ICES Journal of
Marine Science

ICES Journal of Marine Science; doi:10.1093/icesjms/fsw073

The impact of alternative rebuilding strategies to rebuild overfished stocks

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Wetzel, C. R., and Punt, A. E. The impact of alternative rebuilding strategies to rebuild overfished stocks. – ICES Journal of Marine Science, doi: 10.1093/icesjms/fsw073.

Received 12 January 2016; revised 1 April 2016; accepted 4 April 2016.

Ending overfishing and rebuilding fish stocks to levels that provide for optimum sustainable yield is a concern for fisheries management worldwide. In the United States, fisheries managers are legally mandated to end overfishing and to implement rebuilding plans for fish stocks that fall below minimum stock size thresholds. Rebuilding plans should lead to recovery to target stock sizes within 10 years, except in situations where the life history of the stock or environmental conditions dictate otherwise. Federally managed groundfish species along the US West Coast have diverse life histories where some are able to rebuild quickly from overfished status, while others, specifically rockfish (*Sebastes* spp.), may require decades for rebuilding. A management strategy evaluation which assumed limited estimation error was conducted to evaluate the performance of alternative strategies for rebuilding overfished stocks for these alternative US West Coast life histories. Generally, the results highlight the trade-off between the reduction of catches during rebuilding vs. the length of rebuilding. The most precautionary rebuilding plans requiring the greatest harvest reduction resulted in higher average catches over the entire projection period compared with strategies that required a longer rebuilding period with less of a reduction in rebuilding catch. Attempting to maintain a 50% probability of rebuilding was the poorest performing rebuilding strategy for all life histories, resulting in a large number of changes to the rebuilding plan, increased frequency of failing to meet rebuilding targets, and higher variation in catch. The rebuilding plans that implemented a higher initial rebuilding probability ($\geq$60%) for determining rebuilding fishing mortality and targets generally resulted in fewer changes to the rebuilding plans and rebuilt by the target rebuilding year, particularly for stocks with the longer rebuilding plans (e.g. rockfishes).

Keywords: management strategy evaluation, rebuilding, simulation, US West Coast.

Introduction

Eliminating overfishing and achieving sustainable fisheries has been, and continues to be, a challenge worldwide. Up to 63% of global stocks have been estimated to be below biomass target reference points for maximum sustainable yield (Worm *et al.*, 2009). In the United States, 23% of federally managed stocks were estimated to be below their biomass limit reference points (and thus meeting the overfished definition) in 2012, with 85 stocks being declared overfished during 1997–2011 (NRC, 2013). The United States has made commitments to end overfishing and to rebuild overfished stocks. Reducing fishing mortality is the first critical step to end overfishing. Beyond reducing harvest, successful rebuilding of overfished stocks is greatly facilitated by implementation of rebuilding plans that have clearly defined objectives and strategies and that have stakeholder and management support (Mora *et al.*, 2009). Additionally, successful rebuilding plans should consider a precautionary approach in the face of management and scientific uncertainty (Cadrin and Pastoors, 2008).

For US federally managed fish stocks, rebuilding plans are required when fish stocks are declared overfished, i.e. when they are estimated to be below their minimum stock size threshold (SFA, 1996). Such plans have been shown to successfully rebuild overfished stocks to target levels often when fishing mortality was reduced to a rate that would allow population growth in the absence of unexpected changes in productivity (Milazzo, 2012; NRC, 2013). The development of US rebuilding plans involves three key factors: (i) the Magnuson–Stevens Act, (ii) the National Standard Guidelines, and (iii) court cases. The National Marine Fisheries Service (NMFS) has provided guidelines for the features of a rebuilding plan (SFA, 1996; Federal Register, 1998). US rebuilding plans are required to define the following components (Table 1): (i) the target year for rebuilding (T_{TARGET}), (ii) the minimum amount of time that would allow rebuilding in the absence of fishing with at least a 50% probability (T_{MIN}), and (iii) the maximum amount of time targeted for rebuilding the stock (T_{MAX}). Guidelines from NMFS dictate that a stock must be rebuilt within 10 years (i.e. T_{MAX}= 10 years, $T_{\mathrm{TARGET}} \leq$10 years) if T_{MIN} is <10 years, but the upper limit for rebuilding (T_{MAX}) may be set as high as T_{MIN} plus one mean generation time if the stock is unable to rebuild within 10 years ($T_{\mathrm{MIN}} >$ 10 years). The target year for rebuilding (T_{TARGET}) must fall between T_{MIN} and T_{MAX}.

From 1999 to the present, 10 US West Coast groundfish stocks have been declared overfished and have required rebuilding plans (some of which have since been declared rebuilt; Pacific Fishery Management Council (PFMC), 2014a). During this period, the PFMC, which makes management recommendations for federally managed West Coast fish stocks, has been subject to lawsuits filed directly in opposition to rebuilding plans for overfished groundfish stocks [e.g. Natural Resources Defense Council (NRDC) v. NMFS, 421 F.3d 872 (9th Cir. 2005)] which have had lasting implications on the development of management plans for West Coast groundfish stocks. The stocks that have been declared overfished are highly diverse, ranging from stocks deemed able to rebuild within 10 years [e.g. Pacific hake (*Merluccius productus*) and petrale sole (*Eopsetta jordani*)] to stocks that may require very long rebuilding periods (e.g. 70+ years for yelloweye rockfish (*Sebastes ruberrimus*) (PFMC, 2014a). The PFMC faces the challenge of implementing rebuilding plans that will successfully rebuild stocks across this range of circumstances while meeting the mandate set by the Magnuson–Steven Act requiring a stock to be rebuilt "in as short as possible, taking into account the needs of the fishing communities".

US West Coast federal fisheries management controls fishing mortality rates by setting harvest rates based on spawning potential ratios (*SPR*s). *SPR* is a measure of the impact of fishing mortality on the projected average contribution of each recruit to the spawning output (thus, the smaller the *SPR* value, the higher fishery exploitation). Current practice for establishing rebuilding plans on the US West Coast includes projections that apply a range of fishing mortality rates, expressed in terms of *SPR*, to determine the minimum year for rebuilding in the absence of fishing (T_{MIN}) which, combined with the mean generation time, determines the maximum year for rebuilding (T_{MAX}) to occur (Table 1). The regional management council then selects a target year for rebuilding (T_{TARGET}: must fall between T_{MIN} and T_{MAX}) and the associated *SPR* that reflects a desired level of probability to rebuild the stock (must be $\geq$50%). The results from the projections across this range of *SPR* rates and a range of realized stock dynamics (with process error modelled using recruitment deviations, although other sources of uncertainty are often considered, such as assessment uncertainty) represent a "rebuilding analysis".

Table 1. The US rebuilding plan required components and definitions.

Terminology	Definition
T_{MIN}	The minimum amount of time a stock could rebuild in the absence of fishing.
T_{MAX}	The maximum time allowed for a stock to rebuild, which cannot exceed the T_{MIN} plus one mean generation time.
T_{TARGET}	The target year for rebuilding, which must fall between T_{MIN} and T_{MAX}.
P_{INIT}	The initial probability for rebuilding by T_{MAX}, which determines the appropriate rebuilding SPR value for rebuilding by T_{MAX}. Defined by management, but must be $\geq$50%.
P_{TARGET}	The probability of rebuilding by T_{TARGET} based on the intended SPR. Set by management.

Stocks that are managed under a rebuilding plan are monitored during rebuilding, and subsequent rebuilding analyses are conducted to ensure that the stock remains on course to rebuild by the target year according a prespecified probability (P_{TARGET}). Adjustments are made to the *SPR* as needed to meet rebuilding targets. Additionally, changes in the understanding of population scales during rebuilding could require adjustments to the rebuilding *SPR* and rebuilding timelines. The rebuilding analysis provides the scientific guidance for determining the rebuilding targets and the harvest rates for the rebuilding plan.

During rebuilding, managers generally prefer minimal revisions to the rebuilding plan to minimize the impact of harvest reductions to the stakeholders, while still meeting rebuilding targets (and for ease of application). Continuity during rebuilding also provides a measure of predictability for fishery stakeholders and allows them to plan. Rebuilding strategies that are overly sensitive to assessment noise can result in needless changes to the rebuilding plan, increasing the variability in catches during rebuilding.

Punt and Ralston (2007) conducted a management strategy evaluation (MSE) for rockfish stocks that evaluated the performance of several alternative rebuilding strategies, the method for assessing rebuilding progress, and the guidelines for adjusting rebuilding plans based on changes in perceived stock status. This paper provides an updated MSE for rebuilding US West Coast groundfish stocks that has been developed iteratively based on discussions and feedback received from stakeholders, groundfish management advisory bodies, and the PFMC. Specifically, this paper evaluates the performance of six rebuilding strategies across various West Coast life histories that apply alternative approaches to set initial rebuilding harvest rates and when to update harvest rates during rebuilding. A variety of sensitivity analyses are also undertaken that explore the sensitivity to model misspecification, the frequency of assessment, or alternative thresholds for updating harvest rates during rebuilding.

Material and methods

General approach

The majority of life history strategies of fishes that are federally managed along the US West Coast fall into the categories of either periodic or intermediate strategy (King and McFarlane, 2003). Periodic strategies are defined as slow-growing, long-lived demersal species with low variability in recruitment, and intermediate strategies, as defined by King and McFarlane (2003), have mid-range longevity (10–20 years) that can have dramatic changes in biomass. Two intermediate and two periodic life history strategies were simulated: (i) flatfish with a moderately high natural mortality rate and a high recruitment compensation rate [e.g. petrale sole

(*Eopsetta jordani*) and Dover sole (*Microstomus pacificus*)], (ii) roundfish with an intermediate natural mortality and recruitment compensation rate [e.g. Pacific hake (*Merluccius productus*) and lingcod (*Ophiodon elongatus*)], (iii) medium-lived rockfish with a moderately low natural mortality rate and moderate recruitment compensation rate [e.g. greenstriped rockfish (*Sebastes elongates*) and widow rockfish (*Sebastes entomelas*)], and (iv) long-lived rockfish with a low natural mortality rate and a low recruitment compensation rate [e.g. canary rockfish (*Sebastes pinniger*) and yelloweye rockfish (*Sebastes rubberimus*)] (Table 2). For ease of presentation, the intermediate and periodic life history strategies will be referred to as either flatfish, roundfish, medium-, or long-lived rockfish life histories. Additionally, these life histories generally correspond to the categorization of stocks as applied by federal US West Coast management.

The simulation study involves three separate submodels: (i) an operating model which simulates the population, (ii) an estimation model that conducts assessments and rebuilding analyses, and (iii) a management decision model that determines the management actions following alternative strategies. The simulated population was age-structured, where an annual index of abundance was observed with error, and age composition data were collected for selected years. These data were used by the stock estimation method to estimate population size and project the catch. When a stock was estimated to be below the minimum stock size threshold, as defined given its life history for the first time (i.e. the stock was not currently under a rebuilding plan), the assessment estimated catch was modified based on a rebuilding plan that calculated an *SPR* that would result in a given estimated probability of recovery at a specific future point in time. The rebuilding strategy was applied, and the stock assessment was updated iteratively for a specified number of years based on life history that generally allowed for recovery to target biomass levels under a variety of conditions (flatfish and roundfish, 50 years; medium-lived rockfish, 75 years; long-lived rockfish, 125 years). Results for alternative rebuilding strategies and sensitivities for each life history were based on 100 simulated stocks.

Operating model

The numbers-at-age at the start of the year are computed as

$$N_{t+1,\gamma,a} = \begin{cases} 0.5R_t & \text{if } a = 0 \\ N_{t,\gamma,a-1}e^{-(M_\gamma+S_{\gamma,a}F_t)} & \text{if } 1 \le a \le A-1 \\ N_{t,\gamma,A-1}e^{-(M_\gamma+S_{\gamma,A-1}F_t)} + N_{t,\gamma,A}e^{-(M_\gamma+S_{\gamma,A}F_t)} & \text{if } a = A \end{cases} \quad (1)$$

where $N_{t+1,\gamma,a}$ is the number of fish of sex γ and age a at the start of year t, R_t is the number of age 0 animals at the start of year t, $S_{\gamma,a}$ is the selectivity by sex and age, A is the plus group, F_t is the instantaneous fishing mortality rate during year t, and M_γ is the instantaneous rate of natural mortality for sex γ.

The number of age 0 fish is related to spawning biomass according to the Beverton and Holt (1957) stock–recruitment relationship:

$$R_t = \frac{4hR_0SB_t}{SB_0(1-h)+SB_t(5h-1)}e^{-0.5\sigma_R^2+\varepsilon_t^R} \quad \varepsilon_t^R \sim N(0;\sigma_R^2) \quad (2)$$

where SB_0 is the unfished spawning biomass, SB_t is the spawning biomass at the start of the spawning season in year t, R_0 is the unfished recruitment, σ_R is the standard deviation of recruitment in log space, and h is the recruitment compensation (also known as steepness).

A non-equilibrium starting condition was created by applying equations (1) and (2) for the number of years equal to the

Table 2. Life history parameters used in the operating model for each life history type.

Parameter	Sex	Flatfish	Roundfish	Medium-lived rockfish	Long-lived rockfish
Natural mortality (year^{-1})	Female	0.15	0.20	0.08	0.05
	Male	0.17	0.20	0.09	0.06
Steepness (h)		0.85	0.70	0.65	0.50
Maximum length (L_∞) (cm)	Female	58	65	34	64
	Male	51	58	32	66
Growth coefficient (k) (year^{-1})	Female	0.133	0.120	0.115	0.047
	Male	0.213	0.150	0.153	0.047
Body weight $w_1 = \alpha L^\beta$ (kg)					
Growth coefficient (α)	Female	2.08×10^{-6}	8.50×10^{-6}	7.40×10^{-6}	9.76×10^{-6}
	Male	3.05×10^{-6}	7.70×10^{-6}	8.30×10^{-6}	8.70×10^{-6}
Growth exponent (β)	Female	3.50	3.10	3.17	3.17
	Male	3.40	3.05	3.13	3.10
Maturity slope (year^{-1})		−0.75	−0.70	−0.67	−0.44
Length at 50% maturity (cm)		33	35	21	38
Mean generation time (year)		18	28	40	50
Recruitment variation (σ_R)		0.60	0.60	0.60	0.60
Catchability coefficient (Q)		1	1	1	1
Survey standard error (σ_S)		0.20	0.20	0.20	0.20
Fishery selectivity (logistic)					
Age at inflection		7	5	7	15
Width for 95% selection		2	2	5	7
Survey selectivity (logistic)					
Age at inflection		5	3	3	10
Width for 95% selection		2	2	3	7
Initial relative stock size ($SB_{t=50}$ / SB_0)		0.05	0.10	0.10	0.10

maximum age for each life history, with variation in recruitment and no fishing. Following this, an initial fishery was simulated (along with the population) over 50 years, with the catch of fish of sex γ and age a during year t in numbers determined by

$$C_{t,\gamma,a} = \frac{S_{\gamma,a}F_t}{M_\gamma + S_{\gamma,a}F_t} N_{t,\gamma,a}(1 - e^{-M_\gamma - s_{\gamma,a}F_t}) \qquad (3)$$

This simulated historical fishing mortality increased linearly over 50 years such that, always, the populations were in an overfished state (flatfish $0.05SB_0$, roundfish and rockfish $0.10SB_0$; Table 2) at the time of the first assessment in year 50, based on the PFMC minimum biomass threshold levels for each life history type (flatfish $0.125SB_0$, roundfish and rockfish $0.25SB_0$). The fishery and the survey both assumed an age-based logistic selectivity (Table 2).

An annual survey index of abundance ($CV = 0.20$) and age composition data ($n = 100$) from the survey and the fishery were available for 20 years before the first assessment, and catches were known without error for all years. Index and age composition data were generated annually following the first assessment. The start and frequency of the survey were selected to mimic the data available for West Coast groundfish stocks.

The observation model was used to generate an index of abundance for each year t:

$$I_t = Q\tilde{B}_t e^{-0.5\sigma_s^2 + \varepsilon_t^s} \quad \varepsilon_t^s \sim N(0; \sigma_s^2) \qquad (4)$$

where Q is the catchability coefficient for the survey (arbitrarily set equal to 1, since the scale does not matter here, given how this index is included in the assessment), and σ_s is the standard deviation of survey catchability in log space (see Table 2). The expected biomass index is given by

$$\tilde{B}_t = \sum_{\gamma} \sum_{a=1}^{A} w_{\gamma,a} S_{s,\gamma,a} N_{t,\gamma,a} e^{-0.5(M_\gamma + S_{f,\gamma,a}F_t)} \qquad (5)$$

where $w_{\gamma,a}$ is the average weight by sex at age, $S_{s,\gamma,a}$, is the selectivity for the survey by sex and age, and $S_{f,\gamma,a}$ is the selectivity for the fishery by sex and age. The observed age composition data for the fishery and survey catch were assumed to be multinomially distributed.

Estimation method and rebuilding analyses

The simulated stocks were assessed using stock synthesis (Methot and Wetzel, 2013), an integrated statistical catch-at-age model. Growth, natural mortality, and the steepness of the Beverton–Holt stock–recruitment relationship were assumed to be known without error. The unfished recruitment (R_0), annual recruitment deviations, and the selectivity parameters for the survey and the fishery were estimated. The ratio of the current spawning biomass to the unfished spawning biomass (relative stock status) was estimated and, based on the estimated stock status, one of three actions was performed:

1. If the relative stock status was estimated to be below the minimum stock size threshold, as defined by the PFMC by life history type (flatfish $0.125SB_0$; rockfish and roundfish $0.25SB_0$) for the first time, the stock was declared overfished and a rebuilding analysis was performed which defined the initial rebuilding plan for the stock, setting a rebuilding harvest level (*SPR*) associated with the predefined probability of rebuilding by a maximum year (P_{INIT}).
2. If the stock was already under a rebuilding plan and estimated to still be below the target biomass level, a rebuilding analysis was conducted to evaluate the current probability of rebuilding by the target year. The rebuilding *SPR* and rebuilding targets were adjusted, if necessary, so that rebuilding could occur within the allowable time.
3. If the stock size was found to be above the target biomass level, the stock was declared rebuilt, and catches were estimated using the default harvest control rule (Figure 1). The PFMC harvest control rule reduces the catch linearly when stock is below the target stock size (flatfish: $0.25SB_0$, roundfish and rockfish $0.40SB_0$), to zero when the stock is at or below the management lower threshold (flatfish: $0.05SB_0$, roundfish and rockfish $0.10SB_0$, although this is never applied here).

The approach to rebuilding plans and subsequent analyses during rebuilding (i.e. updated rebuilding analyses to evaluate the probability of meeting rebuilding targets given the current harvest rate) can vary by region within the United States (NRC, 2013). The process implemented for developing a rebuilding plan here was based on the current practice for the US West Coast groundfish:

1. The unfished biomass, SB_0, was calculated by multiplying the spawning output-per-recruit in the absence of exploitation by the arithmetic average recruitment (R_0) for the first 10 years of the assessment period.
2. Future recruitment was generated from a Beverton–Holt stock–recruitment relationship with process error variation around that median relationship.
3. The minimum time to rebuild (T_{MIN}) was defined as the median year in which spawning biomass exceeded the management target (flatfish: $0.25SB_0$, rockfish and roundfish: $0.40SB_0$) in the absence of fishing.
4. The maximum time to rebuild (T_{MAX}) was defined relative to minimum time required. If a stock could rebuild in <10 years in the absence of fishing, the maximum time allowed for rebuilding equaled 10 years (i.e. a current requirement for United States rebuilding plans). However, if the minimum time required to rebuild was >10 years, the T_{MAX} was defined as T_{MIN} plus one mean generation.
5. The initial rebuilding *SPR* was defined as the value that would result in recovery of the stock by T_{MAX} equal to a prespecified initial rebuilding probability ($P_{\mathrm{INIT}} \geq 0.50$).
6. The target year to rebuild (T_{TARGET}) was set equal to the first year that the stock was projected to recover to the management target with a $\geq 50\%$ probability based on the specified rebuilding *SPR*.

The initial rebuilding analysis determined the parameters for the rebuilding plan (T_{MIN}, T_{MAX}, T_{TARGET}, and *SPR*) (Table 1). The ensuing year's catches were determined by the rebuilding *SPR*. Subsequent rebuilding analyses evaluated four questions (Figure 1): (i) will the stock rebuild by the target year with a probability greater than a prespecified minimum probability (P_{TARGET}) by applying the current rebuilding plan *SPR*, (ii) if no, is there an *SPR* that would result in rebuilding by the target year, (iii) if no, is there an *SPR* for which the stock would be projected to rebuild if the target

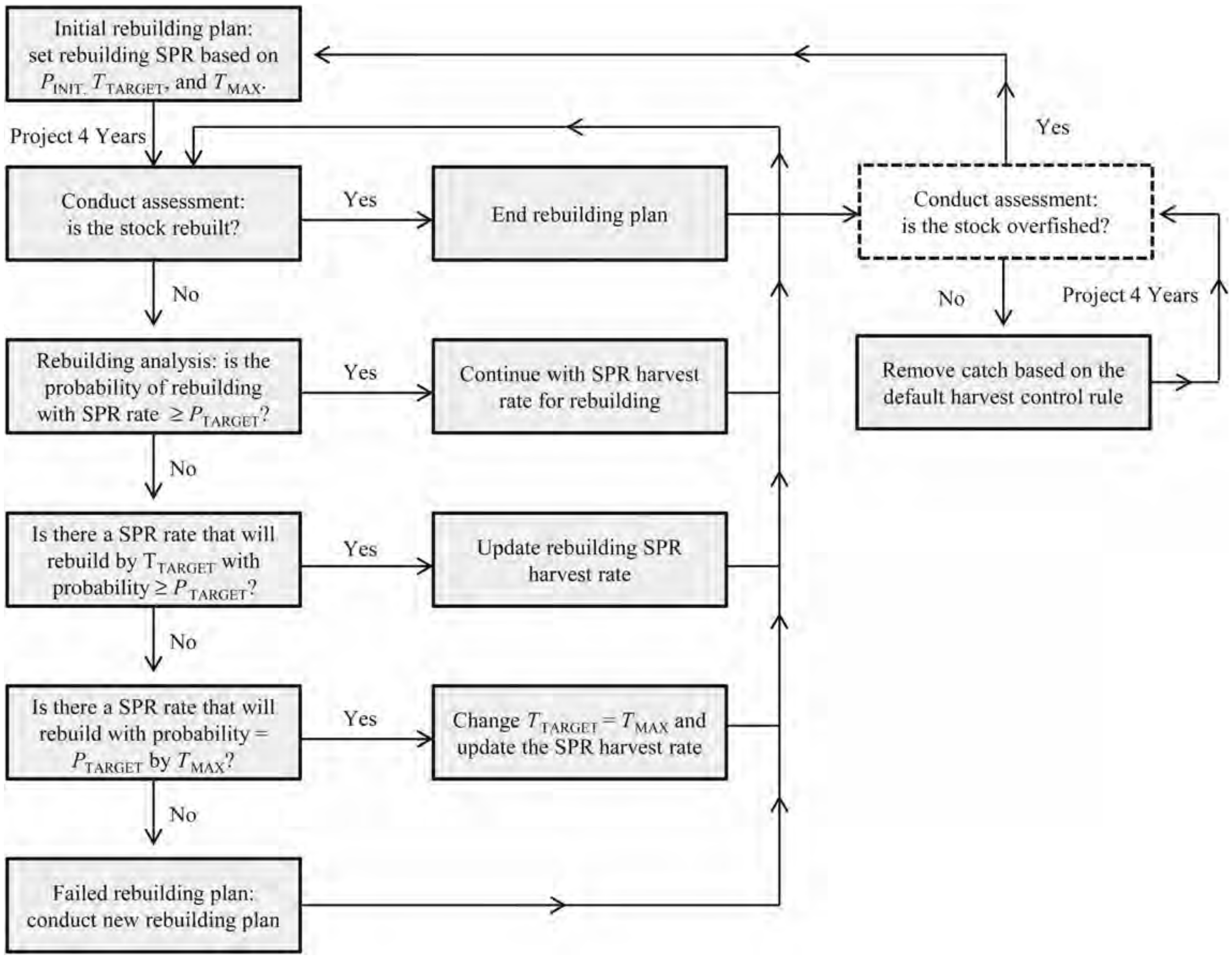

Figure 1. The process followed for determining when a rebuilding plan was implemented, how targets and harvest rates are adjusted during rebuilding, and the assessment for rebuilt stocks. The closed loop process starts by conducting the first assessment in year 50 (white box with dashed border) and continues for a fixed number of years for each life history.

year was set to the maximum rebuilding year (T_{MAX}), and (iv) if there is an *SPR* that met one of the above conditions, would the resulting catch be $>$50% of the previous year's catch? When none of the first three criteria could be met, or when the fourth criterion was not met, the rebuilding plan was determined to be a failure and a new rebuilding plan was implemented that updated the rebuilding parameters. The *SPR* set by the new rebuilding plan was constrained so that it did not result in a lower (i.e. more aggressive) *SPR* compared with the *SPR* in the failed rebuilding plan.

Stocks that successfully rebuilt to the target biomass level were subsequently managed based on the PFMC harvest control rules for non-overfished stocks, where catch was calculated based on the life history *SPR* proxy value (flatfish: $SPR_{30\%}$, roundfish: $SPR_{45\%}$, rockfish: $SPR_{50\%}$).

Alternative management actions: rebuilding strategies

This work evaluated the performance of alternative initial probability of recovery (P_{INIT}) determining a rebuilding strategy and target probability (P_{TARGET}) of recovery threshold values while rebuilding, as applied to rebuild West Coast groundfish stocks. In practice, the value for the probability of recovery by the maximum year allowed for rebuilding (T_{MAX}) is selected by the PFMC. The current guideline from the Council is that the initial rebuilding plan will select an *SPR* corresponding to a probability of recovery by target year with $\geq$50% probability (P_{INIT}; although it has often been set much higher than 50%; PFMC, 2014b). The subsequent rebuilding analyses conducted during rebuilding evaluate whether the current *SPR* was predicted to result in at least a 50% probability (P_{TARGET}) of rebuilding by the target year. If the probability of recovery to the target year with the current *SPR* falls $<$50%, the current practice of the Council is to adjust the *SPR* to a value that corresponds to a 50% probability of recovery.

The following alternative rebuilding strategies were simulated and their performance evaluated (Table 3):

1. "*Status quo*": The "*status quo*" strategy attempted to mimic as best as possible the species-specific rebuilding strategies used by the PFMC for rebuilding West Coast groundfish stocks. The *SPR* in the initial rebuilding plan was determined based on a rebuilding probability of 60% (i.e. $P_{INIT} = 60\%$) by T_{MAX}. The stock and fishery were simulated for 4 more years, assessed, and if the stock was estimated still below the biomass target, a new rebuilding analysis was performed to determine if the stock was on target to rebuild by the target year, based on the

Table 3. The alternative initial rebuilding probability (P_{INIT}), threshold probability during rebuilding (P_{TARGET}), and the assessment frequency explored by each of the rebuilding strategies and sensitivities.

	P_{INIT} (%)	P_{TARGET} (%)	Assessment frequency (years)	Special conditions
Rebuilding strategy				
Status quo	60	50	4	See *Alternative management actions* for additional details.
Flexible	60	40	4	See *Alternative management actions* for additional details.
Risk averse	75	60	4	See *Alternative management actions* for additional details.
Risk neutral	50	50	4	The *SPR* in the initial rebuilding plan was determined based on rebuilding by the T_{MAX} with a 50% probability ($T_{TARGET} = T_{MAX}$). See *Alternative management actions* for additional details.
Fixed	60	-	4	During rebuilding the *SPR* was not updated until the rebuilding target year. See *Alternative management actions* for additional details.
Constant harvest rate	-	-	4	No rebuilding plan, but allowed for rebuilding by reducing harvest by setting the *SPR* rate to 125% of the PFMC SPR_{PROXY} until the stock rebuilt. See *Alternative management actions* for additional details.
Sensitivity				
Status quo—natural mortality	60	50	4	Natural mortality was biased high by 10% in the estimation model relative to the true (operating model). See *Sensitivities* for additional details.
Status quo—steepness	60	50	4	Steepness was biased high by 10% in the estimation model relative to the true (operating model). See *Sensitivities* for additional details.
Status quo—assessment frequency	60	50	2/8	Either increased or decreased the assessment frequency based on the life history (flatfish and roundfish assessed every second year, both rockfishes assessed every eighth year). See *Sensitivities* for additional details.
Flexible—assessment frequency	60	40	2/8	As for "*status quo*—assessment frequency", but based on the "flexible" strategy. See *Sensitivities* for additional details.
Risk averse—flexible	75	40	4	See *Sensitivities* for additional details.
Risk neutral—maintain 50%	50	50	4	*SPR* was adjusted every four years to maintain a 50% probability of rebuilding by T_{TARGET}. See *Sensitivities* for additional details.
Fixed rebuilding—mid-course update	60	50	4	The *SPR* was adjusted upwards if the probability of rebuilding fell below 50% halfway through the initial estimated rebuilding period. See *Sensitivities* for additional details.

See the *Alternative management actions* and *Sensitivities* in Methods for additional details.

rebuilding *SPR*. The *SPR* was adjusted upwards (i.e. reducing fishing mortality) during rebuilding to maintain at least a 50% probability (P_{TARGET}) of rebuilding by the target year (T_{TARGET}). If no *SPR* was found that predicted rebuilding by the target year with at least a 50% probability, the target year was revised and set equal to the current value for T_{MAX}. An updated *SPR* was selected that would rebuild the stock by the new target year ($T_{TARGET} = T_{MAX}$) with a 50% probability. However, the rebuilding plan was declared a failure if the stock was predicted to be unable to rebuild by the T_{MAX} under any *SPR*. If a rebuilding plan failed, a new rebuilding plan was conducted (calculating new values for *SPR*, T_{TARGET}, and T_{MAX}) and implemented in the current year (Figure 1).

2. "Flexible": The *SPR* in the initial rebuilding plan was determined based on rebuilding by T_{MAX} with a $P_{INIT} = 60\%$. The *SPR* was adjusted upwards if the predicted probability (P_{TARGET}) of rebuilding by target year under the current *SPR* fell $<$40% to an *SPR* that was estimated to rebuild by the target year given a 50% probability. Other specifications are as for the "*status quo*" strategy.
3. "Risk averse": The *SPR* in the initial rebuilding plan was determined based on rebuilding by T_{MAX} with a probability of 75%. The *SPR* was adjusted upwards if the predicted probability of rebuilding by the target year under the current *SPR* fell $<$60% to an *SPR* that was estimated would rebuild with a 60% probability by T_{MAX}.
4. "Risk neutral": The *SPR* in the initial rebuilding plan was determined based on rebuilding by the T_{MAX} with a 50% probability ($T_{TARGET} = T_{MAX}$). The *SPR* was adjusted upwards if the predicted probability of rebuilding by the target year under the current *SPR* fell $<$50% to an *SPR* that was estimated would rebuild with a 50% probability by T_{MAX}.
5. "Fixed": The *SPR* in the initial rebuilding plan was determined based on rebuilding by T_{MAX} with a $P_{INIT} = 60\%$. During rebuilding, the *SPR* was not updated until the rebuilding target year. If the stock was estimated not to have rebuilt by the target year, the *SPR* was set equal to either 125% of the PFMC *SPR* maximum sustainable yield proxy value by life history (SPR_{PROXY}: flatfish $SPR_{30\%}$, roundfish $SPR_{45\%}$, and rockfish $SPR_{50\%}$) or remained at the rebuilding *SPR*, whichever value was higher, until the stock was estimated to be rebuilt (i.e. this constraint prevented catch from increasing when the stock failed to rebuild if the rebuilding *SPR* was more conservative relative to 125% of the SPR_{PROXY}).
6. "Constant harvest rate": The "constant harvest rate" rebuilding strategy deviates from all other strategies. The "constant harvest rate" strategy did not apply a rebuilding plan, but allowed for rebuilding by reducing harvest by setting the *SPR* rate to 125% of the PFMC SPR_{PROXY}. Since a rebuilding plan was not performed, an estimated minimum year, target year, and maximum year for recovery, including the rebuilding probability, were not estimated. While this rebuilding strategy would

not currently be allowed under US law, it does represent a rebuilding alternative that may be applied outside the United States.

The alternative rebuilding plans and sensitivities, except the constant harvest rate and fixed strategies including the fixed sensitivity test (see below), applied some rules to govern the amount catch could change between rebuilding analyses. The lower and upper limits of the multiplicative change to catches were 50% and 120%, respectively, of the previous catch. If the new estimated catch exceeded the upper bound, the catch was lowered. If the new estimated catch was below the lower bound, the target year was changed to maximum year for rebuilding and a new catch was estimated based on the updated target year. If the estimated catch was still below one-half of the previous catch, the current rebuilding plan was deemed a failure and a new plan was put in place (calculating new values for T_{TARGET} and T_{MAX}). In this case, the new rebuilding *SPR* was constrained to not be lower (result in a higher harvest rate) than the previous plan's *SPR*. In addition, these conditions for limiting the degree of changing in catch levels were not applied when the stock was first declared overfished and the initial rebuilding plan put in place, which is consistent with actual practice when a West Coast groundfish stock is initially placed under a rebuilding plan (although in practice, management has 2 years to implement a rebuilding plan and may proactively reduce catches before the rebuilding plan implementation). Similarly, when a stock was declared rebuilt, no conditions on the degree of change in catch were applied. The limits on the change in catch were arbitrarily selected, but were designed to capture the PFMC behavior when altering catch during and between rebuilding plans. Historically, management has been reactive to reduce catches during rebuilding based on more pessimistic assessments, but has been more apt to take a precautionary approach when the perception of stock biomass becomes more optimistic restricting large increases in catch during rebuilding.

Sensitivities

A number of sensitivity analyses were conducted to evaluate the performance of the rebuilding strategies given specific assumptions (Table 3):

1. "*Status quo*—natural mortality": The natural mortality rate was biased high by 10% in the estimation model relative to the true (operating model) value in assessments through the first half of the initially estimated rebuilding period. Assuming a positively biased natural mortality value in the assessment will result in an estimate of stock status that is less pessimistic regarding the true state of the stock. A misspecification of 10% was applied because it was a level of error that still resulted in the estimation method estimating the stock to be overfished in the first assessment year. The natural mortality rate in the estimation method was updated to the true value halfway through the initially estimated rebuilding period ($T_{\mathrm{TARGET}}/2$). This sensitivity explored the impact of overly optimistic assessment estimates for an extended period during rebuilding on the likelihood of meeting the rebuilding targets.
2. "*Status quo*—steepness": The steepness parameter was biased high by 10% in the estimation model relative to the true (operating model) value in assessments through the first half of the initially estimated rebuilding period. A similar logic was applied in selecting a positive bias of 10%, as was considered for natural mortality, where this value resulted in the assessment estimating a less depleted stock relative to its true operating model status, but the stock was still estimated to be overfished in the first year. Steepness in the estimation method was updated to the true value halfway through the initially estimated rebuilding period ($T_{\mathrm{TARGET}}/2$). Similar to the natural mortality sensitivity, this sensitivity explored the impact of overly optimistic assessment estimates for an extended period during rebuilding on the likelihood of meeting the rebuilding targets.
3. "*Status quo*—assessment frequency": The assessment frequency during rebuilding was either increased or decreased based on the life history type. The frequency of assessment increased for the shorter-lived flatfish and roundfish life histories to every 2 years, while the frequency of assessment decreased for both rockfish life history types from every 4 years to every 8 years. This sensitivity explored the relationship between assessment frequency and performance of the rebuilding plan (i.e. are there benefits to increased or decreased monitoring of the stock during rebuilding?).
4. "Flexible—assessment frequency": As for "*status quo*—assessment frequency", but based on the "flexible" strategy. This sensitivity explored the interaction between reduced thresholds for updating the *SPR* during rebuilding and reduced or increased assessment frequency.
5. "Risk averse—flexible": The *SPR* in the initial rebuilding plan was determined based on rebuilding by T_{MAX} with a 75% probability (P_{INIT}). The *SPR* was adjusted upwards if the probability of rebuilding by T_{TARGET} fell $<$40% to a new *SPR* that would rebuild with a 75% probability by the T_{TARGET}. This sensitivity explored the interaction and rebuilding performance if the initial rebuilding *SPR* is set conservatively and the threshold for updating the *SPR* during rebuilding is reduced (i.e. do these two adjustments offset each other?).
6. "Risk neutral—maintain 50%": The *SPR* in the initial rebuilding plan was determined based on rebuilding by T_{MAX} with a 50% probability. The *SPR* was adjusted upwards or downwards in each subsequent analysis to maintain an *SPR* that would rebuild with a 50% probability by T_{TARGET}. The key difference in this sensitivity is that the *SPR* was adjusted each time the rebuilding analysis was conducted to maintain a 50% probability of rebuilding by the T_{TARGET}, whereas the other strategies and sensitivities (except the "fixed" strategies) only adjusted the *SPR* if the probability of rebuilding by T_{TARGET} was less than the probability threshold value (P_{TARGET}). This sensitivity examined the impact of maintaining a 50% probability over the course of the rebuilding plan and whether this approach performed similarly to alternative approaches that allowed fluctuations in the rebuilding probability.
7. "Fixed—mid-course update"—The *SPR* in the initial rebuilding plan was determined based on rebuilding by T_{MAX} with a 60% probability (P_{INIT}). If the rebuilding period was $>$10 years, an updated rebuilding analysis was conducted at the halfway point to the target rebuilding year to evaluate progress. The *SPR* was adjusted upwards if the probability of rebuilding by T_{TARGET} fell $<$50% to a new *SPR* that would rebuild by T_{TARGET} with a 50% probability. If the stock failed to rebuild by T_{TARGET}, the *SPR* was set equal to either 125% of the SPR_{PROXY} value (flatfish: $SPR_{30\%}$, roundfish: $SPR_{45\%}$, and

rockfish: $SPR_{50\%}$) or remained at the rebuilding *SPR*, whichever value was higher until the stock was estimated to have rebuilt. This sensitivity examined the impact of reevaluating the rebuilding performance and making any required adjustments to the rebuilding plan mid-course ($T_{\mathrm{TARGET}}/2$ if rebuilding time was >10 years) compared with the "fixed" strategy which did not apply any adjustments during rebuilding.

Performance measures

The following eight performance metrics were used to evaluate each alternative rebuilding strategy across the 100 simulations (using the median and 80% simulation interval):

1. The number of *SPR* changes during rebuilding which was used as a proxy measurement for predictability during rebuilding for management and stakeholders.
2. The number of times the value of the target rebuilding year was changed, an additional measurement for predictability during rebuilding.
3. The number of times a rebuilding plan failed to recover the stock to the target stock size, requiring a new rebuilding plan.
4. The annual average variability of the catches (abbreviation AAV) over the whole projection period, defined as:

$$AAV = 100\frac{\sum_y |C_y - C_{y+1}|}{\sum_y C_y} \quad (6)$$

   where C_y is the catch during year y. Decreased variability in catches would provide additional predictability for management and stakeholders.
5. The average catch during a set number of years when the resource was under a rebuilding plan (flatfish: 5, roundfish: 10, medium-lived rockfish: 25, and long-lived rockfish: 50 years), which was used as a measure of the average catch attained during rebuilding for each alternative strategy. The vast majority of simulated stocks were not yet rebuilt at the end of the defined number of years by the life history. However, when a stock rebuilt more quickly, the average was calculated over the shortened period of rebuilding.
6. The average catch over the entire projection period (rebuilding period and recovery catches), which was a measure of the trade-off between the length of rebuilding with reduced catches and the benefit of increased catches from a recovered stock.
7. The "rebuilding ratio", the ratio of the number of years under rebuilding (until the stock was assessed to be rebuilt) divided by the number of years that it was expected that rebuilding would take place by the initial rebuilding plan (the initial T_{TARGET}) to evaluate the ability of each alternative rebuilding strategy to meet the initial rebuilding estimates.
8. The number of years estimated for the overfished stock to rebuild to the target stock size from the initial rebuilding plan.

Results

Rebuilding strategies

The six alternative rebuilding strategies led to successful rebuilding for the majority of simulations across the life histories (Table 4). However, there were differences in performance across the strategies by life history type where varying adjustments to the *SPR* were required to meet the rebuilding timeline (Figure 2: "*Status quo*" rebuilding example). The extent of increase (decrease in fishing effort) from the SPR_{PROXY} to the *SPR* applied during the initial rebuilding plan varied among life histories (Figure 3). The most severe changes in the *SPR* occurred for the flatfish life history (Figure 3a) and a small subset of the simulated roundfish stocks (Figure 3b). These simulated flatfish and roundfish stocks were determined to be able to rebuild in <10 years in the absence of fishing, triggering the 10-year rebuilding rule as required by the current US federal guidelines, requiring large adjustments to the *SPR* to meet the rebuilding time frame.

Estimation error resulted in a number of simulated stocks being incorrectly declared rebuilt when the true operating model stock was still below the target biomass (Table 4). The difference between these values was most marked for the long-lived rockfish life history. This occurred when the true stock was close to being rebuilt, but still below the management proxy target stock size and the estimation method overestimated stock status resulting in the stock being declared rebuilt. Once rebuilt, catch was set using an *SPR* proxy value applied for all US West Coast rockfish stocks. The *SPR* proxy value ($SPR_{50\%}$) will maintain the population at the management target ($SB_{40\%}$) when steepness is equal to 0.60 (based on the Beverton–Holt stock–recruit relationship), but the long-lived rockfish steepness was lower (0.50) resulting in an average stock size slightly below the management target biomass ($SB_{40\%}$).

Performance of the "*status quo*" and the "flexible" rebuilding strategies were nearly identical for both the flatfish and roundfish life histories (Figures 4 and 5). The faster dynamics of each of these life histories resulted in shorter rebuilding times with little variance in the number of times the *SPR* was adjusted between the two strategies (Figures 4a and 5a). The median number of *SPR* changes during rebuilding was higher for the roundfish life history. However, the rebuilding time was generally twice that required for the flatfish life history (Table 5). Across all life histories, both strategies resulted in median rebuilding times that were equal to or less than the rebuilding time estimates during the initial rebuilding analysis (Figures 4f–7f). However, the slower dynamics and longer rebuilding periods associated with rockfishes led to differences between the "*status quo*" and the "flexible" rebuilding strategies for those life histories. The lower threshold probability of rebuilding by the target year (P_{TARGET}) for the "flexible" strategy resulted in fewer *SPR* updates during rebuilding for the two rockfish life histories (median *SPR* changes—"*status quo*": 3, "flexible": 1). The average catch over the fixed period and the total average catch over all projection years did not vary greatly among strategies (Figures 6 and 7e and Table 6), and the "*status quo*" and "flexible" rebuilding strategies resulted in nearly identical rebuilding times for the medium- and long-lived rockfish life histories (Table 5).

The "risk averse" rebuilding strategy resulted in an ~10% faster rebuilding time relative to the "*status quo*" strategy for each of the life history types (Table 5). The faster rebuilding times of the "risk averse" strategy were achieved by having lower average catches during rebuilding (Figures 4e–7e) compared with the "*status quo*" strategy. However, the average catch over all projection years for each strategy were comparable across all life histories (Table 6). This highlights the trade-off between the length of rebuilding with reduced catches and the benefit of increased catches from a recovered stock. The higher probability associated with rebuilding by the target year (P_{TARGET}) for the "risk averse" strategy resulted in

Table 4. The percentage of stocks that failed to rebuild according to the estimation method compared with the percentage of stocks that actually (i.e. within the operating model) failed to rebuild for each life history by alternative rebuilding strategy and sensitivity.

	Flatfish		**Roundfish**		**Medium-lived rockfish**		**Long-lived rockfish**	
	True per cent not rebuilt	**Estimated per cent not rebuilt**	**True per cent not rebuilt**	**Estimated per cent not rebuilt**	**True per cent not rebuilt**	**Estimated per cent not rebuilt**	**True per cent not rebuilt**	**Estimated Per cent Not Rebuilt**
Alternative strategy								
Status quo rebuilding	4	0	6	0	6	0	32	0
Flexible rebuilding	4	0	6	0	5	0	32	0
Risk averse rebuilding	4	0	6	0	3	0	30	0
Risk neutral rebuilding	3	0	8	0	8	0	33	0
Fixed rebuilding	4	1	11	1	8	0	34	0
Constant harvest rate rebuilding	7	0	8	1	2	0	47	25
Sensitivity								
Status quo—natural morality	4	0	7	1	7	0	36	1
Status quo—steepness	4	0	8	0	6	0	32	1
Status quo—assessment frequency	3	0	11	0	2	0	26	0
Flexible—assessment frequency	3	0	12	0	2	0	27	0
Flexible—risk averse	3	0	9	0	2	0	32	0
Risk neutral—maintain 50%	6	2	11	2	8	0	41	11
Fixed—mid-course update	4	0	10	1	7	0	34	1

an increased number of *SPR* changes for both the rockfish life histories (Figures 6a and 7a), but did not result in a median increase in the number of *SPR* changes for the flatfish or roundfish life histories (Figures 4a and 5a).

The "risk neutral" rebuilding strategy defined the rebuilding *SPR* assuming a 50% probability of rebuilding by T_{MAX}. Relative to the "*status quo*" strategy, the "risk neutral" approach resulted in modest increases in the median average catch over the rebuilding period (Figures 4e–7e), similar average catch over all projection years (Table 6), and lower median AAV (Figures 4d–7d). However, compared with "*status quo*", the "risk neutral" strategy had an increased frequency of rebuilding failure (increased 80% simulation interval) for the rockfish life histories (Figures 6c and 7c). Apart from flatfish, this strategy resulted in longer and more variable rebuilding times compared with the other strategies (Table 5).

The "fixed" rebuilding strategy resulted in a median average catch during rebuilding comparable with the other strategies (Figures 4e–7e), but with longer median rebuilding periods relative to the "*status quo*" strategy for the rockfish and the roundfish life histories (Table 5). The extended rebuilding period resulted in lower average catches over all projection years (Table 6). Across life histories, the "fixed" rebuilding strategy estimated rebuilt stocks by the target rebuilding year for the majority of the simulations [88% (flatfish), 72% (roundfish), 58% (medium-lived rockfish), and 72% (long-lived rockfish)] without requiring additional adjustments to the *SPR* due to not rebuilding by the target year.

The "constant harvest rate" rebuilding strategy that did not apply a rebuilding plan, but rather reduced harvest by an increase in the *SPR* rate while the stocks were overfished resulted in a lower AAV in catches for all life histories (Figures 4d–7d) and higher average catches during rebuilding (Figures 4e–7e), except for the medium-lived rockfish life history. However, the average catch over the projection period was lower relative to the "*status quo*" strategy for all life histories (Table 6). The *SPR* rate applied while the stocks were overfished was lower (higher catches) for all life histories, except for the medium-lived rockfish (Figure 3), which resulted in higher catches while the stocks were rebuilding, but also generally increased the number of years to rebuild (Table 5) and hence lower average catches in the projection period (Table 6). The "constant harvest rate" strategy resulted in rebuilding times that were greater than the "*status quo*" strategy initial rebuilding plan T_{MAX} year for 97, 55, 5, and 82% of the simulations for the flatfish, roundfish, medium-lived, and long-lived rockfish life histories, respectively. The maximum time allowed for rebuilding under a formal rebuilding plan is defined as the minimum time to rebuild in the absence of

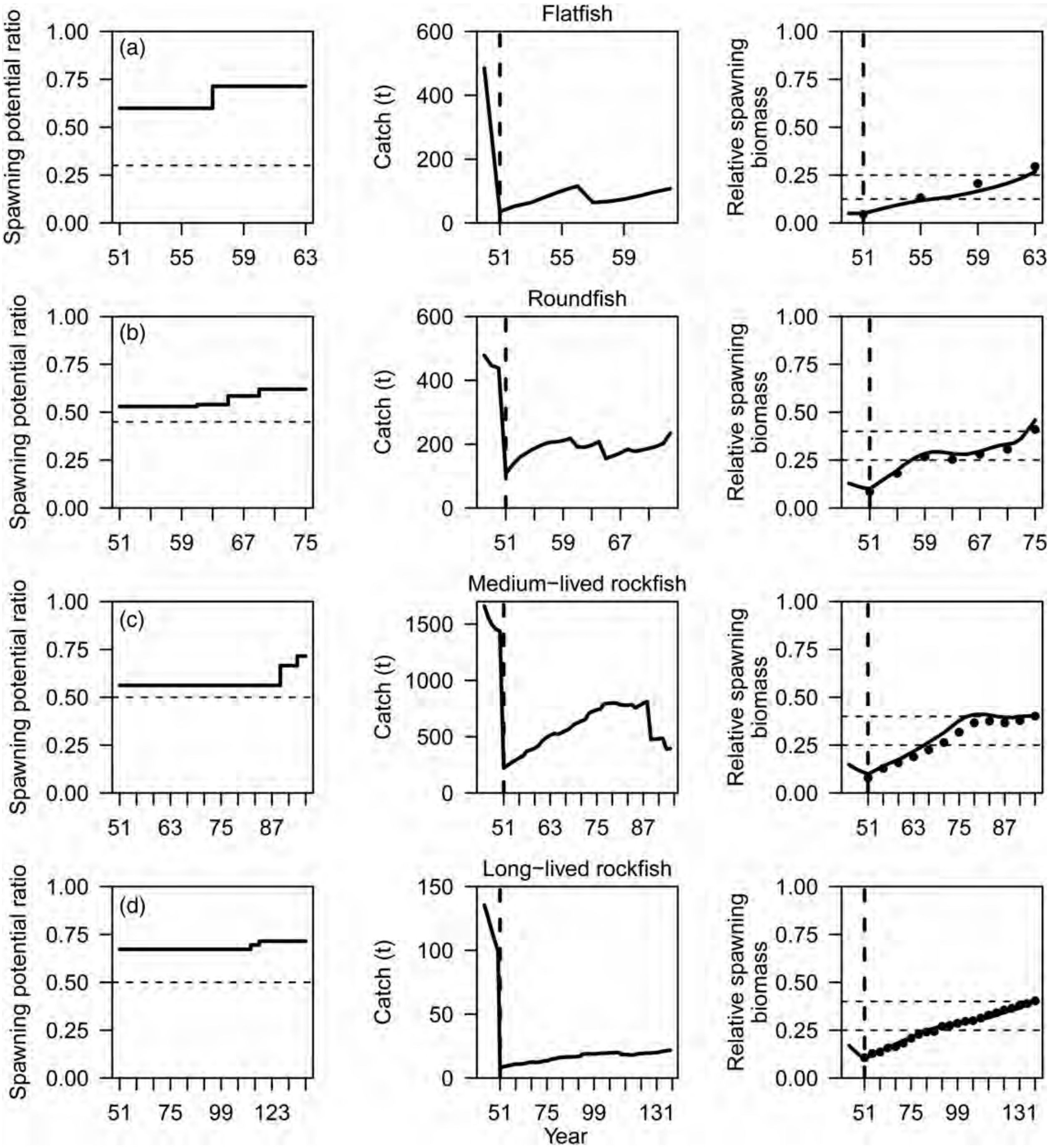

Figure 2. Results from an illustrative simulation for the "status quo" rebuilding strategy for each life history evaluated. The left set of panels summarizes the changes in the *SPR* during rebuilding, with the dashed line indicating the SPR_{PROXY} value for each life history. The middle panels give the trajectory of the catches during rebuilding for the example simulations. The right panels show the estimated relative spawning biomass (solid dots) and the true operating model relative spawning biomass trajectory (solid line), with the horizontal dashed lines indicating the overfished threshold and the target levels for each life history.

fishing plus one mean generation period, but the "constant harvest rate" strategy did not impose this requirement. This differing application resulted in the varying results for the medium-lived rockfish life history where the strategies that applied a rebuilding strategy were allowed a longer period to rebuild the stock and hence applied more aggressive *SPR* rates during rebuilding relative to the "constant harvest rate" strategy (Figure 3).

Sensitivities

Impact of parameter misspecification on rebuilding performance

Both sensitivities that examined the impact of parameter misspecification, natural mortality ("*status quo*—natural mortality") and steepness ("*status quo*—steepness") resulted in an increase in the median times the *SPR* needed to be changed in the attempt to rebuild by the target year for each rockfish life history relative to

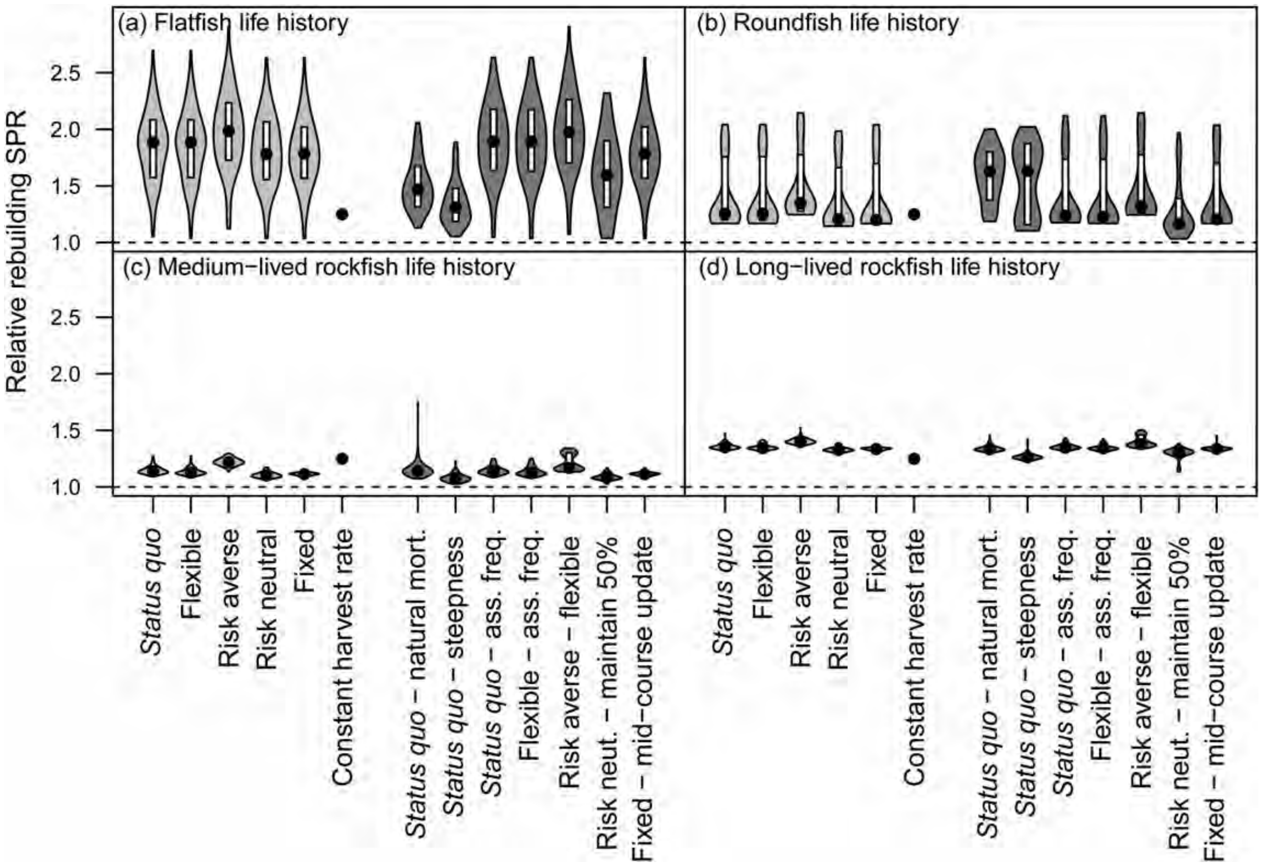

Figure 3. The mean *SPR* value during rebuilding relative to the management proxy *SPR* value [e.g. the ratio of the rebuilding *SPR* to the management target *SPR* (flatfish: 0.30, roundfish: 0.45, rockfish: 0.50)] for each alternative rebuilding strategy (light grey) and sensitivity (dark grey) for flatfish (a), roundfish (b), medium-lived rockfish (c), and long-lived rockfish (d) life history types, where the points are the median value and the white bars indicate the 80% simulation interval.

the "*status quo*" strategy (Figures 4a–7a). The majority of simulations for the shorter-lived flatfish and roundfish life histories failed to rebuild the stock by the initial estimate of T_{MAX}, requiring a new rebuilding plan (Figures 4c and 5c). The longer-lived life histories only required adjustments to target rebuilding year for the sensitivity that misspecified natural mortality (Figures 6b and 7b). The longer rebuilding times associated with the majority of rockfish life histories simulations allowed for sufficient time to adjust the rebuilding *SPR* to still rebuild in similar median rebuilding times relative to the "*status quo*" strategy once the misspecified parameter was corrected halfway through the initial rebuilding period (Table 5). Additionally, the misspecified parameters led to an overly optimistic estimate of the initial stock status resulting in estimated shorter rebuilding times relative to the true time required to rebuild the stock. This underestimate resulted in shortened rebuilding timelines relative to the "*status quo*" strategy, and even when the stock was not rebuilt by the target rebuilding year, the stock was often rebuilt in a similar time frame as the strategies without parameter misspecification (Table 5).

Impact of assessment frequency to meet rebuilding deadlines

The impact of either increasing or decreasing the assessment frequency varied based on the life history. The sensitivity runs that examined assessment frequency for the "*status quo*" and the "flexible" strategies for the medium- and long-lived rockfishes resulted in similar median rebuilding times, with either the same or fewer changes to the *SPR* during rebuilding relative to the "*status quo*" and "flexible" strategies, which have assessments every fourth year (Figures 6a and 7a). Reducing the frequency of assessment for the rockfishes from every fourth to every eighth year also resulted in a higher average catch during rebuilding for both the medium- and long-lived rockfish (Figures 6e and 7e). However, increasing the assessment frequency for the fast dynamic life histories (flatfish and roundfish) from every fourth to every second year resulted in lower average catches during rebuilding (Figures 4e and 5e), with a larger range of median *SPR* changes (Figures 4a and 5a), and did not rebuild in shorter periods relative to each of the base strategies (Table 5).

Exploration of alternative threshold values for setting and changing the rebuilding SPR

The impact of altering the threshold probability that triggered a change to the *SPR* during rebuilding varied based on the initial probability of rebuilding selected to define the rebuilding timeline. The "risk averse—flexible" strategy that applied a high initial probability of rebuilding and allowed for increased flexibility before altering the rebuilding plan compared with the "risk averse" strategy resulted in generally fewer *SPR* changes during rebuilding (Figures 4a–7a), while rebuilding the stock in a similar amount of time (Table 5) with comparable AAV (Figures 4d–7d), average

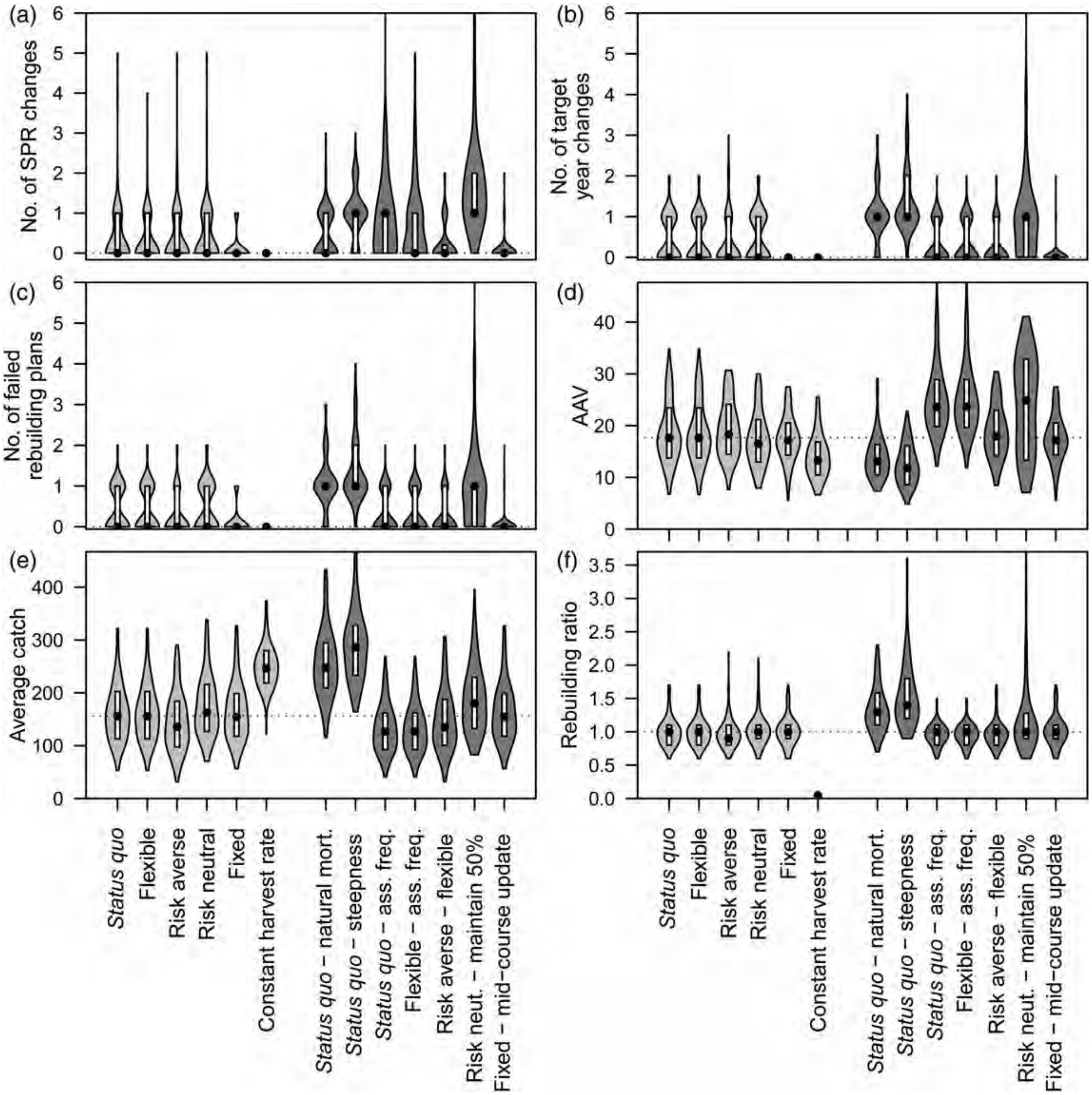

Figure 4. The flatfish life history median values (black points) and 80% simulation intervals (white bars) for the number of *SPR* changes (a), number of changes to the target rebuilding year (b), the number of failed rebuilding plans (c), the average annual variation in catch (AAV) (d), the average catch over the first 5 years of the rebuilding period (e), and the rebuilding ratio (f) for each of the alternative rebuilding strategies (light grey) and sensitivities (dark grey). The dashed horizontal line indicates the median value for the "*status quo*" strategy for visual reference for plots (a–e). The dashed horizontal line in (f) is set at 1.

rebuilding catch (Figures 4e–7e), and average catch over all projection years (Table 6) compared with the "risk averse" strategy.

Across all life histories, the "risk neutral—maintain" 50% rebuilding strategy, which maintained a 50% probability of rebuilding by T_{TARGET} for the duration of the rebuilding period, resulted in an increase in the median number of *SPR* and T_{TARGET} changes with an increase in failed rebuilding plans compared with the base "risk neutral" strategy (Figures 4–7a–c). This result was most evident for the long-lived rockfish life history which resulted in 22 (median across simulation) *SPR* changes over the course of rebuilding (Figure 7a). Across the alternative rebuilding strategies, this strategy led to the highest median average catch during the defined rebuilding periods (Figures 4e–7e) but had the longest median rebuilding times (Table 5) and the highest median AAV in catch for each of the life histories (Figures 4d–7d).

Updating the *SPR* for the "fixed mid-course update" rebuilding strategy did not alter the overall results compared with the "fixed" rebuilding strategy where no update was performed (Figures 4–7). The mid-course update was only performed if the rebuilding period was >10 years, which resulted in almost no updates for the flatfish life history (Figure 4). A similar number of simulations successfully rebuilt by the target rebuilding year for the "fixed

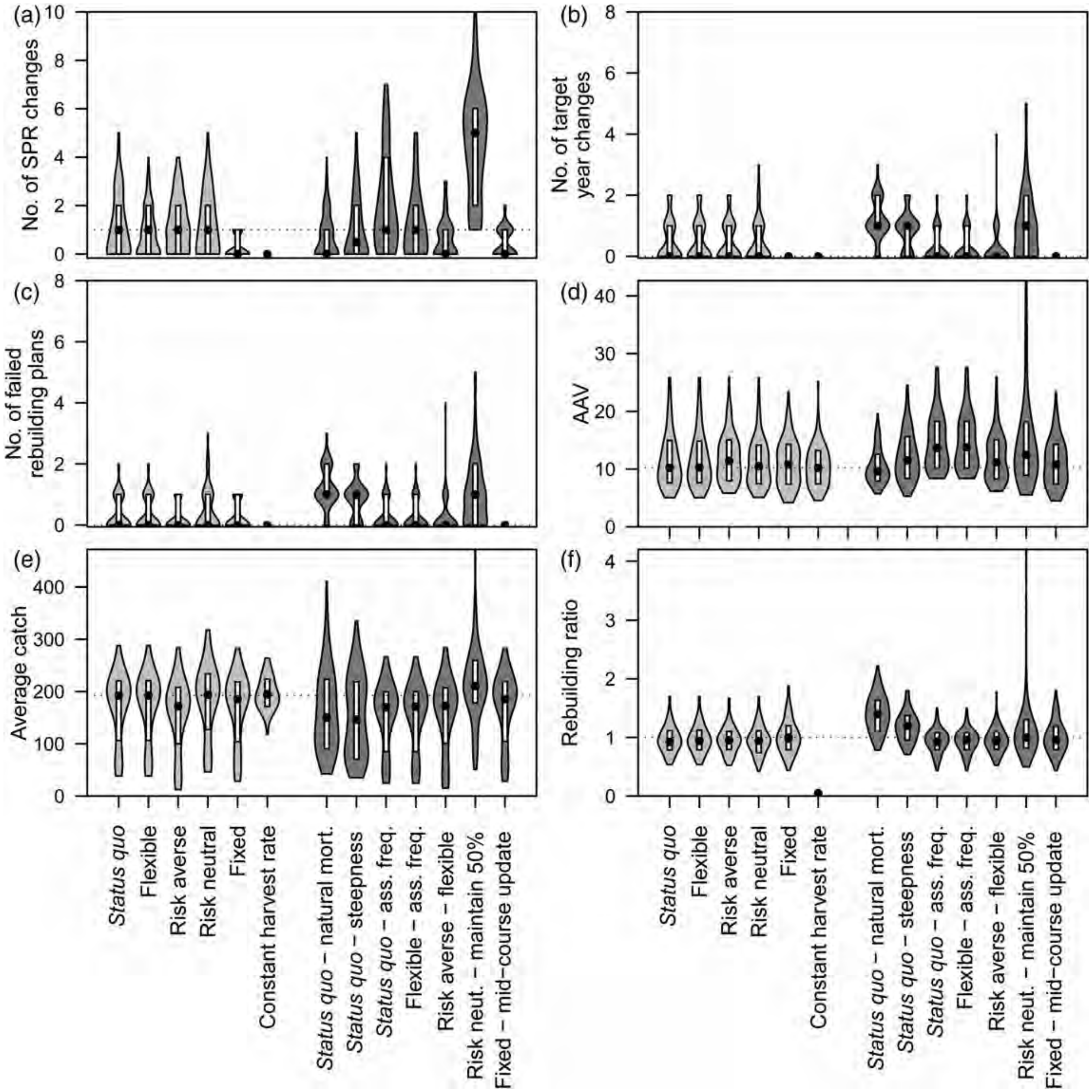

Figure 5. The roundfish life history median values (black points) and 80% simulation intervals (white bars) for the number of *SPR* changes (a), number of changes to rebuilding target year (b), the number of failed rebuilding plans (c), the average annual variation in catch (AAV) (d), the average catch over the first ten years of the rebuilding period (e), and the rebuilding ratio (f) for each of the alternative rebuilding strategies (light grey) and sensitivities (dark grey). The dashed horizontal line indicates the median value for the "*status quo*" strategy for visual reference for plots (a–e). The dashed horizontal line in (f) is set at 1.

mid-course update" strategy [88% (flatfish), 71% (roundfish), 61% (medium-lived rockfish), and 74% (long-lived rockfish)] compared with the "fixed" strategy [88% (flatfish), 72% (roundfish), 58% (medium-lived rockfish), and 72% (long-lived rockfish)].

Discussion

The performance of alternative rebuilding plans that applied alternative values for the initial rebuilding probability and various threshold probabilities for updating the *SPR* during rebuilding were explored. The rebuilding plans that implemented a higher initial rebuilding probability (≥60%) for determining rebuilding fishing mortality and targets generally resulted in fewer changes to the rebuilding plans and rebuilt by the target rebuilding year, particularly for stocks with the longer rebuilding plans (e.g. rockfishes). Punt and Ralston (2007) also determined that a key to a successful rebuilding plan was setting targets and fishing mortality at a rate that can buffer against future uncertainty to ensure that rebuilding deadlines are met. The strategies that not only incorporated a higher initial rebuilding probability, but also allowed for a lower threshold probability ($P_{\mathrm{TARGET}} = 40\%$) during rebuilding were less responsive to noise, resulting in fewer changes to fishing mortality and rebuilding targets while still successfully rebuilding stocks.

Table 5. The median estimated number of years to rebuild the stock to the target relative stock size and the 80% simulation interval for each life history by alternative rebuilding strategy and sensitivity.

	Flatfish		Roundfish		Medium-lived rockfish		Long-lived rockfish	
	Years	Interval	Years	Interval	Years	Interval	Years	Interval
Alternative strategy								
Status quo rebuilding	10	(7–17)	20	(8–34)	41	(30–57)	87	(65–100)
Flexible rebuilding	10	(7–17)	20	(8–34)	41	(30–54)	87.5	(68–101)
Risk averse rebuilding	9	(6–20)	18	(9–30)	36	(26–45)	80	(68–95)
Risk neutral rebuilding	9	(6–20)	21.5	(9–36)	43	(32–56)	90	(73–105)
Fixed rebuilding	10	(6 –17)	19	(8–41)	43.5	(33–60)	91	(72–111)
Constant harvest rate rebuilding	14	(8–27)	21	(11–43)	34	(24–53)	105	(79–119)
Sensitivity								
Status quo—natural morality	13	(8–21)	16	(10–29)	38	(31–48)	88	(69–113)
Status quo—steepness	14	(9–26)	14	(9–32)	40	(33–48)	84	(71–100)
Status quo—assessment frequency	10	(7–16)	20	(8–32)	41	(31–57)	88	(69–100)
Flexible—assessment frequency	10	(7–16)	20	(9–32)	41	(31–56)	88.5	(72–100)
Flexible—risk averse	10	(6–18)	18	(8–29)	37	(27–49)	81	(66–95)
Risk neutral—maintain 50%	10	(6–28)	23	(9–40)	46	(32–64)	96	(77–115)
Fixed—mid-course update	10	(6–17)	20	(8–40)	43	(32–60)	91	(69–111)

Attempting to maintain a 50% probability of rebuilding was the poorest performing rebuilding strategy based on the performance metrics, resulting in a large number of changes to the rebuilding plan, an increased frequency of failing to meet rebuilding targets, and a higher variation in catch.

The current US federal guideline to rebuild in $\leq$10 years were possible given that the biology of the stock impacted the performance of the alternative rebuilding plans for the flatfish and roundfish life histories. The majority of flatfish stocks and a select number of the simulated roundfish stocks were estimated to be able to rebuild in $\leq$10 years in the absence of fishing, requiring the maximum rebuilding time to be set at $\leq$10 years. An estimated minimum rebuilding time for a majority of simulated flatfish stocks was ca. 6–8 years across the simulations. The limited number of years between the minimum and maximum years for rebuilding resulted in extreme reductions in the fishing mortality rate at the start of rebuilding relative to the other life histories (Figure 3). Overall, the results of the alternative rebuilding strategies for the flatfish life history showed little contrast across strategies, highlighting that the 10-year rule was the primary driver for rebuilding performance rather than the strategy applied. Additionally, the fact that only some roundfish simulations were estimated to be able to rebuild in <10 years resulted in bimodal distributions for the average catch and rebuilding *SPR* rates, requiring relatively large reductions to harvest to rebuild within 10 years, compared with stocks that were allowed an average of 20 years to rebuild. This behavior highlights the discontinuity in the current US rebuilding guidelines, resulting in very different rebuilding plans for stocks where the minimum time for rebuilding is less than or >10 years. Patrick and Cope (2014) have outlined several alternatives for defining the maximum time allowed for rebuilding short-lived stocks that would be consistent across life histories. One suggestion made by Patrick and Cope (2014) would change the definition of the maximum year being set at twice the minimum rebuilding time ($T_{MAX} = 2 \times T_{MIN}$), which for the flatfish life history would reduce the extreme initial reduction in fishing mortality rates required for rebuilding while only extending rebuilding timelines by ca. 2–6 years.

When a stock is declared rebuilt, an additional challenge is the potential substantial change in the catch level compared with the limited catches allowed during rebuilding. This was an issue for each of the life histories explored, but perhaps the most extreme for the flatfish life history where the rebuilding harvest rate was the most constrained relative to the management proxy harvest level. When a stock rebuilds, harvest predictions are based on the management harvest control rule and proxy harvest levels which are designed to obtain the maximum acceptable biological catch at the target biomass. This catch level can be substantially larger than the rebuilding catches (Thorson and Wetzel, 2015). An alternative rebuilding approach has been applied by the PFMC for West Coast petrale sole (PFMC, 2011). The stock was deemed able to rebuild in $\leq$10 years based on projections using the management harvest control rule which reduces catches linearly when the stock is below the relative target biomass to zero at a lower threshold relative stock size. In this instance, the Council adopted rebuilding catches based on the harvest control rule rather than the catches predicted by the traditional rebuilding plan. Predicting catches based on the harvest control rule that applied a linear reduction resulted in a smooth ramp between the rebuilding and rebuilt catch values while successfully rebuilding the stock.

Currently, the US federal rebuilding plans are required to contain specific components that define a rebuilding time-line, the probability of rebuilding by the target year, and harvest rate to achieve rebuilding. However, there are distinct trade-offs between rebuilding as quickly as possible through sometimes extreme harvest reductions and the economic and societal costs of doing so (Hilborn *et al.*, 2011). The "constant harvest rate" strategy involved simple reductions in harvest that are consistent over the rebuilding period and also may limit the amount in lost yield by applying less extreme harvest restrictions. The "constant harvest rate" strategy resulted in higher average catches during rebuilding with lower annual variation (except for the medium-lived rockfish), but averaged longer rebuilding periods and lower average catch over the whole projection period, highlighting the trade-offs that should be considered by management and stakeholders when determining the strategy for rebuilding an overfished stock.

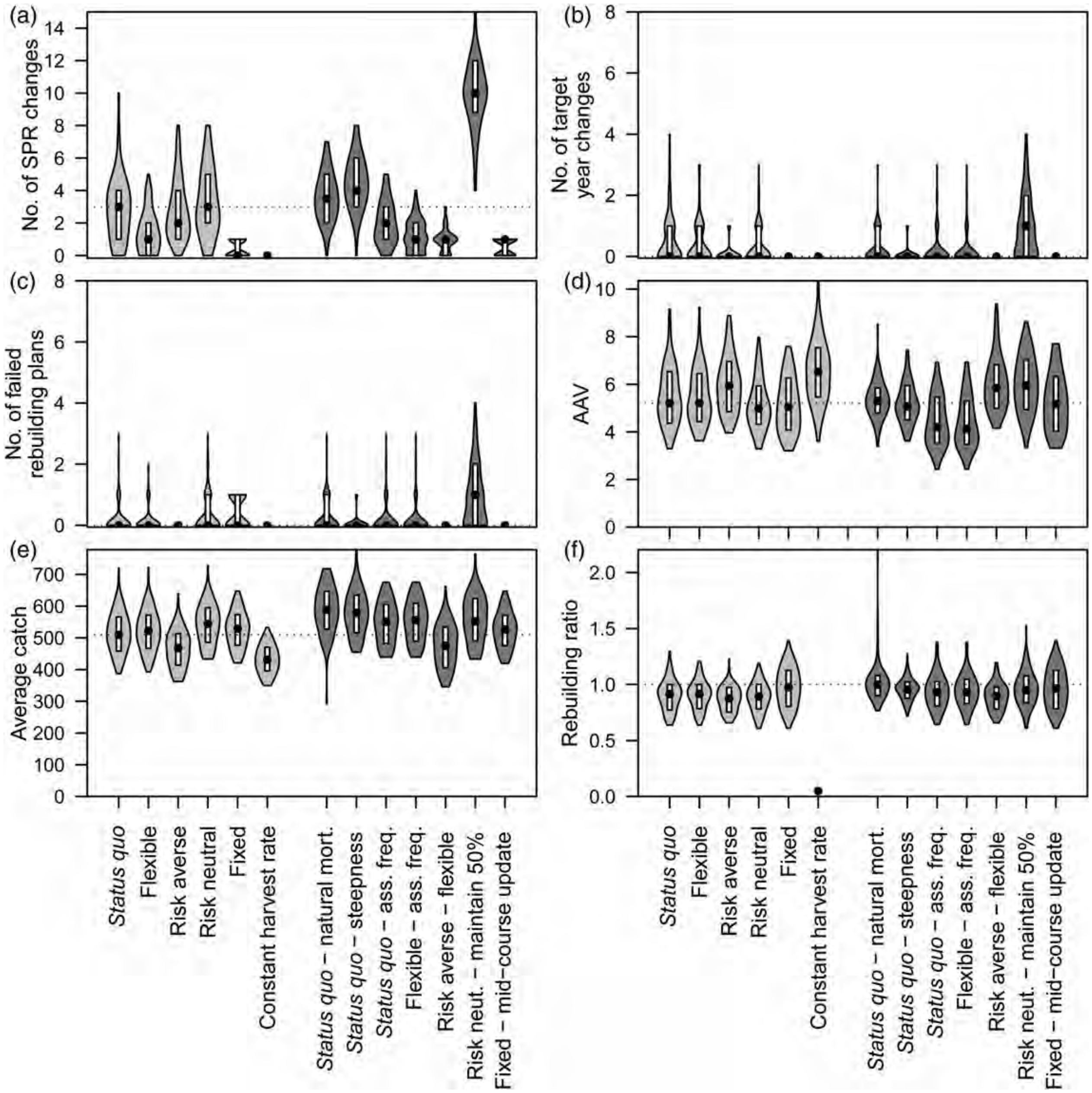

Figure 6. The medium-lived rockfish life history median values (black points) and 80% simulation intervals (white bars) for the number of *SPR* changes (a), number of changes to rebuilding target year (b), the number of failed rebuilding plans (c), the average annual variation in catch (AAV) (d), the average catch over the first 25 years of the rebuilding period (e), and the rebuilding ratio (f) for each of the alternative rebuilding strategies (light grey) and sensitivities (dark grey). The dashed horizontal line indicates the median value for the "*status quo*" strategy for visual reference for plots (a – e). The dashed horizontal line in (f) is set at 1.

A rebuilding strategy will only be effective when management is responsive and is able to control fishing mortality to a rate at or below the level required for the stock to rebuild (Patrick *et al.*, 2013). Once a stock is identified as being overfished, a delay in implementing a rebuilding plan can negatively impact rebuilding (Shertzer and Prager, 2007) if that stock is experiencing overfishing (i.e. removals exceed the maximum sustainable yield), and can be especially important for stocks that have a low intrinsic rate of growth (Neubauer *et al.*, 2013). All rebuilding strategies in this paper were implemented and rebuilding harvest levels applied the year immediately following the overfished status determination, and catches were taken without error. The rebuilding timelines would have been extended requiring harvest restrictions for longer periods if there had been a delay in implementation of the rebuilding plan and if management was ineffective at reducing catch to a level at or below the rebuilding values.

The results here were designed to evaluate alternative rebuilding strategies for West Coast groundfish stocks. To determine the impact of each alternative rebuilding strategy, misspecification between the operating model and the estimation method was limited and was explored only in some sensitivity analyses, which allowed for the results to be attributed to the rebuilding plan

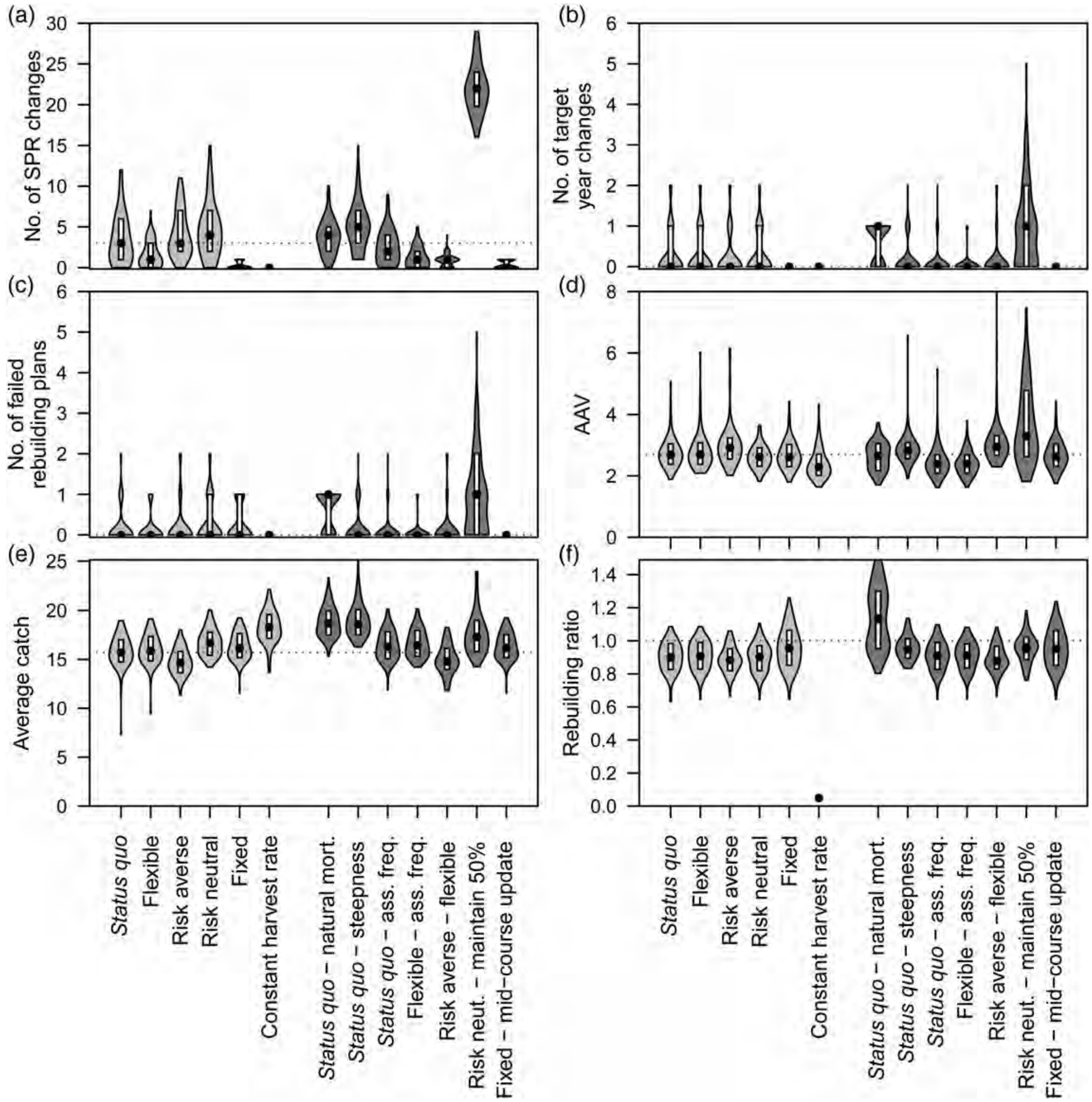

Figure 7. The long-lived rockfish life history median values (black points) and 80% simulation intervals (white bars) for the number of *SPR* changes (a), number of changes to rebuilding target year (b), the number of failed rebuilding plans (c), the average annual variation in catch (AAV) (d), the average catch over the first 50 years of the rebuilding period (e), and the rebuilding ratio (f) for each of the alternative rebuilding strategies (light grey) and sensitivities (dark grey). The dashed horizontal line indicates the median value for the "*status quo*" strategy for visual reference for plots (a–e). The dashed horizontal line in (f) is set at 1.

rather than model misspecification. Although the assessment was fully simulated, the structural assumptions between the operating and estimation model matched, an attribute that is not commonly attainable in real-world assessments; hence, the assessment should not be considered entirely reflective of the uncertainties inherent in traditional stock assessments. Additionally, a relatively high effective sample size of age data that were informative for all life histories (although the sample size likely resulted in greater precision for the long-lived stocks) was provided to the estimation model.

There are two types of error that could impact the results substantially which could be identified with model diagnostics in a real assessment, but something that is not easily done in a simulation framework. The first is poor estimation of key biological parameters (or parameters assumed known at incorrect values) such as natural mortality or steepness. The misspecification of each of these parameters was explored in separate sensitivity runs, but for only limited periods. Long-term misspecification or time-varying changes that are not accounted for in the assessment would reduce the performance of all the rebuilding strategies explored here.

The second type of error that could impact the interpretation of the results is not accounting for changes in the biology, productivity,

Table 6. The median average catch over the projection period covering both the catches obtained during rebuilding and when the stock recovered along with the 80% simulation interval for each life history by alternative rebuilding strategy and sensitivity.

	Flatfish		Roundfish		Medium-lived rockfish		Long-lived rockfish	
	Catch	Interval	Catch	Interval	Catch	Interval	Catch	Interval
Alternative strategy								
Status quo rebuilding	462	(413–516)	338	(294–389)	741	(656–828)	33	(30–36)
Flexible rebuilding	462	(413–516)	338	(294–389)	742	(651–827)	33	(30–36)
Risk averse rebuilding	464	(414–516)	340	(295–387)	767	(675–847)	34	(31–37)
Risk neutral rebuilding	460	(405–519)	334	(287–379)	728	(643–822)	33	(30–36)
Fixed rebuilding	439	(384–502)	314	(266–369)	728	(620–837)	26	(23–29)
Constant harvest rate rebuilding	435	(385–498)	313	(269–363)	719	(621–822)	25	(22–29)
Sensitivity								
Status quo—natural morality	455	(405–517)	356	(306–405)	763	(683–857)	34	(31–38)
Status quo—steepness	451	(399–504)	343	(298–400)	739	(651–829)	33	(30–35)
Status quo—assessment frequency	460	(411–519)	337	(290–383)	743	(656–828)	33	(30–36)
Flexible—assessment frequency	460	(411–519)	336	(290–383)	741	(653–827)	33	(30–36)
Flexible—risk averse	463	(414–522)	341	(296–387)	760	(673–849)	34	(31–37)
Risk neutral—maintain 50%	456	(402–514)	328	(282–372)	724	(634–808)	32	(29–35)
Fixed—Mid-Course Update	439	(384–502)	314	(268–369)	730	(622–841)	26	(23–29)

or species interactions of the stock over time. Rebuilding projections depend on the values of biological parameters in the final year of assessment and predict future recruitment by sampling from historical recruitments from the stock–recruitment curve. There has been considerable concern about the impact of climate change on fish stocks, specifically how it may affect future recruitment (Hollowed *et al.*, 2011; Ianelli *et al.*, 2011; Mueter *et al.*, 2011; Stachura *et al.*, 2014). Decadal swings in productivity could result in rebuilding trajectories that deviate below or above the projected probability of rebuilding by the target year. Simulation testing has shown that detecting, predicting, and making the correct management adjustments to shifts in productivity can be very challenging (Haltuch and Punt, 2011; Szuwalski and Punt, 2013). Management strategies that specifically account for environmentally driven recruitment have not always been shown to outperform those that assume a form of average recruitment in the future (A'mar *et al.*, 2009; Punt, 2011; Punt *et al.*, 2013). Under these conditions over long rebuilding periods, the overall average recruitment may not deviate greatly from the forecasted levels even if there were periods that were above or below predicted levels. However, long-term rebuilding plans based on historical recruitment level will likely not perform well and could fail to reduce fishing mortality to a level required to rebuild the stock. Additionally, changing future conditions may result in long-term shifts in biological parameters (e.g. natural mortality, growth) (Swain and Benoit, 2015), altering the sustainable yield available from a stock and if not accounted for could impact the ability to rebuild a stock (Legault and Palmer, 2015).

This work focused specifically on rebuilding strategies applied for US West Coast groundfish. However, the results can be informative for fisheries managers outside of this region to determine rebuilding plans that best meet management goals. There are trade-offs that must be considered when determining rebuilding fishing mortality levels for rebuilding overfished stocks. The development of rebuilding plans should consider the life history of the stock and the major sources of uncertainty. Future work applying selected rebuilding strategies identified here should be conducted to explore the impact of additional misspecification between the operating and estimation models and how varying future conditions may impact rebuilding performance.

Acknowledgements

This paper benefited greatly from comments by Ray Hilborn, Tim Essington, Trevor Branch, Ian Stewart, Owen Hamel, Michelle McClure, Chris Legualt, and an anonymous reviewer. Additionally, feedback from the Pacific Fishery Management Council and the advisory groups (Groundfish Management Team, Groundfish Advisory Panel, Science and Statistical Committee) was instrumental in the development and analysis of this work.

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