing management of any groundfish species based on the RMP.

A management system that can cope with limited information is essential for making sound decisions regarding harvest management strategies. The RMP has been used to manage whale harvests given limited information, and seems to achieve biological and economic objectives managing the harvest of a long-lived, low productivity fish population when catch information from the beginning of the fishery is available.

Tables

Table 1 Parameters that control the shape and functioning of the control rule

Revised Management Procedure Parameters		
Parameter		Description
Pprob	-	Probability level of selected TAC
Pymax	-	Maximum MSYR
Pbmin	-	Minimum bias
Pbmax	-	Maximum bias
Pscale	-	Scalar for likelihood
Ptmout	-	Number of years with no surveys before TAC reduction
Pcycle	-	Maximum number of years before assessment
Plevel	-	Internal protection level
Pslope	-	Slope of the catch control rule

Table 2 Settings evaluated during sensitivity analyses, baseline settings are in bold

Settings evaluated during sensitivity analyses		
	Factor	Values
"True" population Parameters		
	Pre-Mgmt Traj	{Constant, **Variable**}
	Carrying capacity	→, ↗, ↘, ↘↗
	Starting Biomass	{**K**, 20% of K}
	Natural Mortality	{**0.04**, 0.2}
Observation Model Parameters		
	CV	{0.2, **0.3**, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1}
	Bias	{0.5, **1**, 1.5}
	Freqency	{3yrs, **5yrs**}
Alternative Mgmt Parameters		
	Fixed HR	{0%, 1%, 2%, 10%, **Hmsy**}
	Fixed Esc	(40% of K, **Bmsy**}
RMP Parameters		
	Plevel	{0%, 10%, **20%**, 25%, 39.6%, 40%, 54%}
	Pprob	{25%, 35%, **42.3%**, 55%}
	Pscale	{2, 3, 3.96, **4**, 5, 6}
	Pslope	{1, 2, 2.97, **3**, 4, 5}
	Pymax	{**5%**, 7.5%}

Table 3 "True" population parameters and RMP parameters.

Baseline Settings

Parameter		Value	
"True" population parameters			
Max age		50	
K		10,000	
Natural Mortality		0.04	
von Bert k		0.04	
von Bert asymptote		900	
von Bert int		0	
Age at 50% mat		5	
Age at 95% mat		8	
Mass at length scale factor		1.13E-06	
Mass at length exponent		3.2	
Rec. compensation		2	
Rec. CV		1	
RMP Parameters			
Pprob	0.423	Pnbstp	10
Pymax	0.05	Pscale	4
Pnystp	10	Ptmout	10
Pkstep	0.2	Pcycle	5
Pdstep	0.025	Plevel	0.2
Pbmin	0	Pslope	3
Pbmax	1.6667		

Table 4 Harvest control rules

Revised Management Procedure Control Rule

Parameters

$$\Phi_{RMP} = \{\mathrm{Pslope},\ \mathrm{r},\ \mathrm{D_T}, \mathrm{Plevel}\}$$

Harvest

$$\mathrm{h} = \mathrm{Pslope} \cdot \mathrm{r}\left(\mathrm{D_T} - \mathrm{Plevel}\right)$$

40-10 Rule Proxy

Parameters

$$\Phi_{40-10} = \{h_{\mathrm{MSY}}, B_{40}, B_{10}\}$$

Harvest

$$D_t = \frac{\widehat{B}_t}{K}$$

$$B_{10} = 10\% \cdot K$$

$$B_{40} = 40\% \cdot K$$

$$h_t = \begin{cases} 0, & \text{if } \hat{B}_t \text{ is } < B_{10} \\ (1/30 \cdot D_t - 1/3) \cdot h_{\mathrm{MSY}}, & \text{if } B_{10} < \hat{B}_t < B_{40} \\ h_{\mathrm{MSY}}, & \text{if } \hat{B}_t > B_{40} \end{cases}$$

Fixed Escapement

Parameters

$$\Phi_{Bmsy} = \{B_{\mathrm{MSY}}\}$$

Harvest

$$h_t = \begin{cases} 0, & \text{if } B_t \le B_{\mathrm{MSY}} \\ \frac{B_t - B_{\mathrm{MSY}}}{B_t}, & \text{if } B_t > B_{\mathrm{MSY}} \end{cases}$$

Variable Exploitation Rate

Parameters

$$\Phi_{Hmsy} = \{h_{\mathrm{MSY}}, B_{\mathrm{MSY}}\}$$

Harvest

$$h_t = \begin{cases} h_{\mathrm{MSY}} \cdot \frac{B_t}{B_{\mathrm{MSY}}}, & \text{if } B_t < B_{\mathrm{MSY}} \\ h_{\mathrm{MSY}}, & \text{if } B_t \ge B_{\mathrm{MSY}} \end{cases}$$

Table 5 Performance of the RMP across tuning parameters (Plevel-protection level, Pslope-slope of the harvest control rule, Pscale-Likelihood scalar, Pprob-posterior percentile of accepted TAC), bold values = baseline parameters. Only one parameter was altered at a time.

RMP tuning results				
Plevel	0.10	**0.20**	0.30	0.40
Mean Catch	101	**95**	88	78
AAV	0.046	**0.045**	0.043	0.042
Fishery Closure Proportion	0	**0**	0.0008	0.0019
Average Depletion	0.51	**0.58**	0.64	0.7
Proportion of Years < 20%K	0.013	**0.0025**	0.00031	0
Pslope	1	2	**3**	4
Mean Catch	51	82	**95**	101
AAV	0.03	0.037	**0.045**	0.052
Fishery Closure Proportion	0	0	**0**	0.00051
Average Depletion	0.82	0.68	**0.58**	0.51
Proportion of Years < 20%K	0	0.00007	**0.0025**	0.01
Pscale	2	3	**4**	5
Mean Catch	94	95	**95**	95
AAV	0.07	0.054	**0.045**	0.039
Fishery Closure Proportion	0.0039	0.0003	**0**	0
Average Depletion	0.57	0.57	**0.58**	0.59
Proportion of Years < 20%K	0.012	0.0057	**0.0025**	0.00099
Pprob	0.25	0.35	**0.423**	0.55
Mean Catch	74	89	**95**	101
AAV	0.041	0.043	**0.045**	0.05
Fishery Closure Proportion	0.00007	0	**0**	0.00037
Average Depletion	0.73	0.64	**0.58**	0.47
Proportion of Years < 20%K	0	0.00054	**0.0025**	0.019

Table 6 Results of the baseline scenario using various management strategies

Baseline Scenario Alternative Strategy Performance				
	RMP	40-10 Rule Proxy	B_{msy} Escapement	h_{msy}-based
Mean Catch	95	93	102	96
AAV	0.045	0.064	0.34	0.011
Fishery Closure Proportion	0.00	0.15	0.13	0.00
Average Depletion	0.58	0.63	0.56	0.6
Proportion of Years < 20%K	0.0025	0	0	0.00003

Table 7 Performance of the RMP and 40-10 given biased and high variability survey data

Data Challenge Performance of RMP and 40-10 Proxy				
	Survey Biased High		Survey Biased Low	
	Tuned RMP	40-10 Rule Proxy	Tuned RMP	40-10 Rule Proxy
Mean Catch	106	110	90	44
AAV	0.048	0.12	0.039	0.22
Fishery Closure Proportion	0.000073	0.23	0	0.58
Average Depletion	0.5	0.52	0.78	0.99
Proportion of Years < 20%K	0.011	0.00025	0	0
	Survey CV 50%		Survey CV 90%	
	Tuned RMP	40-10 Rule Proxy	Tuned RMP	40-10 Rule Proxy
Mean Catch	92	89	75	84
AAV	0.068	0.17	0.13	0.29
Fishery Closure Proportion	0.0015	0.31	0.069	0.57
Average Depletion	0.6	0.65	0.7	0.64
Proportion of Years < 20%K	0.0068	0.00003	0.017	0.042

Table 8 Performance of the RMP, 40-10 rule, and h_{MSY}-based rule managing a population starting at 20% of K in three periods; (a) Near term-first 10 years of management, (b) Mid term-the following 10 years of management, and (c) Long term-the following 20 years.

Starting Management at 20% of Carrying Capacity			
(a) Year 1 to 10	Tuned RMP	40-10 Rule Proxy	h_{msy}-based
Mean Catch	28	1	34
AAV	0.067	NA	0.008
Fishery Closure Proportion	0.00	0.98	0.00
Average Depletion	0.22	0.23	0.22
Proportion of Years < 20%K	0.0024	0.00073	0
(b) Year 11 to 21	Tuned RMP	40-10 Rule Proxy	h_{msy}-based
Mean Catch	38	8	37
AAV	0.041	NA	0.007
Fishery Closure Proportion	0.00	0.89	0.00
Average Depletion	0.24	0.30	0.24
Proportion of Years < 20%K	0.0065	0	0
(c) Year 22 to 42	Tuned RMP	40-10 Rule Proxy	h_{msy}-based
Mean Catch	41	15	39
AAV	0.040	NA	0.008
Fishery Closure Proportion	0.00	0.82	0.00
Average Depletion	0.25	0.33	0.25
Proportion of Years < 20%K	0.023	0	0.012

Figures

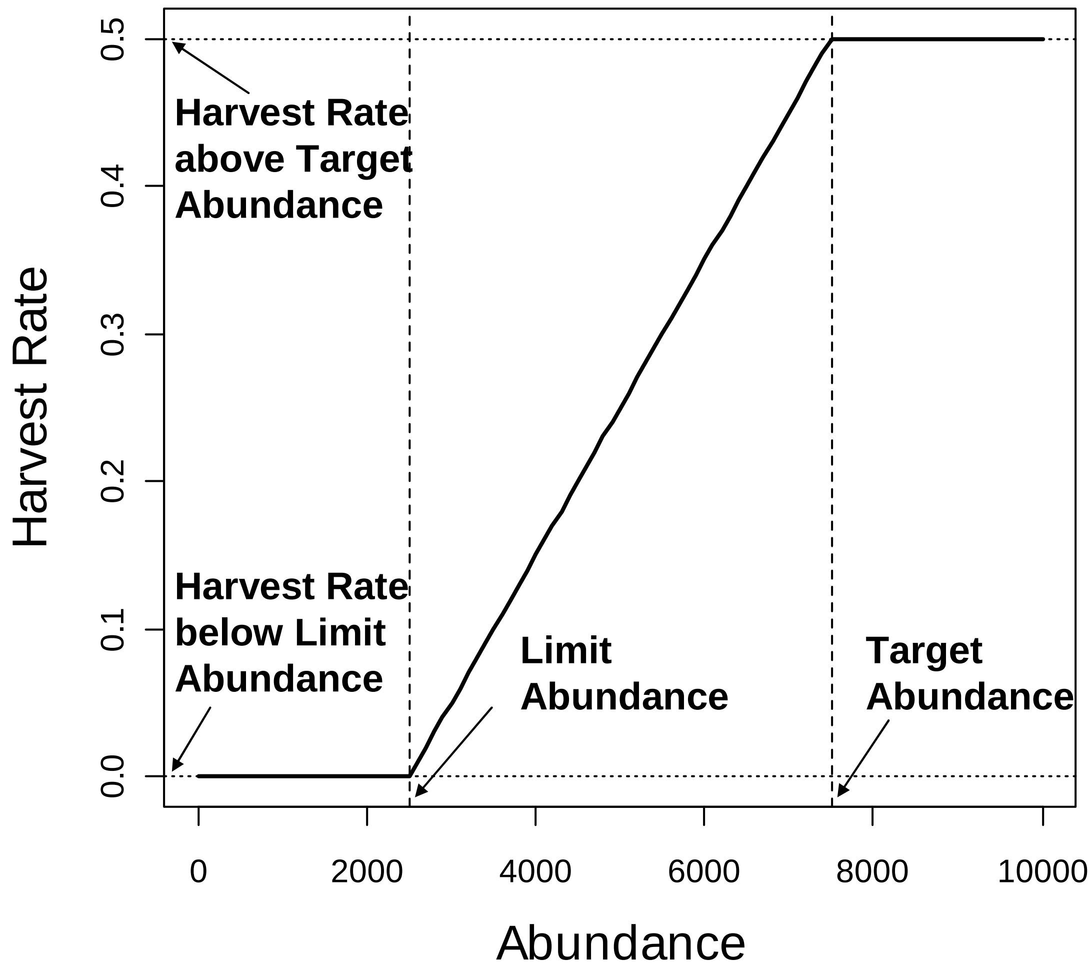

Figure 1 Threshold control rule: The harvest rate is a function of abundance. Dashed lines indicate the limit and target abundances, dotted lines indicate the harvest rates above the target abundance and below the limit abundance.

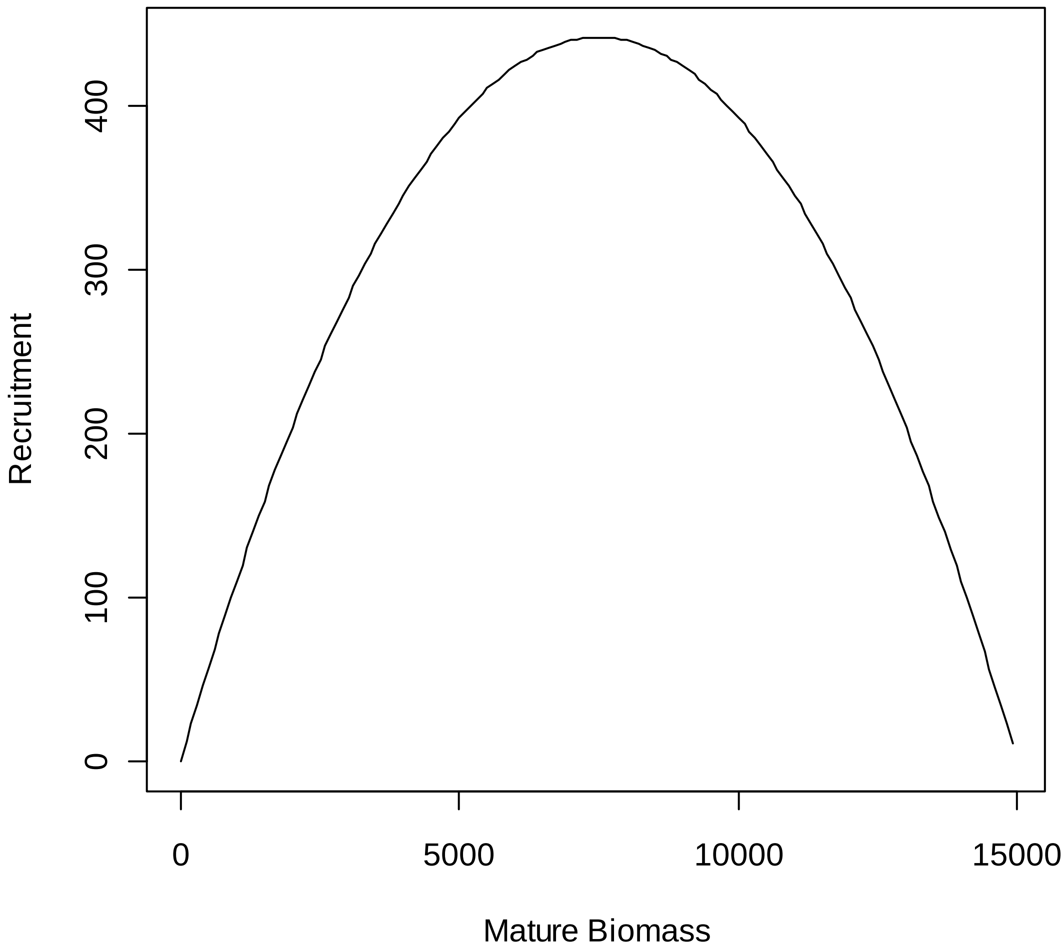

Figure 2 "True" population recruitment curve for the simulated species (*r*=0.039). The carrying capacity equals 10,000 and recruitment compensation equals 2, and annual natural mortality is 0.04.

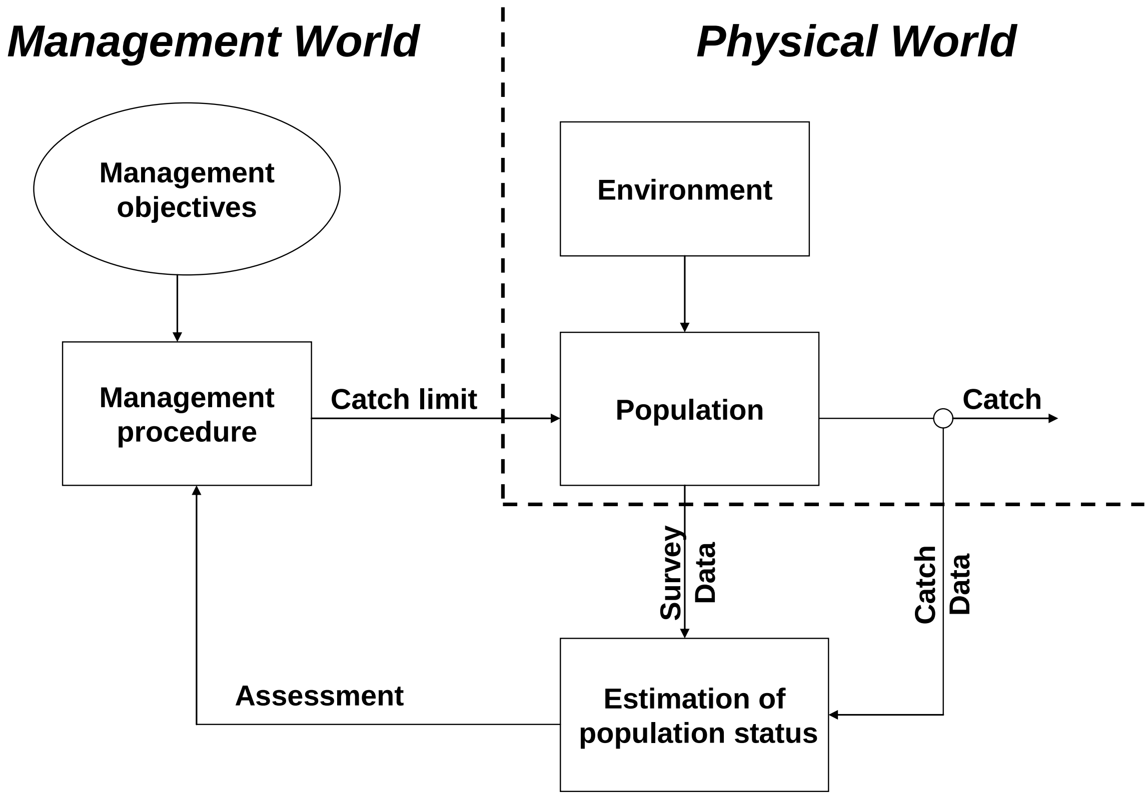

Figure 3 A diagram of an operating model in which the complete management system can be evaluated. The management world only has access to catch data and survey data to keep the "true" model from influencing estimates (adapted from de la Mare 1996).

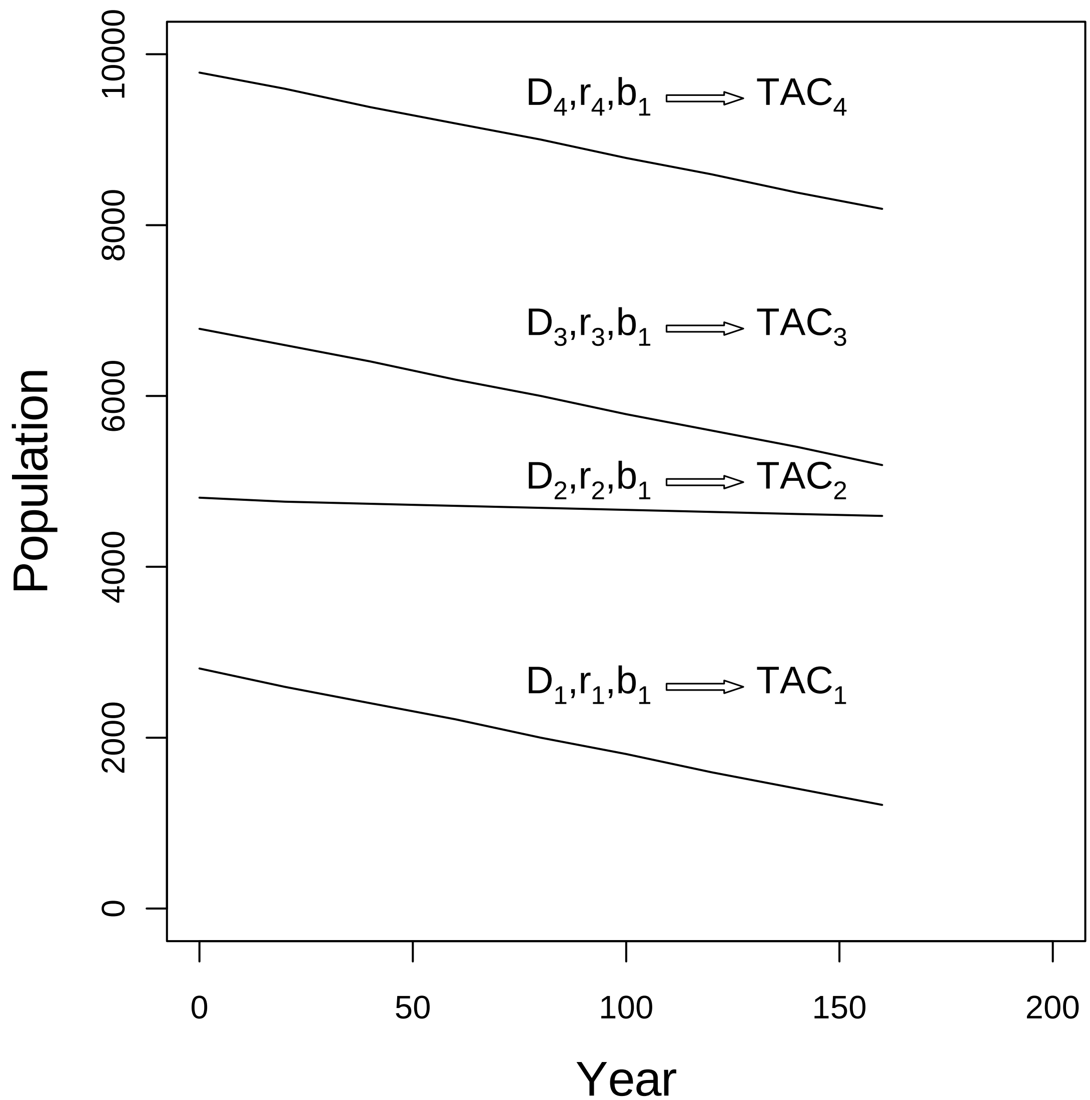

Figure 4 Catch limits are generated in a probabilistic way taking into account the prior probabilities of the depletion (D), productivity (r), and bias (b), and the likelihood of the current population estimate given the abundance index time series. From the uniform prior distributions, one of each parameter is selected to generate a population trajectory, the current abundance estimate is the value of the trajectory in the current year (in this case, year 160). The same parameters also generate a catch limit (TAC) based on the harvest control rule (adapted from de la Mare 1996).

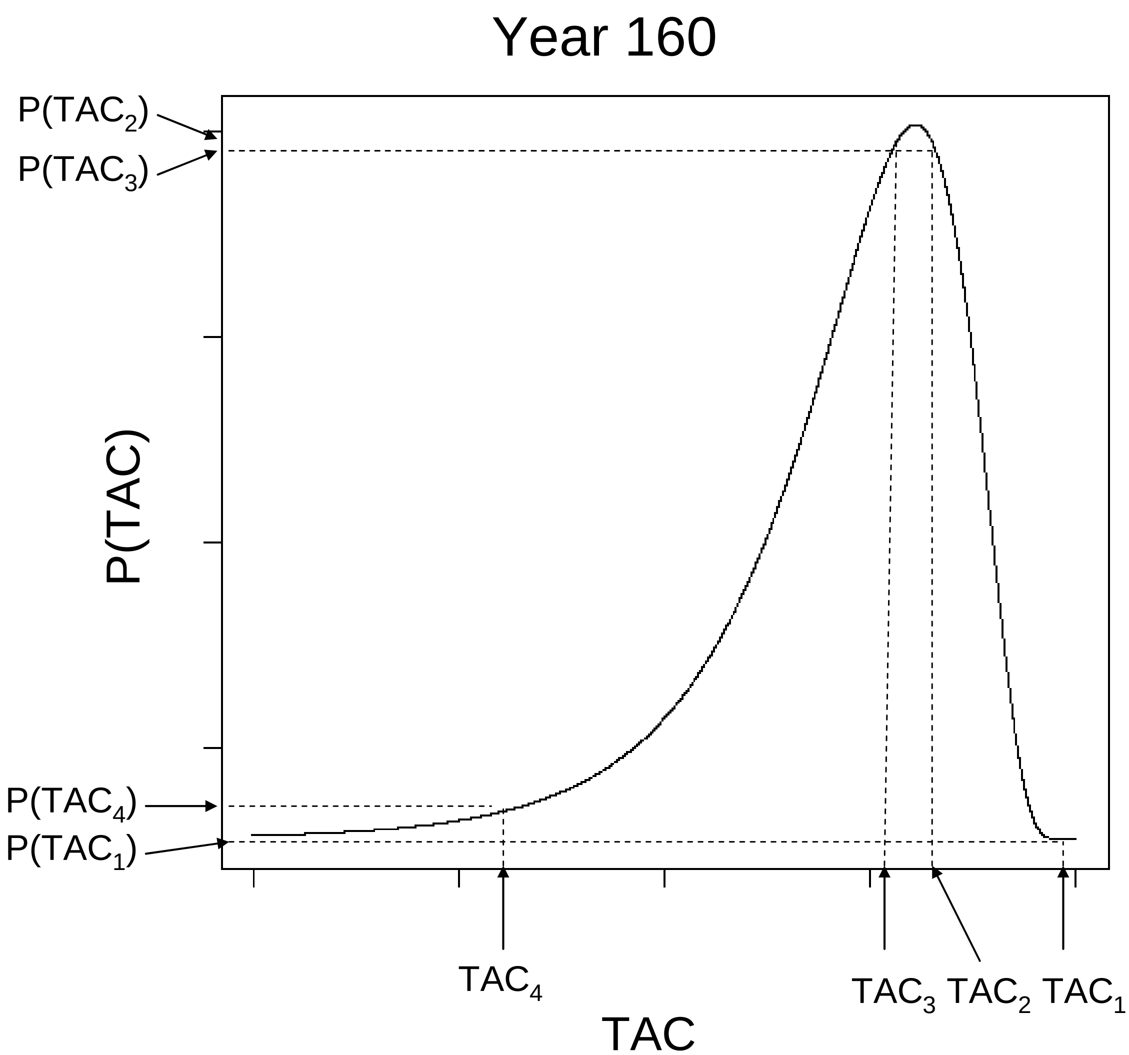

Figure 5 The likelihood of a current abundance estimate and the associated catch limit is based on the abundance index data. In the above example, the likelihood associated with the catch limit (TAC_1) generated based on D_1, r_1, b_1 would be low. The catch limits (TAC_2 and TAC_3) based on D_2, r_2, b_1 and D_3, r_3, b_1 respectively would have equally high likelihoods, and the catch limit (TAC_4) based on D_4, r_4, b_1 would have a low likelihood (figure adapted from de la Mare 1996).

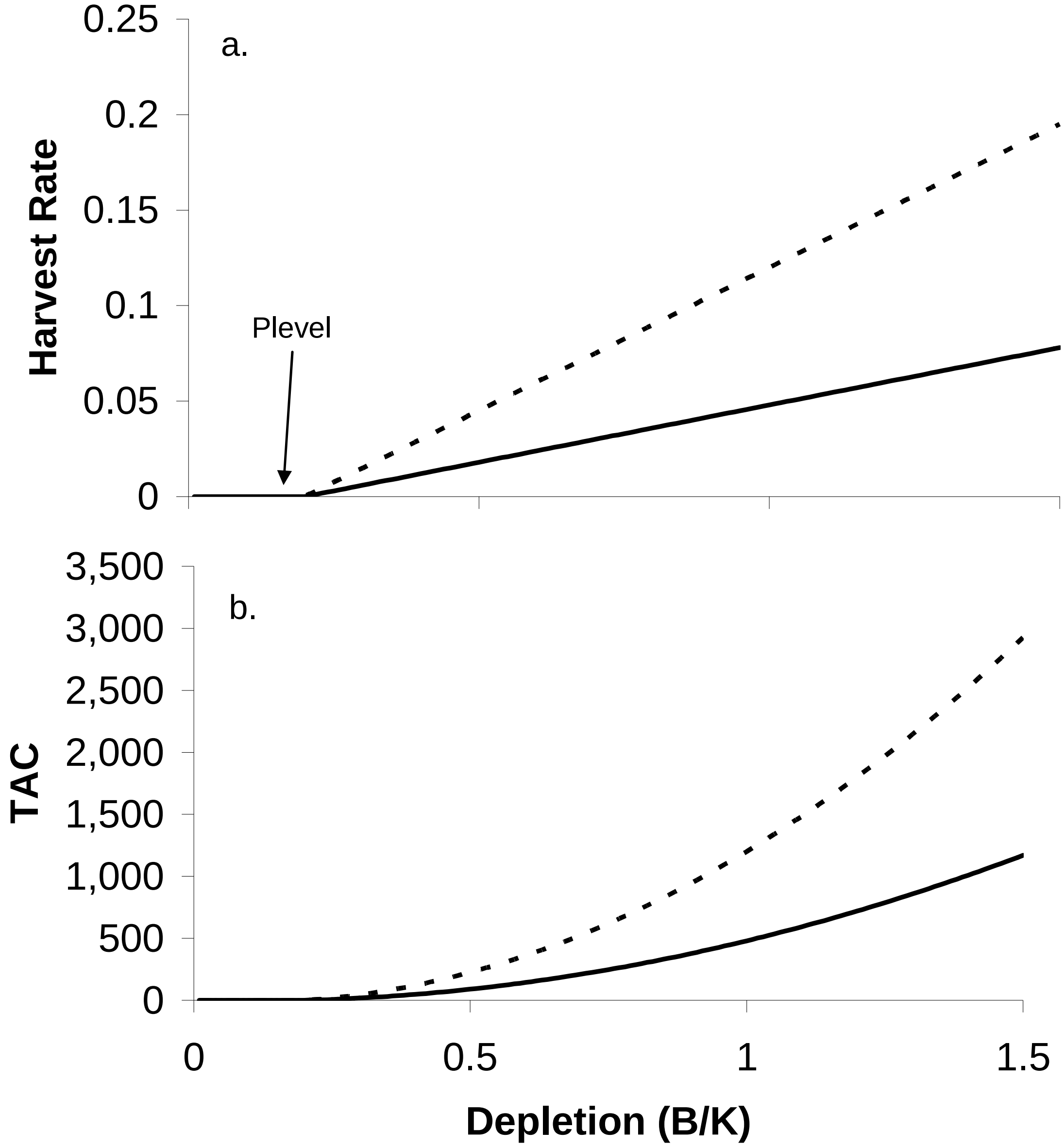

Figure 6 An example of the RMP harvest rule, a. Harvest rate as a function of depletion, Plevel is the no-fishing benchmark and Pslope = 3. b. TAC as a function of depletion given a carrying capacity of 10,000. The dashed line is based on an r of 0.05, the solid line is based on an r of 0.02.

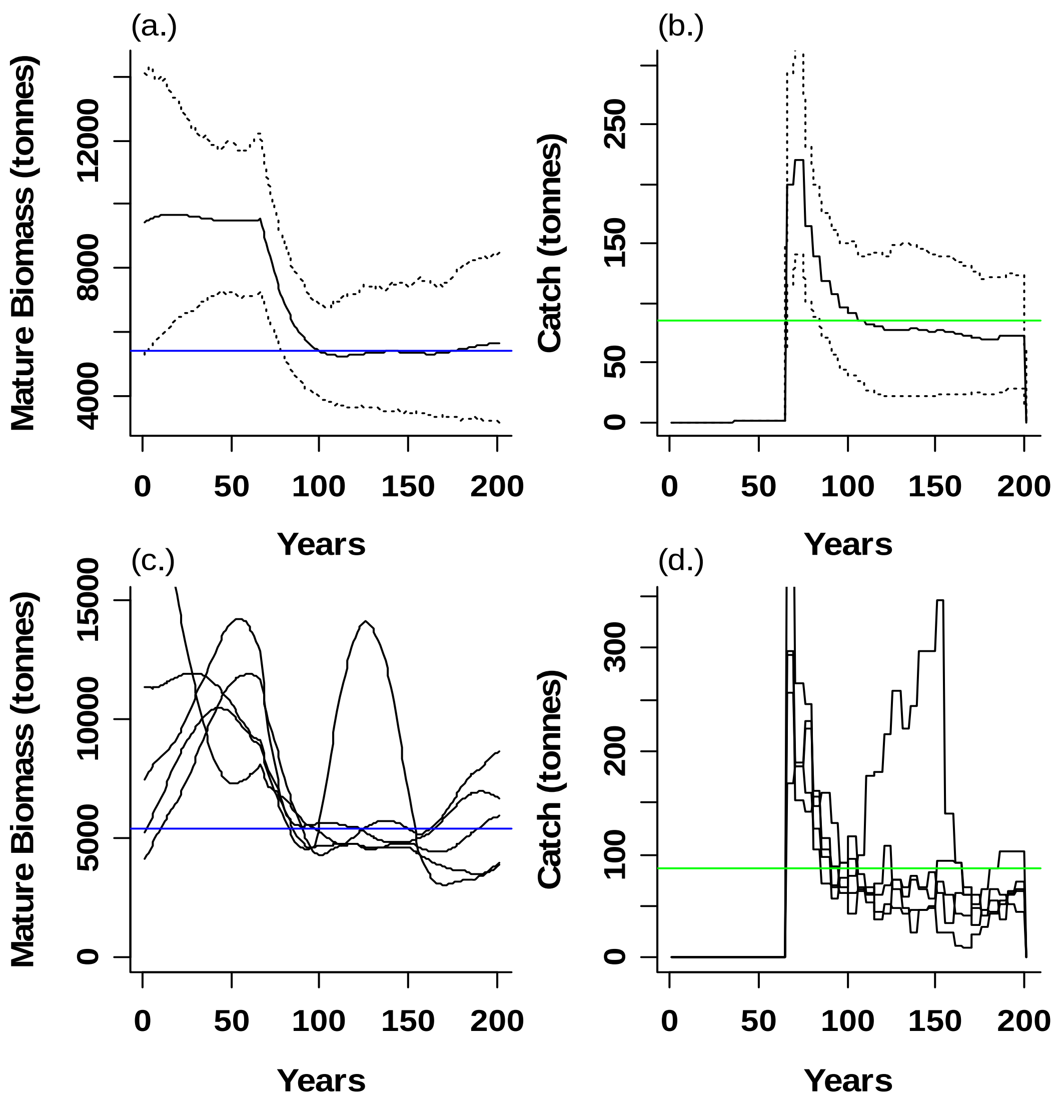

Figure 7 RMP performance in the baseline scenario, RMP applied starting in year 65: In the upper set of figures, the solid lines are the mean value in each year and the upper and lower lines are the 90th and 10th percentiles respectively. (a.) Biomass trajectory in 500 simulations. (b.) Catch trajectory in 500 simulations. (c.) Five individual biomass time series. (d.) Five individual catch time series. The blue lines are B_{MSY}, and the green lines are MSY.

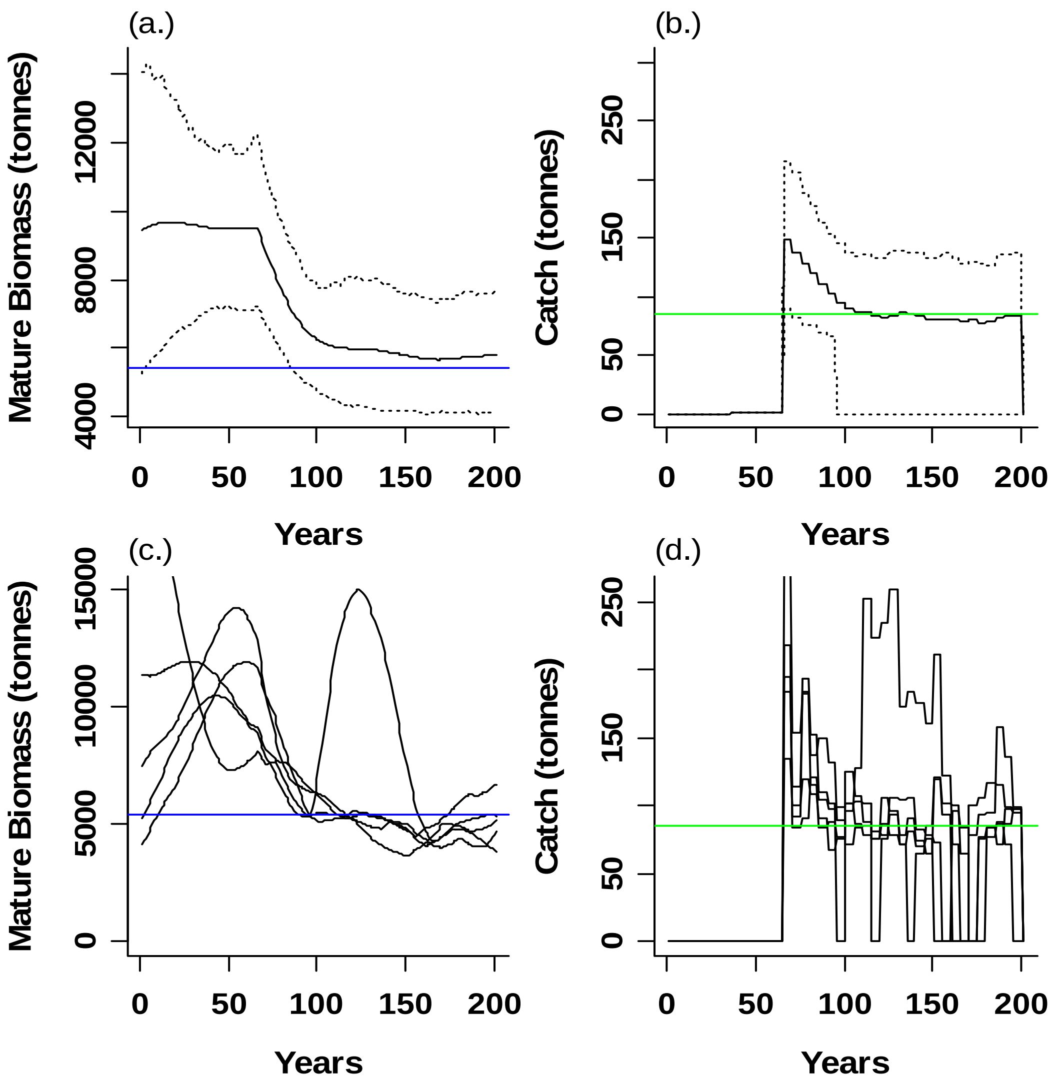

Figure 8 40-10 performance in the baseline scenario, 40-10 rule applied starting in year 65: In the upper set of figures, the solid lines are the mean value in each year and the upper and lower lines are the 90th and 10th percentiles respectively. (a.) Biomass trajectory in 500 simulations. (b.) Catch trajectory in 500 simulations. (c.) Five individual biomass time series. (d.) Five individual catch time series. The blue lines are B_{MSY}, and the green lines are MSY.

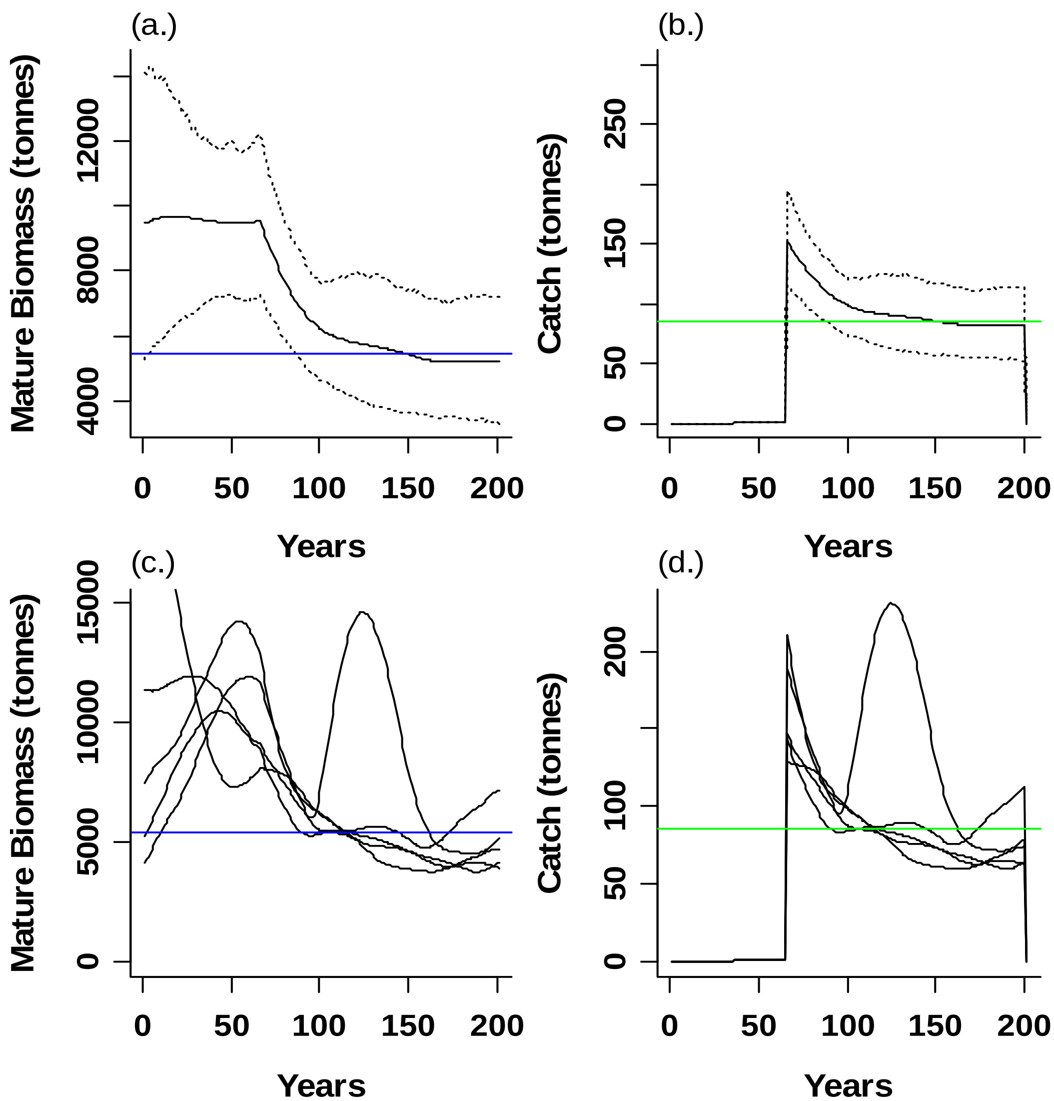

Figure 9 h_{MSY} rule performance in the baseline scenario, h_{MSY} rule applied starting in year 65: In the upper set of figures, the solid lines are the mean value in each year and the upper and lower lines are the 90th and 10th percentiles respectively. (a.) Biomass trajectory in 500 simulations. (b.) Catch trajectory in 500 simulations. (c.) Five individual biomass time series. (d.) Five individual catch time series. The blue lines are B_{MSY}, and the green lines are MSY.

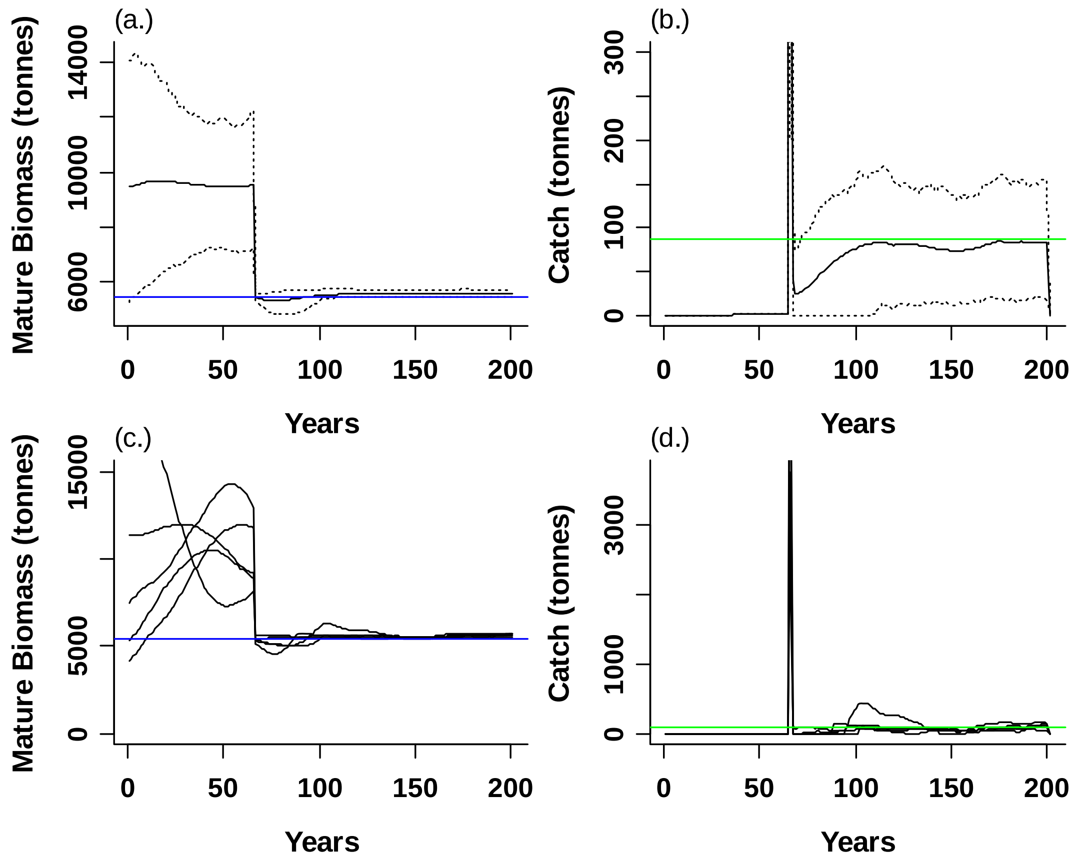

Figure 10 B_{MSY} escapement performance in the baseline scenario, h_{MSY} rule applied starting in year 65: In the upper set of figures, the solid lines are the mean value in each year and the upper and lower lines are the 90th and 10th percentiles respectively. (a.) Biomass trajectory in 500 simulations. (b.) Catch trajectory in 500 simulations. (c.) Five individual biomass time series. (d.) Five individual catch time series. The blue lines are B_{MSY}, and the green lines are MSY.

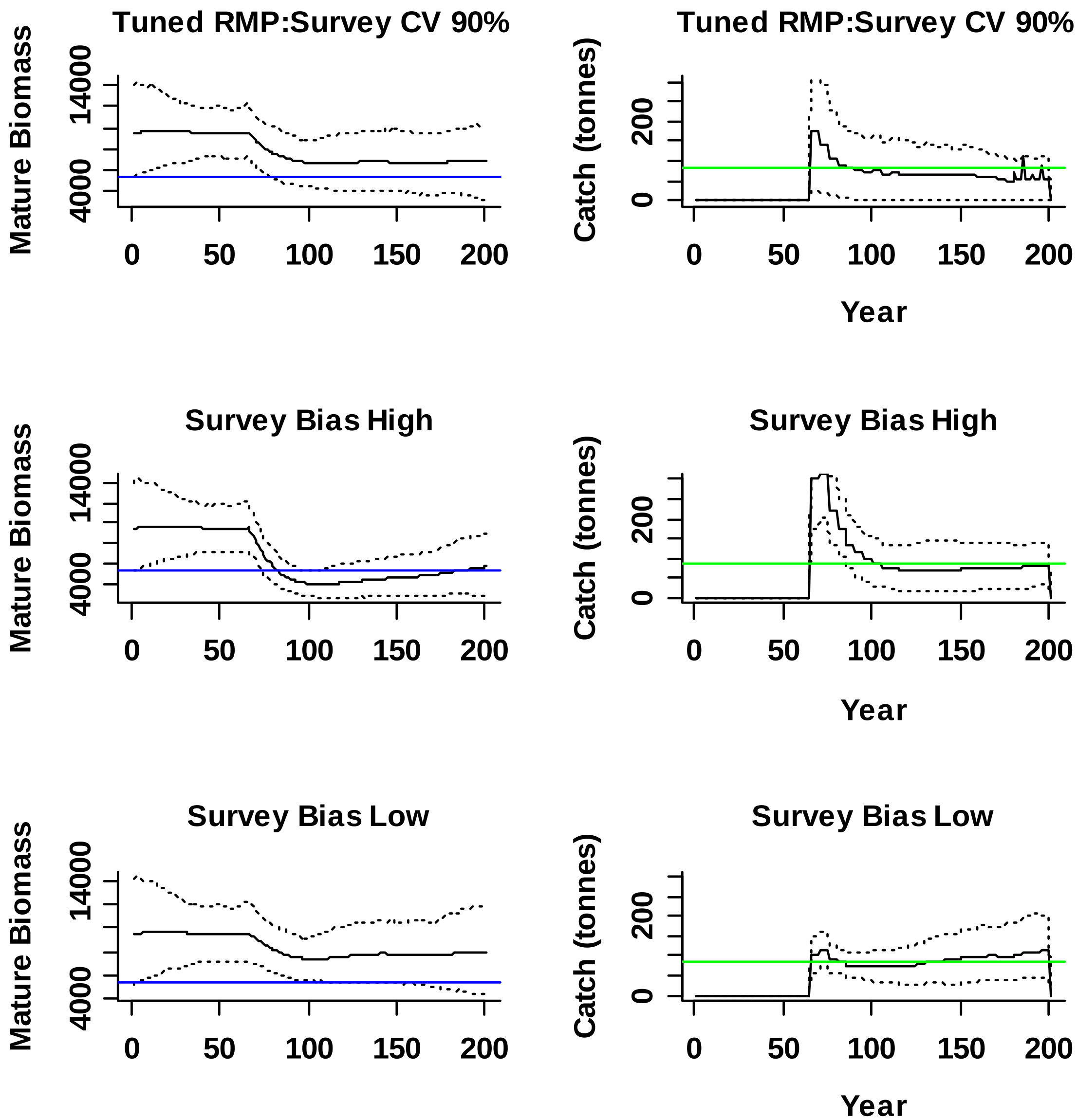

Figure 11 RMP survey variability and bias results: the solid lines are the mean value in each year and the upper and lower lines are the 90th and 10th percentiles respectively. The blue line is B_{MSY}, and the green line is MSY.

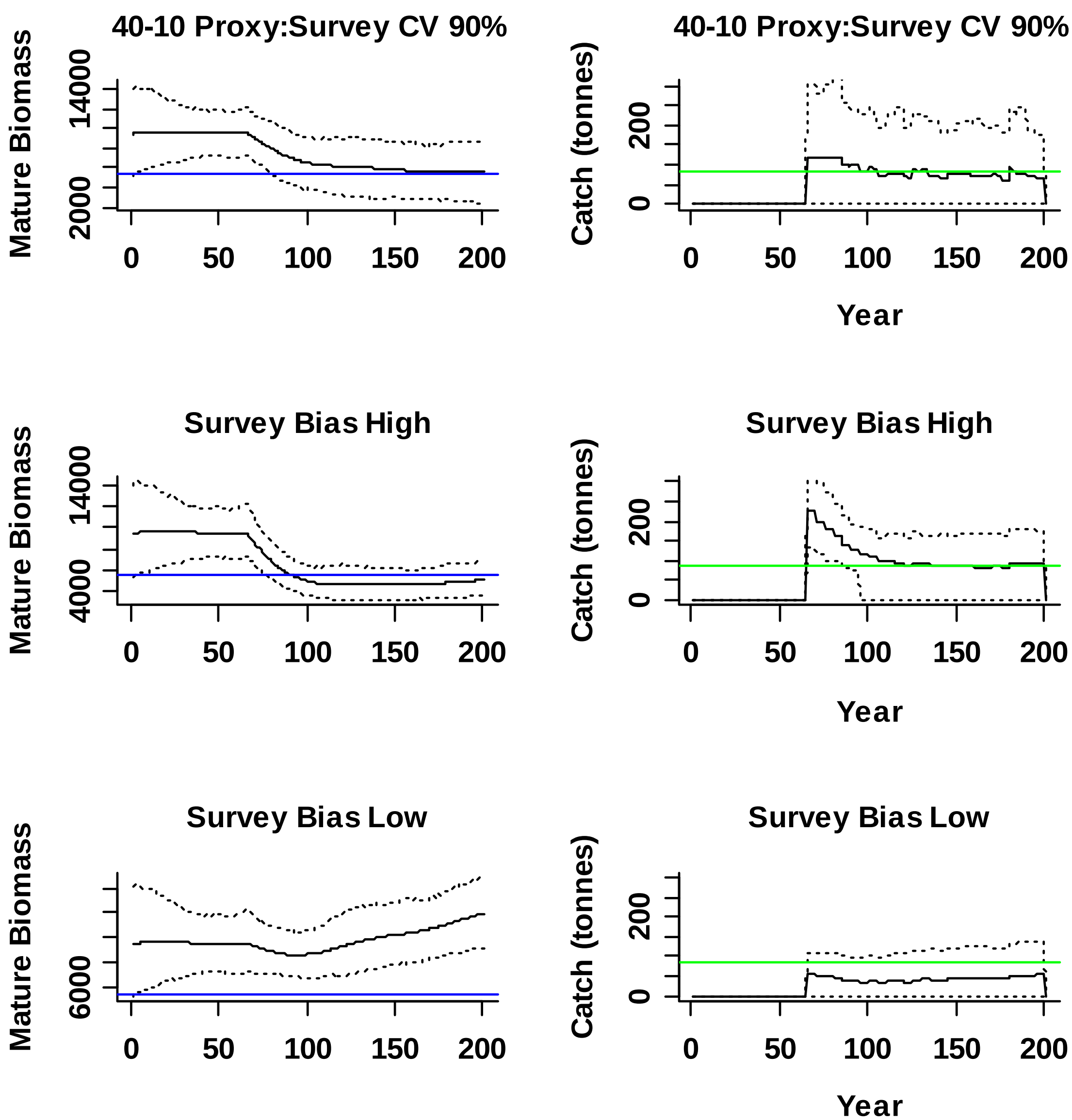

Figure 12 The 40-10 rule survey variability and bias results: the solid lines are the mean value in each year and the upper and lower lines are the 90th and 10th percentiles respectively. The blue line is B_{MSY}, and the green line is MSY.

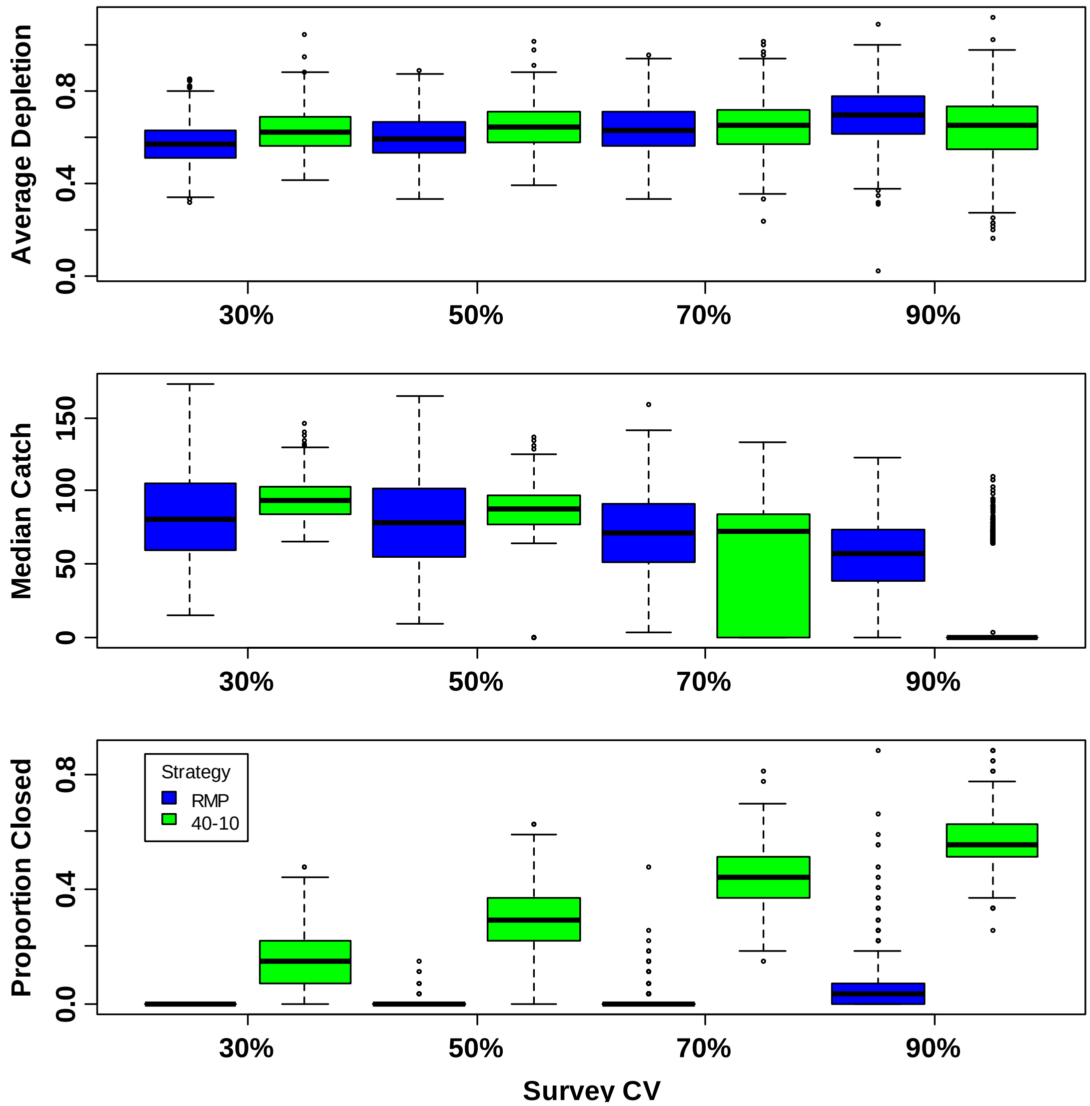

Figure 13 Performance of the RMP and the 40-10 rule at various levels of survey variability: These plots were generated based on the baseline species and scenario varying only the survey CV.

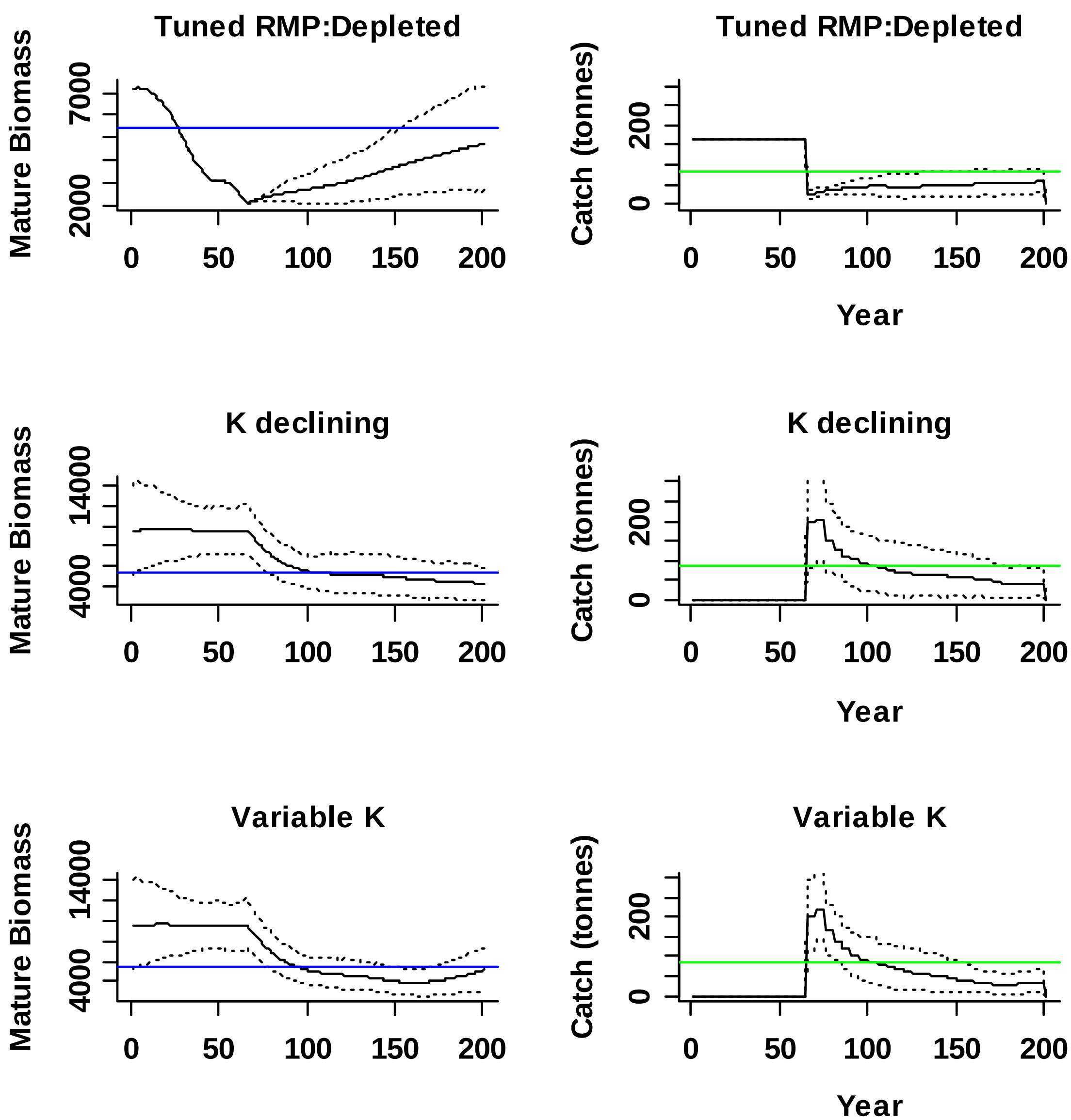

Figure 14 RMP depletion and changes in carrying capacity results: The solid lines are the mean value in each year and the upper and lower lines are the 90th and 10th percentiles respectively. The blue line is B_{MSY}, and the green line is MSY.

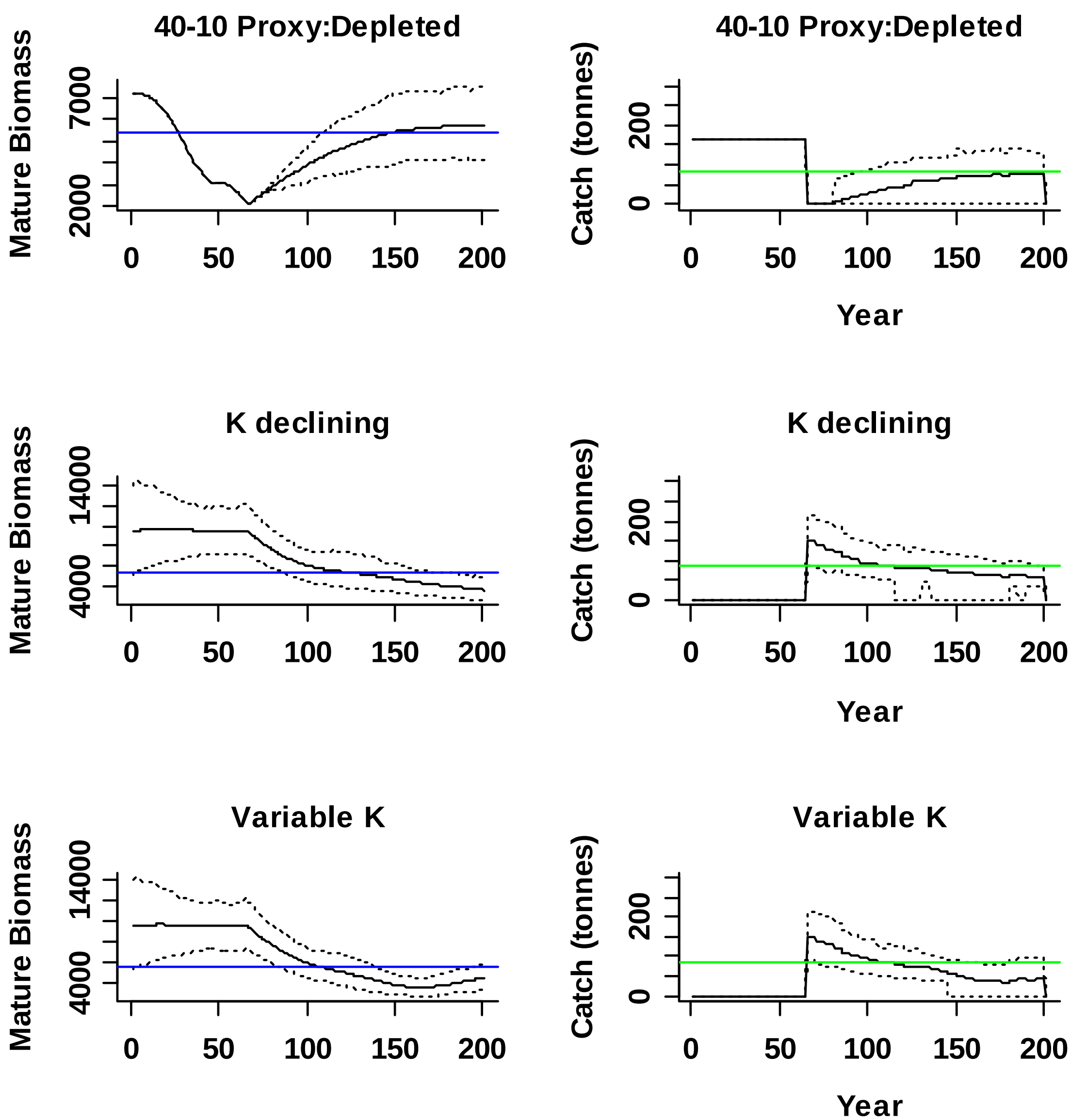

Figure 15 40-10 rule depletion and changes in carrying capacity results: the solid lines are the mean value in each year and the upper and lower lines are the 90th and 10th percentiles respectively. The blue line is B_{MSY}, and the green line is MSY

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