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The impact of climate change on the performance of rebuilding strategies for overfished groundfish species of the U.S. west coast

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ABSTRACT

Management Strategy Evaluation is used to evaluate the performance of management procedures based on how management decisions are made for groundfish stocks off the U.S. west coast. The analyses focus on rebuilding the stock of Pacific ocean perch to its target level when future recruitment may exhibit a long-term trend, owing to environmental forcing. Several variants of the management procedure currently used to provide scientific management advice for U.S. west coast groundfish are evaluated. The performance of variants of this management procedure which “know” (on average) the true relationship between recruitment and the environmental variable driving recruitment is not superior to that of a management procedure which bases forecasts of recruitment on average historical recruitment. Moreover, the best performance in terms of recovery rates occurs when rebuilding decisions are based on a relatively high probability of recovery.

1. Introduction

The U.S. Magnuson-Stevens Fishery Conservation and Management Act, as amended by the Sustainable Fisheries Act of 1996 (U.S. Public Law 104–297) requires that rebuilding plans be developed for stocks designated as “overfished” to rebuild them to the biomass (B_{MSY}) associated with maximum sustainable yield (MSY). Each of the U.S. Regional Fishery Management Councils has a slightly different definition of “overfished”, and this definition can also depend on taxon. The Pacific Fishery Management Council (PFMC), which provides management recommendations for fisheries off the U.S. west coast (California, Oregon and Washington), defines a groundfish stock to be “overfished” if spawning output (usually based on spawning biomass) is assessed to be below a pre-specified percentage (15% for flatfishes and 25% for all other groundfish) of the estimated spawning output in an unfished state. Eight groundfish stocks are currently under rebuilding plans because they have been declared to be overfished: bocaccio rockfish (*Sebastes paucispinis*), canary rockfish (*S. pinniger*), Pacific ocean perch (*S. alutus*), cowcod (*S. levis*), dark-blotched rockfish (*S. crameri*), widow rockfish (*S. entomelas*), yelloweye rockfish (*S. ruberrimus*), and petrale sole (*Eopsetta jordani*).

Rebuilding plans are informed by technical rebuilding analyses that use age-structured simulation models to project populations forward in time (PFMC, 2008; Punt, 2003; Holt and Punt, 2009). The projections reflect the current state of the stock as it is perceived through stock assessments and how stock biomass is expected to change in the future under different harvest strategies (generally, levels of fishing mortality). For U.S. west coast groundfish, the PFMC then chooses a fishing mortality rate (usually expressed in terms of spawning potential ratio, *SPR*[1]) given the trade-off between recovery time and reductions in yield, and hence impacts on fishing communities.

Recovery of some of these stocks may require decades because they are slow-growing (>50-year lifespan in some cases) and appear to be to have very low productivity (Table 1). However, despite compelling evidence for climate effects on fish populations off the U.S. west coast (Hare and Mantua, 2000; Hollowed et al., 2001; Mantua et al., 1997; Schirripa and Colbert, 2006), the projections that underlie rebuilding plans have not included environmental drivers.

Holt and Punt (2009) extended the conventional approaches used to conduct rebuilding analyses to evaluate the sensitivity of outputs from these analyses to two hypotheses about climate effects on recruitment (temporal auto-correlation due to unknown factors, and reduction in expected recruitment due to a delay in the date of spring transition) for an overfished stock, *S. alutus*. They found that catch limits, probabilities of rebuilding to target lev-

[1] The Spawning Potential Ratio (*SPR*) is a measure of the expected spawning output-per-recruit, given a particular fishing mortality rate, *F*, the fishery selectivity pattern, and the stock’s biological characteristics, i.e., there is a direct mapping of *SPR* to *F* (and *vice versa*).

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Table 1
Rebuilding plan specifications for eight depleted U.S. west coast groundfish species (John DeVore, PFMC, pers. commn).

Species	Year stock declared overfished	T_{MAX}[a]	$T_{F=0}$[b]	T_{TARGET}[c]	P_{rec}[d]	Harvest control rule (SPR harvest rate)
Bocaccio rockfish	1999	2031	2019	2022	0.868	$F_{77.7\%}$
Canary rockfish	2000	2046	2024	2027	0.750	$F_{88.7\%}$
Cowcod	2000	2097	2060	2071	0.662	$F_{79.0\%}$
Darkblotched rockfish	2000	2037	2016	2025	0.852	$F_{64.9\%}$
Pacific ocean perch	1999	2045	2018	2020	0.897	$F_{86.4\%}$
Widow rockfish	2001	2035	2010	2015	1.000	$F_{91.7\%}$ [e]
Yelloweye rockfish	2002	2089	2047	2084	0.523	$F_{72.8\%}$
Petrale sole	2010	2020	2014	2016		NA [f]

[a] T_{MAX} is the year by which recovery must occur with 50% probability.
[b] $T_{F=0}$ is the median year in which the stock will rebuild if all fishing-related mortality were eliminated beginning in 2011.
[c] T_{TARGET} is the median year in which the stock will rebuild given the current harvest control rule.
[d] P_{rec} is the probability of recovery by the T_{MAX} given the current harvest control rule.
[e] The preferred ACL alternative for 2011–2012 is a constant catch of 600 mt. This level of catch corresponds to an SPR harvest rate of $F_{91.7\%}$ in 2011.
[f] The preferred rebuilding plan for petrale sole is to apply a variable harvest rate strategy after 2011 using the 25-5 harvest control rule.

els, and times for rebuilding were sensitive to assumptions about recruitment.

Holt and Punt (2009) conducted projections under the assumption of a fixed time-invariant fishing mortality rate. However, this is not how management decisions for overfished stocks are made in reality. Rather, the target fishing mortality rate, and occasionally even the target year for recovery, are updated regularly (usually every 2nd year for species that are under rebuilding plans for PFMC-managed fisheries) taking account of the results of the most recent stock assessment. The process of conducting regular stock assessments and updating management regulations using predetermined decision rules can be considered to be an instance of a management procedure (Butterworth, 2007; Punt, 2006). As such, it is possible that some of the effects observed by Holt and Punt (2009) could be ameliorated by the feedback nature of the management system.

Therefore this paper evaluates the performance of the current approach to constructing and using rebuilding plans for management decision making.[2] Additional rebuilding plan variants evaluated include cases where productivity is assumed to be driven by climate. Specific scenarios include the timing of spring transition, where it has been postulated that delayed (early) spring transition could lead to much lower (faster) recovery times for overfished species (Holt and Punt, 2009). For example, annual recruitment of sablefish (*Anoplopoma fimbria*), expressed as deviations from expected recruitment given the amount of spawning output, is significantly positively related to the timing of spring transition (i.e., recruitment was poor when spring transition was delayed) (1972–2006; $r^2 = 0.44$, $p < 0.001$, M. Schirripa, Northwest Fisheries Science Center, NOAA Fisheries, Newport, Oregon, 97365, USA, unpublished analyses). Several studies have linked abundance and recruitment of Pacific groundfishes to environmental variables (e.g. Brodeur et al., 2006; Laidig et al., 2007; Moser et al., 2000). In common with Holt and Punt (2009), the analyses are based on the situation for Pacific ocean perch because this species spawns and rears at similar locations and time as sablefish (Starr et al., 2002), and unlike sablefish, Pacific ocean perch is overfished. This study differs from others (e.g. A'mar et al., 2009) that have explored the impact of climate-induced forcing on the performance of management procedures because the focus of this paper is on strategies which apply during rebuilding after a stock has been declared overfished. The aim of this paper is not to make predictions of what will occur (the similarity between sablefish and Pacific ocean perch early life history is not that great), but rather whether the management system is robust to the possibility of climate-induced changes in mean recruitment.

[2] To the extent that a decision making process can ever be represented in the form of a set of decision rules that might be applied over an extended period of time.

2. Material and methods

2.1. Basic approach

Evaluation of the performance of a management procedure (in this case the combination of a method of stock assessment and a method for specifying catch limits given objectives related to recovery), often referred to as Management Strategy Evaluation (MSE), involves the following steps (Punt, 2006):

(a) Specification of an 'operating model' that represents the true dynamics of the population for the purposes of the simulations.
(b) For each year of the projection period:
   1. Generate the data available for stock assessment purposes.
   2. Every fourth year, assess the status of the stock:
      i. apply a stock assessment method to estimate stock status; and
      ii. determine whether it is necessary to modify the current rebuilding plan (either the target fishing mortality rates or the entire plan) given the results of the assessment and make the modifications to the plan if necessary.
   3. Calculate a catch limit given the results of the most-recent assessment and rebuilding plan.
   4. Update the dynamics of the population represented in the operating model under the assumption that the catch limit is taken exactly[3] (recruitment will depend on scenarios regarding how, if it all, climate impacts expected recruitment).
(c) Repeat step (b) many times and compile a set of performance metrics.

The projections are conducted over a 80-year period although recovery occurs in the bulk of the Monte Carlo replicates within the first 20–40 years for the scenarios without declining recruitment.

2.2. The operating model

S. alutus are found from southern California across the North Pacific to Japan. In the North Pacific, they are caught in trawl fisheries and are managed separately off Alaska, Canada, and the West Coast of the U.S. (California, Oregon and Washington). In common with many Northeast Pacific rockfishes, *S. alutus* is long-lived (aged up to 98 years in Alaska waters) and slow-growing. The operating model is an age- and sex-structured population dynamics model that mimics the 2007 stock assessment model for *S. alutus* (Hamel, 2007a). Although the stock assessment included a fitted

[3] This study therefore ignores "implementation error".

Table 2
(a) Parameter values for two models of age-3 recruitment that include either temporal autocorrelation (Eq. (1)) or an environmental variable, the date of spring transition (Eq. (2)). (b) Parameter values for the trends over time and random variability in dates of spring transition for four scenarios (Eq. (3)). *Source*: Holt and Punt (2009).

Scenario	Parameter value		
(a)			
	b_0	ρ	σ_ν
With autocorrelation	7.672	0.459	0.662
	c_0	c_1	σ_ε
With environmental variable	8.665	−0.0102	0.674
(b)			
	d_0	d_1	σ_τ
No trend in the date of spring transition	4.536	0	0.211
15-Day delay in spring transition over 100 years	4.536	0.00137	0.211
30-Day delay in spring transition over 100 years	4.536	0.00273	0.211
60-Day delay in spring transition over 100 years	4.536	0.00547	0.211

stock-recruitment relationship, it was not considered adequate for projection purposes in rebuilding calculations (Hamel, 2007b). In common with Holt and Punt (2009), this stock-recruitment relationship was only used to determine the unfished average spawning biomass (which is assumed to remain constant over the simulations for the purpose of defining the true management targets). Following Holt and Punt (2009), it was assumed that future recruitment at age 3 is either governed by an auto-regression (AR-1) process or is related to the timing of spring transition 3 years prior.

The temporally auto-correlated recruitment scenario for Pacific ocean perch involved generating future age-3 recruitments using the equation:

$$\ell n(R_y) = b_0 + u_y, \quad u_y = \rho u_{y-1} + \nu_y, \quad \nu_y \sim N(0, \sigma_\nu^2) \tag{1}$$

where R_y is age-3 recruitment in year y, b_0 is a constant, u_y is the lag-one auto-correlated deviation from that constant, ρ is an autoregressive coefficient, and ν_y is normally distributed error with variance σ_ν^2 (Table 2a). The deviation for the year prior to the first year of the projection period, u_{2007}, is set to $\ell n(R_{2007}) - b_0$. Recruitments are in thousands of fish and are corrected for back-transformation bias (i.e., $E(R_y) = \exp(E(\ell n(R_y)) + \sigma_\nu^2/2)$.

Although precise projections of the timing of spring transition over the next several decades are not available, one regional climate model of the California Current (Snyder et al., 2003) suggests that spring transition will be delayed by up to one month with a doubling of atmospheric CO_2 concentrations (occurring over the next 100 years). Holt and Punt (2009) assumed an exponential increase in the date of spring transition over time corresponding to that prediction (over 100 years) with log-normal random variation in those dates around expected values, corresponding to the historical pattern of variability, i.e.:

$$\ell n(R_y) = c_0 + c_1 x_y + \varepsilon_y, \quad \varepsilon_y \sim N(0, \sigma_\varepsilon^2) \tag{2}$$

$$\ell n(x_y) = d_0 + d_1 (y - 2007) + \tau_y, \quad \tau_y \sim N(0, \sigma_\tau^2) \tag{3}$$

where c_0, c_1, d_0 and d_1 are parameters, x_y is the date of spring transition (lagged 3 years to account for the age-at-recruitment), ε is a normally distributed random error with variance σ_ε^2, and τ is normally distributed error with variance σ_τ^2. The x_y values for 2006–2010, were based on the actual estimates of spring transition for 2003–2007; after 2010, age-3 recruitments were generated from forward projections of dates of spring transition using Eq. (3). Scenarios considered different delays in spring transition (and related declines in recruitment) (Table 2b) to assess the sensitivity of outcomes of the management decision making framework to various hypotheses about future trends in spring transition.

The data generated for each year of the projection period are the annual catch (assumed to be known exactly), a survey index of abundance (CV = 0.5), and the age-composition of the fishery and survey catches (effective sample sizes of 50 for both types of data). These values are consistent with the data in the actual assessment.

2.3. The management procedure

The management procedure consists of a number of components; each is discussed in turn below:

(A) application of a stock assessment method to estimate time-series of historical numbers-at-age, spawning biomass, recruitment, etc. The stock assessment method is based on the 2007 stock assessment (Hamel, 2007a), which estimates parameters related to recruitment, catchability, natural mortality, stock-recruitment steepness, fishing mortality, and survey and fishery selectivity;
(B) application of a rebuilding analysis (in the first year of the projection period and every time a stock assessment is conducted); and
(C) application of rules to decide how to change management actions (catch limits) given the results of the stock assessment and the rebuilding analysis.

The objective of a rebuilding analysis is to evaluate the consequences of alternative harvesting strategies (levels of fishing mortality), in terms of the catches during the rebuild period and the time to recover to 40% of the unfished spawning output, $0.4B_0$. $0.4B_0$ is the default proxy for the target biomass of B_{MSY} for rockfishes off the U.S. west coast. The main steps involved in conducting a rebuilding analysis (PFMC, 2008; Punt, 2003; Holt and Punt, 2009) are:

(1) estimate B_0 by multiplying the average historical recruitment by the estimated spawning output-per-recruit in the absence of exploitation;
(2) calculate the minimum rebuilding time, T_{MIN}, by projecting the population forward 1000 times in the absence of future fishing mortality to generate future recruitments by either (a) sampling at random from past recruitments or (b) using a relationship between recruitment and timing of spring transition. T_{MIN} is the defined as the median of the years when projected spawning output first reaches $0.4B_0$;
(3) set T_{MAX} to the maximum of 10 years and the sum of the mean generation time and T_{MIN}; and
(4) project the population forward under a range of harvest strategies based on various constant fishing mortality rates, equivalent to constant SPR harvest strategies. The target fishing mortality, and the time-series of future catches, is selected so that the probability of recovery by T_{MAX} is equal to a pre-specified value, P_{rec} (see below for details).

A rebuilding analysis is always conducted at the start of the first year of the projection period. This rebuilding analysis determines the initial value for T_{MAX} and the fishing mortality (and the SPR, referred to as SPR_{curr}) corresponding to P_{rec}, the probability of recovery to $0.4B_0$ by T_{MAX}. The data supplied to the assessment (and hence the rebuilding plan) are the same at the start of each Monte Carlo replicate (it is the actual data for *S. alutus*) and so the values for quantities such as T_{MAX} are the same for all replicates for a given management procedure. Each year, t, that an assessment is conducted (every 4th year for 80 years – selected to reduce the computational demands of the analyses to a reasonable amount), the

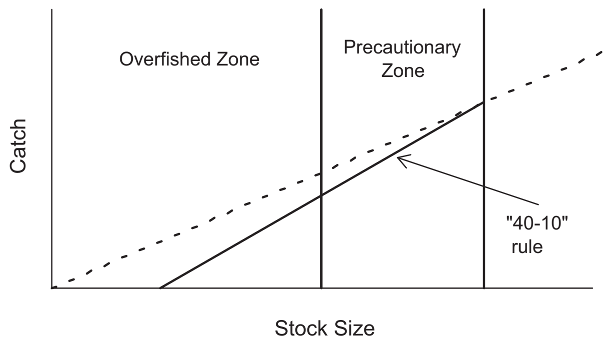

Fig. 1. The 40-10 control rule used to set catch limits for stocks that are not considered overfished.

catch limits for the subsequent 4 years are set using the following algorithm:

(1) If the stock is assessed to be above $0.4B_0$ or the stock is not currently under a rebuilding plan (because it rebuilt in some earlier year) set the catch limit based on the default 40-10 control rule for U.S. west coast groundfish stocks (Fig. 1). The target fishing mortality rate for the control rule is $F_{50\%}$ ($F_{50\%}$ is the fishing mortality for which spawner-biomass-per-recruit is reduced to 50% of its unfished value) End.
(2) If the stock was not under a rebuilding plan during year t, but is now assessed to be overfished (spawning output < $0.25B_0$), use a rebuilding analysis to determine the (new) values for T_{MAX} and the fishing mortality corresponding to a probability of recovery to $0.4B_0$ by T_{MAX} of P_{rec}. End.
(3) Compute the probability of recovery to the target level by T_{MAX} under an SPR of SPR_{curr}, P_{curr}.
(4) If P_{curr} is greater than a threshold probability of recovery, P_{thresh}, then set the catch limits for years $t+1$ to $t+4$ to the catches corresponding to SPR_{curr}. End.
(5) Compute the fishing mortality (and SPR) so that the probability of recovery is P_{thresh}.
(6) If a fishing mortality exists that satisfies step (5), set SPR_{curr} and the catch limits for years $t+1$ to $t+4$ based on this fishing mortality. End.
(7) If no fishing mortality exists that satisfies step (5) because recovery to $0.4B_0$ cannot occur by T_{MAX} with probability P_{thresh} even if fishing mortality is zero, declare the current rebuilding plan a "failure" and start a new rebuilding plan (i.e., compute T_{MAX}, T_{MIN} and SPR_{curr} based on a rebuilding plan starting in year t).

Punt and Ralston (2007) summarize the values for P_{rec} (referred to as P_{MAX} in their paper) for each overfished rockfish species when their rebuilding plans were originally developed and explore the implications of different choices for the values for the parameters P_{rec} and P_{thresh}. The values for these parameters in this study were respectively set to 0.6 (an initial probability of recovery by T_{MAX} of 60%) and 0.5 (a 50% probability of recovery overall) respectively for the "Reference" management procedure, although limited sensitivity is explored to alternative values. A 60% probability allows for a buffer between the value of P_{rec} and the minimum probability of recovery, P_{thresh}. The buffer accounts, to some extent, for the effects of estimation error.

2.4. Performance measures

Many statistics could be used to summarize the performance of a management procedure. This study focuses on the four of the five management goals identified by Punt and Ralston (2007), i.e.: (a) a high probability of the stock recovering by the T_{MAX} selected when the rebuilding plan was originally developed, (b) high catches during rebuilding, (c) low interannual variation in catches, and (d) stability in the rebuilding plan (i.e., minimizing the number of rebuilding plan failures). The first three of these four goals are typical of those commonly selected when evaluating management procedures. The fourth goal is included because it measures the "administrative cost" of a management procedure; changing the SPR used to set the catch limit and changing catch limits themselves is relatively straightforward administratively. In contrast, changing T_{MAX} following a rebuilding plan failure may require an amendment to the Fishery Management Plan.

The performance measures used to quantify these four goals are:

(1) The years in which recovery to the B_{MSY} occurred (if recovery occurred at all) and in which recovery to B_{MSY} was perceived (through the simulated stock assessment) to have occurred.
(2) The "rebuilding ratio," the ratio of the difference in the number of years between the actual and perceived number of years to recovery (y_{rec}^{True} and y_{rec}^{Perc}) to the difference between the actual number of years to recovery and 2048 [the year that recovery to B_{MSY} is predicted to occur based on the reference management procedure when the rebuilding plan is first implemented], i.e.:

$$R = \frac{y_{rec}^{True} - y_{rec}^{Perc}}{y_{rec}^{True} - 2048} \tag{4}$$

if the rebuilding ratio exceeds unity then rebuilding took longer than assessment suggested would be the case, i.e., the stock was declared recovered too early.

(3) The number of times the rebuilding plan was a failure and it was consequently necessary to change the value of T_{MAX} (abbreviation "Plan restarts").
(4) The average catch during the first 10 years of the rebuilding period.
(5) The average catch during the entire 80-year projection period.
(6) A measure of the variability of the catches (abbreviation AAV), defined as:

$$AAV = \frac{\sum_{y=2008}^{2079} |C_y - C_{y+1}|}{\sum_{y=2008}^{2079} C_y} \tag{5}$$

where C_y is the catch during year y.

The results are based on 100 replicates of an 80-year projection period. 80 years is substantially in excess of the initial estimate of how long recovery should take (41 years), while 100 replicates is more than sufficient to enable major differences among the scenarios to be detected.

2.5. Scenarios

The scenarios considered in this paper (Table 3) examine the sensitivity of the values for the performance statistics to the approach used to generate future (true) recruitment, and how the management procedure is applied. Specifically, scenarios 1–5 vary how future recruitment is generated when catch limits are set according to the reference management procedure (i.e., P_{rec} = 0.6; P_{thresh} = 0.5). Scenarios 6 and 7 explore the sensitivity of the results for the most extreme scenario (in terms of the change in expected recruitment over time) to changing the values for the parameters related to when the rebuilding plan is modified. Finally scenarios 8 and 9 examine how performance changes if the rebuilding plan is based on the assumption that there will be a 30-day delay in spring transition over 100 years for cases in which this is and is not the

Table 3
The scenarios considered in the analyses of this paper.

Scenario	Operating model	Management procedure
1	Auto-correlated recruitment	Reference (see text)
2	No trend in the date of spring transition and without autocorrelation	Reference
3	15-Day delay in spring transition over 100 years and without autocorrelation	Reference
4	30-Day delay in spring transition over 100 years and without autocorrelation	Reference
5	60-Day delay in spring transition over 100 years and without autocorrelation	Reference
6	60-Day delay in spring transition over 100 years and without autocorrelation	Reference except for $P_{\text{rec}} = 0.5$
7	60-Day delay in spring transition over 100 years and without autocorrelation	Reference expect for $P_{\text{rec}} = 0.7$, $P_{\text{thresh}} = 0.6$
8	30-Day delay in spring transition over 100 years and without autocorrelation	Reference, known trend in spring transition
9	Auto-correlated recruitment	Reference with assumed 30-day delay in spring transition

case, i.e., for scenario 8 there is a 30-day delay in spring transition and the projections used to provide management advice make this assumption, while for scenario 9 there is no delay in spring transition, but management is based on the assumption that there will be a 30-day delay in spring transition.

3. Results

3.1. Recruitment scenarios

Fig. 2 shows the estimates of historical age-3 recruitment and summarizes the distributions for the simulated age-3 recruitment for scenarios 1, 2, 4 and 5. The median time-trajectories of age-3 recruitment for scenarios 1 and 2 are essentially identical, although the uncertainty associated with scenario 1 is larger than that associated with scenario 2. This is not unexpected because the standard deviation in annual recruitment for scenario 1 is 0.745 ($= \sigma_v/\sqrt{1-\rho^2} = 0.662/\sqrt{1-0.459^2}$). The distributions of age-3 recruitment decline over time for scenarios 4 and (particularly) 5. However, the considerable variation about the relationship between spring transition and year (0.211) and that between age-3 recruitment and spring transition (0.674) implies that the probability of a very strong recruitment is non-zero even in 2080 for scenario 5.

3.2. Scenarios with no trends in recruitment

Recruitment exhibits no trend for scenarios 1 and 2 (these scenarios differ in terms of whether recruitment is temporally auto-correlated or not). The results of applying the reference management procedure for scenario 1 are shown in Fig. 3. The assessment perceives that the stock recovers to the target level in every Monte Carlo replicate (Fig. 3d). However, "true" recovery to $0.4B_0$ only occurs for 93% of the replicates (Fig. 3c). The stock recovers to the target level before the perceived recovery in more than half of the replicates so the median value for the

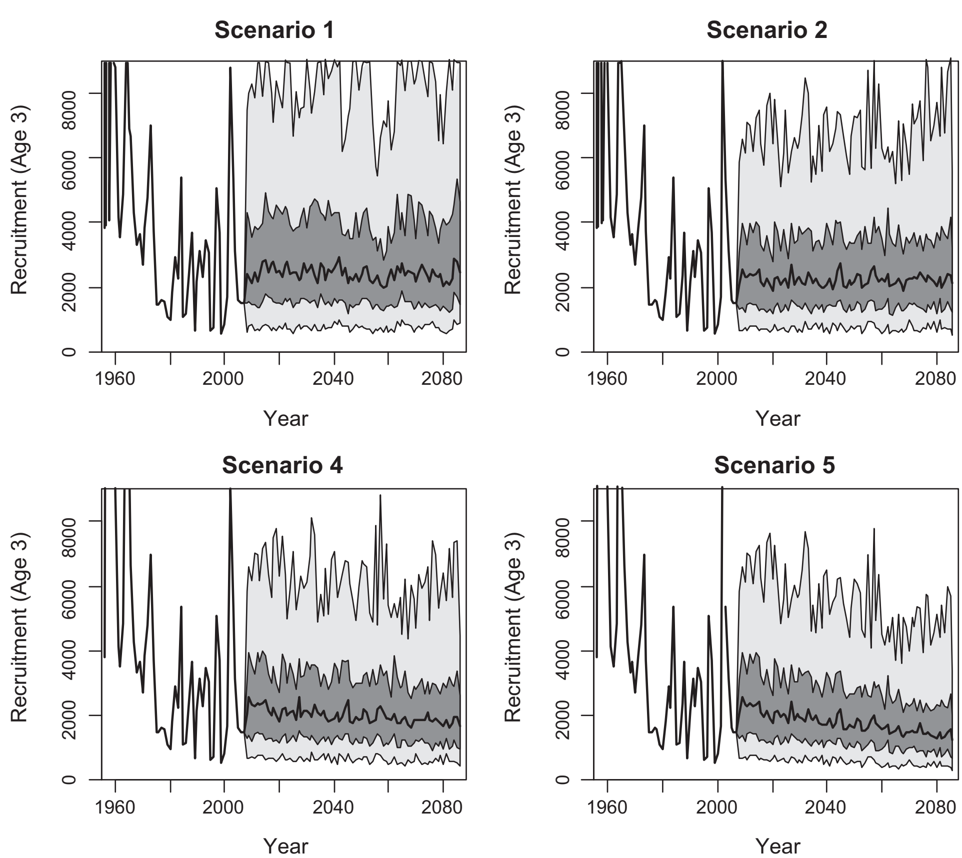

Fig. 2. Historical (1956–2007) and projected (2008–2080) age-3 recruitment for scenarios 1, 2, 4 and 5. The light and dark shaded intervals indicate 90% and 50% simulation intervals and solid line indicates the historical estimates of recruitment (1956–2007) and the median of the simulated recruitments (2008–2080).

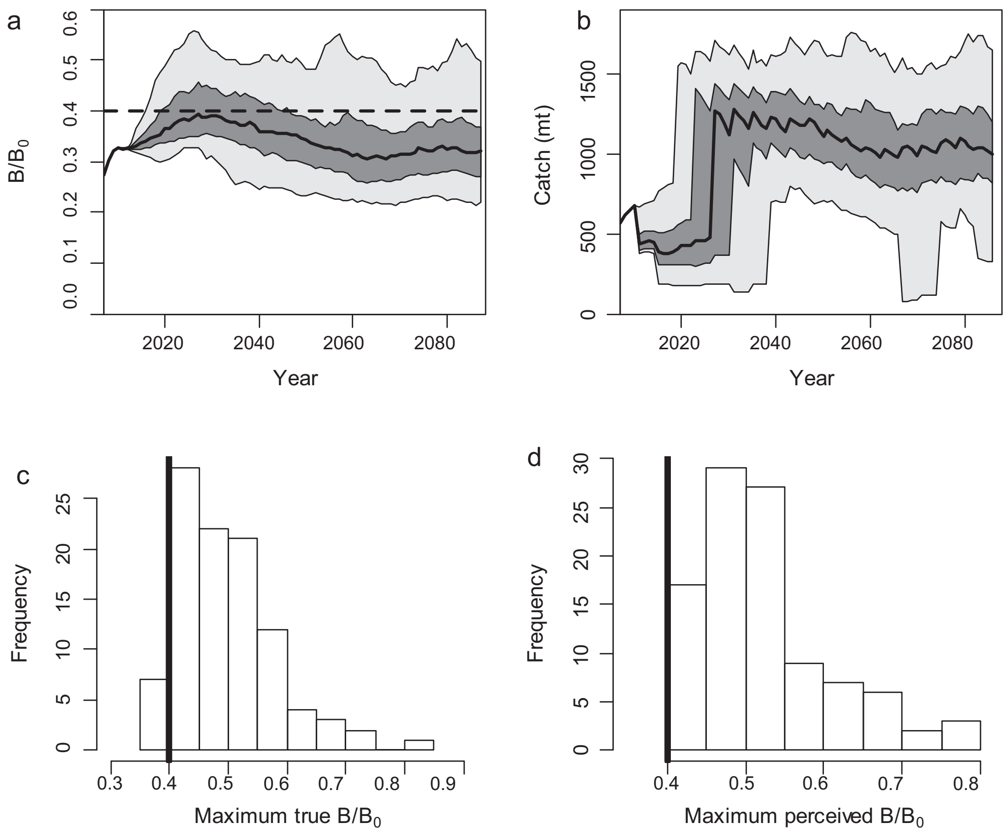

Fig. 3. Time-trajectories of biomass relative to the unfished level (the dashed line denotes the target level; the dark shaded area covers 50% of the distribution and the light shaded area covers 90% of the distribution) and catch (a) and (b), respectively, and histograms of the maxima of the true and perceived relative biomass (biomass relative to the unfished level) (c) and (d), respectively. The results in the figure pertain to scenario 1.

rebuilding ratio is < 0 (Table 4). However, for some replicates, the population never recovers (a value for the actual year of recovery equal to the last year of the projection period, 2087, in Table 4). Moreover, for scenarios 1 and 2, in 84% of replicates recover to the target level occurs before the year it is predicted to occur in the first rebuilding analysis. Catch limits are set using the 40-10 rule (Fig. 1) once the stock is perceived to have recovered to the target level (even if it has not). Unfortunately, the strategy used to set catch limits ($F_{50\%}$) is more aggressive than an F_{MSY} strategy and consequently the biomass declines back below the target level for most replicates.

Catches are initially low (while the stock is perceived not to have recovered to $0.4B_0$), but increase sharply once upon recovery (Fig. 3b). Catches are lower after 2040 as the stock is correctly assessed to be back below the target level. The stock is assessed to be depleted to below $0.25B_0$ again for some replicates after 2040,

Table 4
Performance measures for the nine scenarios. The median (mean for the proportion of plan restarts) and 90% simulation intervals (in square parentheses) are given.

Scenario	Performance measures						
	Actual recovery year	Perceived recovery year	Rebuilding ratio	Plan restarts	Catch (t) (years 1–10)	Catch (t) (years 1–80)	AAV (%) (years 1–80)
1	2025	2027	−9.1	0.02	487	481	18.5
	[2017 2087]	[2019 2039]	[−33 70]	[0 1]	[406 703]	[306 774]	[9.7 32.1]
2	2038	2031	0	0.02	481	466	17.6
	[2020 2087]	[2019 2039]	[−23 75]	[0 1]	[406 577]	[306 613]	[10.3 29.9]
3	2038	2031	2.9	0.01	481	465	17.7
	[2020 2087]	[2019 2039]	[−23 75]	[0 1]	[406 577]	[294 612]	[10.5 29.6]
4	2039	2031	4.7	0.02	481	460	17.8
	[2020 2087]	[2019 2039]	[−23 75]	[0 1]	[406 577]	[286 612]	[10.6 29.6]
5	2087	2031	57.5	0.03	480	457	17.5
	[2020 2087]	[2023 2039]	[−23 75]	[0 1]	[406 577]	[271 611]	[10.5 30.2]
6	2087	2031	45	0.045	493	458	18.7
	[2019 2087]	[2023 2042]	[−23 75]	[0 1]	[439 599]	[293 619]	[12.4 30.6]
7	2026	2027	0	0.06	405	413	23.1
	[2018 2087]	[2019 2035]	[−23 78]	[0 2]	[354 487]	[264 540]	[14.1 36.8]
8	2087	2031	45	0.03	486	504	11.2
	[2019 2087]	[2019 2047]	[−25 75]	[0 1]	[454 523]	[347 585]	[7.7 16.4]
9	2025	2027	−7.2	0	489	524	13.4
	[2016 2087]	[2015 2043]	[−34 65]	[0 0]	[448 762]	[398 631]	[8.9 23.6]

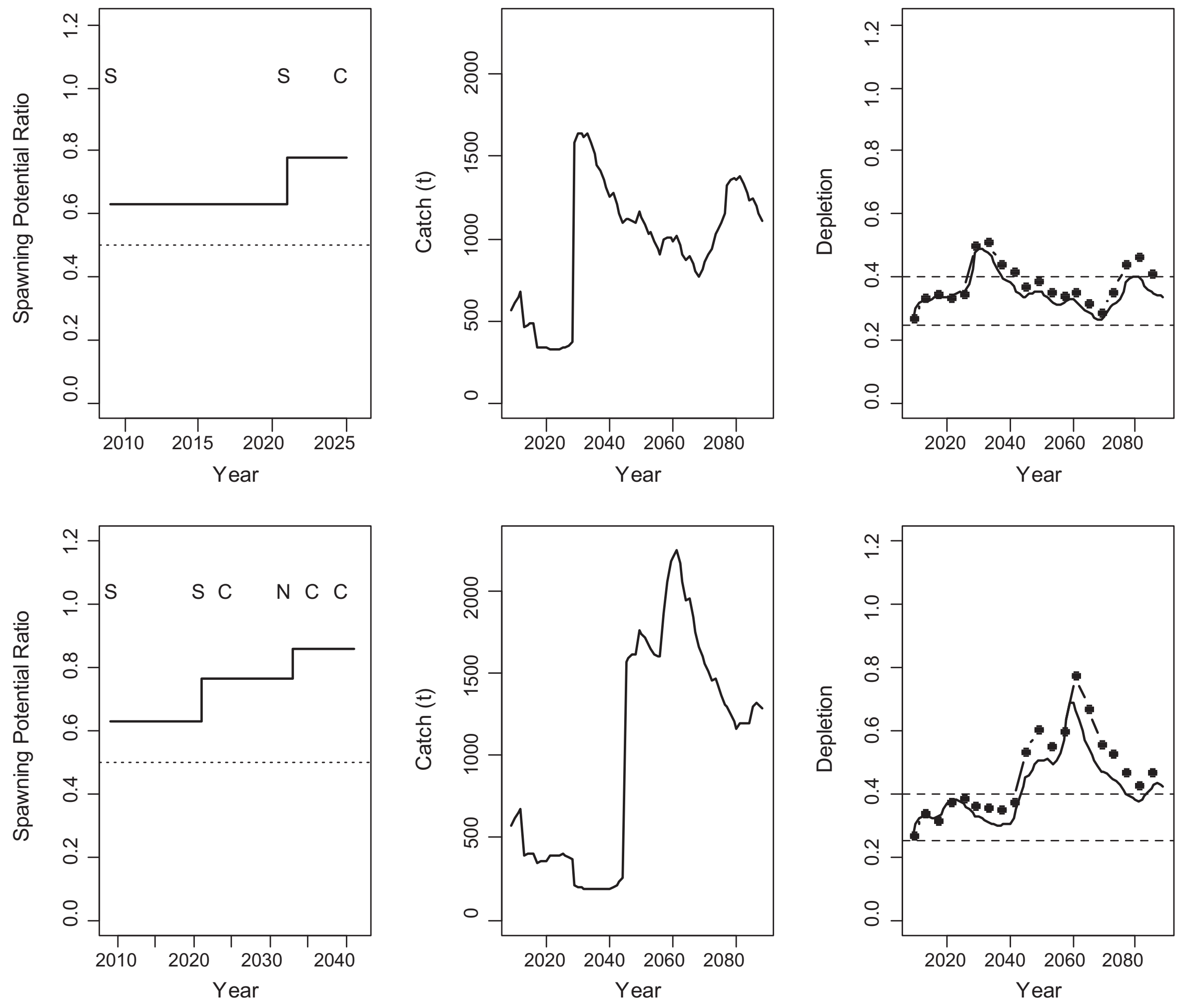

Fig. 4. Results of two illustrative replicates for the reference management procedure for scenario 1 (auto-correlated recruitment). The left panels summarize the decisions arising from the reference management procedure: the solid line indicates SPR_{curr} and dashed horizontal line is the spawning potential ratio (SPR) proxy for F_{MSY}. The letters in the upper parts of the left panels indicate whether SPR is increased ("S"), whether the SPR is unchanged from its previous value ("C"), or whether it is necessary to implement a new Rebuilding Plan ("N"). The center panels show the time trajectories of catch. The right panels show the true (solid lines) and assessment model-based estimates of depletion (solid dots), along with the thresholds that define the proxy for B_{MSY} and the level at which a stock is declared overfished, $0.25B_0$.

leading to low values for the lower 5th percentile of the catch distribution after 2060.

Fig. 4 further examines the behavior of the reference management procedure for scenario 1 by plotting the time-trajectories for the decision regarding the SPR (and hence fishing mortality) used to set the catch limit, the time-trajectory of catch, and the relative biomass (true and perceived) for two illustrative replicates. In one replicate, the SPR remains at the value set in 2007 (0.629) until 2021 when it is increased to 0.782 because it is perceived that recovery to the target biomass will not occur quickly enough. In contrast, in the other replicate, the SPR is increased twice, once in 2021 and once in 2033. The change to the rebuilding plan in 2033 involved developing a completely new rebuilding plan because the rebuilding analysis suggested that it would not be possible to recover to the target level by 2048 with 50% probability even if the fishery was closed from 2033. The assessment is close to unbiased until 2017 for both replicates, after that the assessment over-estimates the true biomass.

The results for scenario 2 are similar to those for scenario 1 (detailed results not shown) although recovery (both actual and perceived) generally occurs later for scenario 2 and the rebuilding ratio is higher (Table 4).

3.3. Scenarios with trends in recruitment

The mean value for the rebuilding ratio increases from 2.9 (scenario 3) to 57.5 (scenario 5) as the delay in spring transition increases from 15 to 60 days and management is based on the reference management procedure. While the assessment suggests that recovery to the target level of $0.4B_0$ occurs before 2087 in all replicates, recovery to the B_{MSY} proxy of $0.4B_0$ actually only occurs before 2087 in 52 replicates (scenarios 3 and 4) and 45 replicates (scenario 5). The value of 57.5 for the rebuilding ratio for scenario 5 therefore reflects that recovery does not occur at all in most replicates. Moreover, the stock is assessed to drop below the overfished threshold of $0.25B_0$ again towards the end of the projection period in most replicates for scenario 5 leading to a second sequence of low catches (e.g. Fig. 5b). The average catches over the first 10 years of the projection period are essentially the same for scenarios 2–5. However, and as expected, catches are lower over the remainder of the projection period for scenarios 4 and 5 than for scenarios 1–3 because the management procedure reduces catch limits in response to lower average levels of recruitment and hence biomass.

Scenarios 6 and 7 involve applying different management procedures for the case when there is a 60-day delay in spring transition.

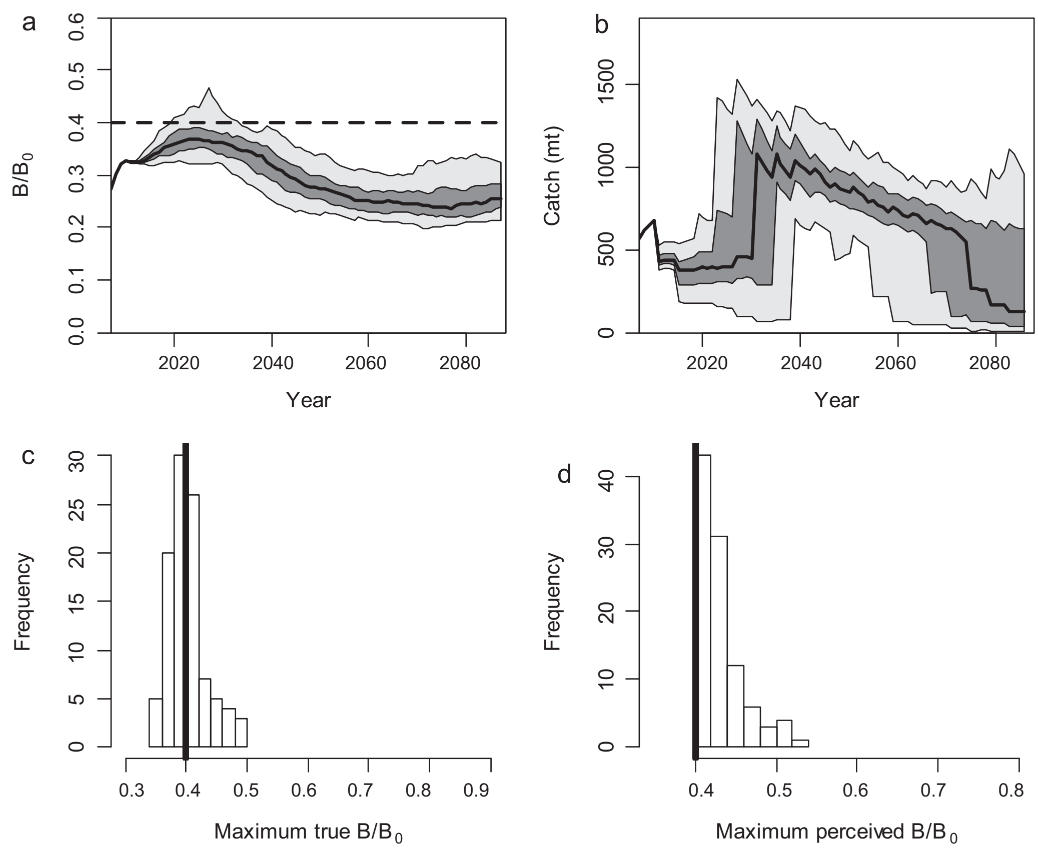

Fig. 5. Time-trajectories of biomass relative to the unfished level (the dashed line denotes the target level; the dark shaded area covers 50% of the distribution and the light shaded area covers 90% of the distribution) and catch (a) and (b), respectively, and histograms of the maxima of the true and perceived relative biomass (biomass relative to the unfished level) (c) and (d), respectively. The results in the figure pertain to scenario 5.

As expected, the actual (and perceived) times to recovery are lower for scenario 7 due to the more conservative management procedure. However, this improved conservation performance occurs at the cost of lower average catches, more variability in catch limits, and a much higher probability of needing to develop a new rebuilding plan (up to 6% of years). Most of the performance measures are similar for scenarios 5 and 6 even though the scenario 6 management procedure is somewhat less conservative. However, the catches and probability of needing to create a new rebuilding plan are, as expected, higher for scenario 6.

3.4. *Management procedures based on climate-driven recruitment*

Scenarios 8 and 9 involve a management procedure that assumes that spring transition will be delayed by 30 days over 100 years and bases forecasts of future recruitment for rebuilding analyses on Eqs. (2) and (3). Performance in terms of the rate of recovery for scenario 8 is not as good as expected, recovery generally occurs later for scenario 8 than for scenario 4, due to catch limits in the early years of the projection period that are not reduced as rapidly as for the reference management procedure. Furthermore, the rebuilding ratio is higher for scenario 8 than for scenario 4 and the number of times it is necessary to develop a new rebuilding plan is slightly higher (Table 4 and Fig. 6). However, the interannual variation in catch is lower for scenario 8 than for scenario 4.

The results are remarkably insensitive to applying a management procedure that assumes spring transition will be delayed by 30 years in 100 years when recruitment is not actually related to spring transition, although the recovery ratio is slightly closer to 0 (−7.2 compared to −9.1) and interannual variation in catch is lower (Table 4).

4. Discussion

The need to rebuild overfished stocks is a key focus for management efforts (e.g. Murawski, 2010) and considerable work has been focused on developing approaches to rebuild overfished stocks. Most rebuilding methods have not, however, been evaluated using MSE, which might explain why failure to rebuild is more common than would be expected given the goals of many rebuilding plans. Several studies have highlighted the interaction between rebuilding rates and long-term environmental forcing (e.g. Collie and Spencer, 1993; Hammer et al., 2010). This paper confirms that environmentally driven trends in average recruitment impact the performance of rebuilding plans. However, basing management decisions on a management procedure that changes the target fishing mortality rate over time in response to data collected from the fishery tends to reduce the impact of long-term environmental forcing, albeit at the expense of lower catches and higher inter-annual variation in catches. Even though the rebuilding analyses that form part of the reference management procedure base recruitment forecasts on average historical recruitment, this management procedure is able to adjust catch limits in the correct direction, although for the most extreme case (scenario 5) most replicates fail to recover to the target level by the end of the projection period.

Several proposals have been made to include environmental variables into catch control rules (e.g. Hurtado-Ferro et al., 2010) and the control rule used to set harvest guidelines (essentially catch limits) for Pacific sardine (*Sardinops sagax caerulea*) modifies the

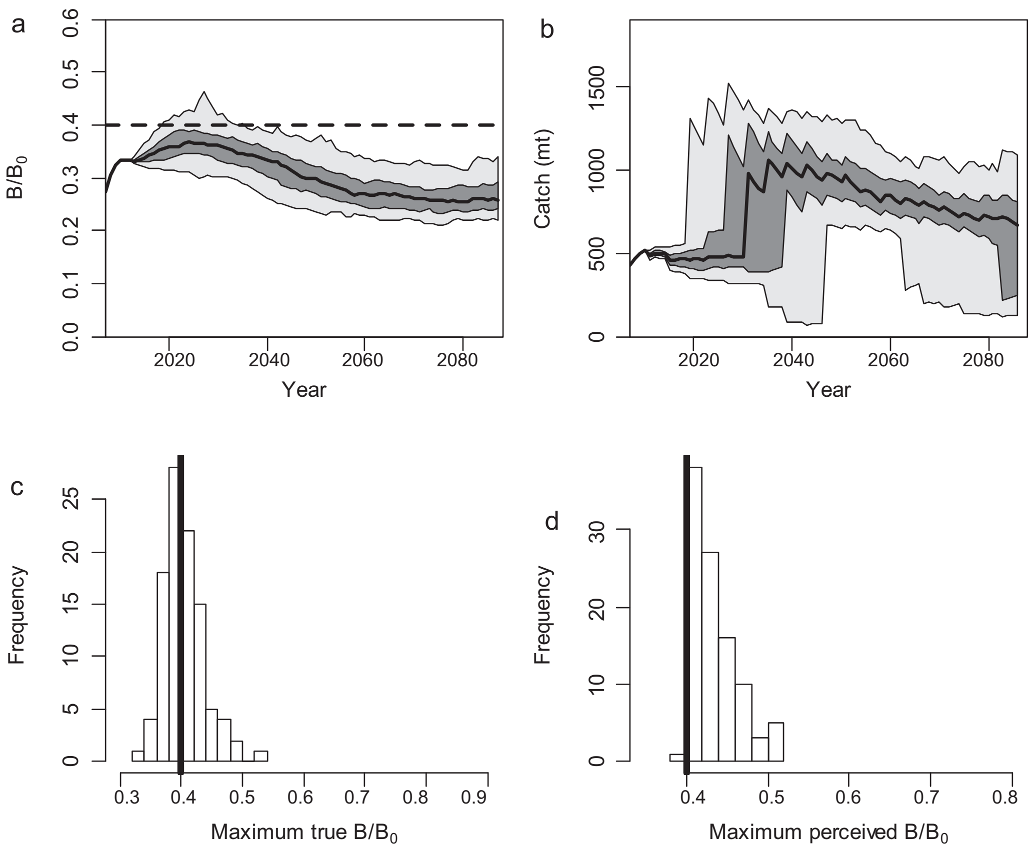

Fig. 6. Time-trajectories of biomass relative to the unfished level (the dashed line denotes the target level; the dark shaded area covers 50% of the distribution and the light shaded area covers 90% of the distribution) and catch (a) and (b), respectively, and histograms of the maxima of the true and perceived relative biomass (biomass relative to the unfished level) (c) and (d), respectively. The results in the figure pertain to scenario 8.

target fishing mortality rate as a function of temperature given a relationship between sardine production and temperature (PFMC, 1998; but see McClatchie et al., 2010). Intuitively, it might have been expected that knowing the correct form of the relationship between recruitment and the environment should have substantially improved the conservation performance of the management system. However, performance is not improved (see the results for scenario 8) because the relationship between spring transition and recruitment suggests a somewhat faster recovery rate than average recruitment during the short-term (the first 20 years of the projection period). Basson (1999) and A'mar et al. (2009) also found that management procedures accounting for environmental drivers of recruitment do not necessarily outperform those that are based on the assumption of a time-invariant environment.

The best performance in terms of achieving rapid recovery of the resource occurs when the parameters that determine the planned probability of recovery and the probability at which a new rebuilding plan has to be developed (P_{rec} and P_{thresh}) are increased from their reference values (scenario 7). In this case, recovery to the target level occurs by 2025 with 50% probability (even for the most pessimistic scenario regarding changes over time in expected recruitment). Scenario 7 is, in fact, the closest strategy to those actually applied for overfished west coast groundfish species (Table 1; the value of P_{rec} is 0.897 for Pacific ocean perch).

The median year of recovery for most scenarios (exceptions are scenarios 6, 7 and 8) is lower than the anticipated year of recovery when the rebuilding plan is first implemented (2048). This occurs because catch limits are adjusted downwards so that (if possible) recovery always occurs by 2048.

The assessment tends to provide positively biased estimates of abundance and hence the rebuilding ratio, the ratio between the true and perceived recovery, is generally larger than 1. The extent of positive bias increases with the extent of environmental impact on recruitment. A key reason for this is that recruitment in the assessment is assumed to be log-normally distributed about an estimated stock-recruitment relationship. However, allowing for environmentally driven trends in recruitment implies that the assumption of a stationary stock–recruitment relationship is invalid (particularly for the cases with a substantial impact of spring transition on recruitment). In principle, the estimate of average recruitment declines over time owing to the estimates of recruitment declining due to the impact of trends in spring transition. However, the effect of this is relatively small because the average is taken a wide range of years.

Although the results of this paper illustrate the impact of environmentally driven effects on the performance of rebuilding plans in general terms, there are several reasons why the quantitative results should be interpreted with some caution for Pacific ocean perch: (a) the PFMC has tended to implement more conservative catch limits than would be suggested by the reference management procedure, and (b) owing to a court decision, the PFMC tends to reduce catch limits if this is suggested by a rebuilding analysis, but has not often increased catch limits even when this is suggested by a rebuilding plan, rather "investing" increases in biomass to enhance recovery rates.

These analyses are based on the system of rules that mimic those actually used to provide management advice for groundfish stocks off the U.S. west coast. Arguably, this is one of the most complicated systems for providing (scientific) management advice anywhere in the world. Future analyses should consider alternative management decision making frameworks (although the results would be less relevant to the example that motivated this study).

Finally, the analyses show that a feedback management system similar to that used to determine catch limits for U.S. west coast groundfish can be responsive to climate-induced changes in biological parameters such as recruitment, even if no environmental data are included in the assessment or the projection methodology and that, as expected, feedback procedures outperform non-feedback strategies when productivity is non-stationary. This suggests that future evaluations of the impacts of, for example, climate change on fishery yields should be based on as close an approximation to the actual management system as possible.

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