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Comparing alternative harvest strategies to address robustness to recruitment variability and uncertainty: implications for Alaska sablefish tested with management strategy evaluation

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Abstract

Developing robust fisheries management strategies for exploited fish stocks is imperative amid rapid ecosystem changes. In Alaska, sablefish (*Anoplopoma fimbria*) have recently experienced several large recruitment events, resulting in rapid population growth and a concomitant increase in catch of small, low value fish. Current management may not ensure long-term economic stability nor maintain the age structure diversity necessary for population resilience. Using a management strategy evaluation (MSE) framework, we assessed alternative management strategies under random, regime-like, and recruitment-failure scenarios. Strategies that substantially reduced fishing mortality improved stock size and age diversity. Catch stability constraint strategies provided minimal long-term benefits and increased risk during recruitment collapses, although they slightly accelerated population recovery times. Harvest caps maintained higher population sizes, promoted moderate, consistent catches, and modestly expanded population age structure. However, no strategy prevented population declines under prolonged recruitment failure. Results underscore the importance of refining harvest control rules to better balance catch and population stability.

Key words: closed-loop simulation, harvest control rules, fisheries management

Introduction

Understanding productivity patterns of marine resources is fundamental to interpreting population trends and informing sustainable harvest levels (Vert-pre et al. 2013). Among the processes influencing future population dynamics, recruitment is often the most uncertain—and one of the most critical for the success of fisheries management strategies (Needle 2001; Plagányi et al. 2019). In the face of accelerating environmental change, proactive and climate-resilient policies are needed that support both economic stability and healthy fish populations. When populations decline due to recruitment failures, managers must weigh the relative roles of fishing pressure and environmental drivers to determine how rapidly harvest should be curtailed (Hilborn and Walters 1992). Therefore, evaluating the robustness of management strategies to uncertain and nonstationary recruitment dynamics is essential for ensuring precautionary responses while maximizing sustainable harvest opportunities.

Many marine fish stocks are managed using harvest control rules (HCRs) which define management actions (e.g., allowable harvest or quota) based on current and projected population trends (Punt 2010). Threshold rules, which reduce fishing mortality when stock size declines below a predefined level, are commonly used for data-rich species and have been shown to be more robust to uncertainty and variability than other HCR types (Punt et al. 2008; Wiedenmann et al. 2017; Kritzer et al. 2019). These rules perform particularly well under uncertainty in stock-recruit dynamics (e.g., steepness) and recruitment variability (Punt et al. 2008), and they increase resiliency under climate-induced shifts in stock productivity (Kritzer et al. 2019). However, threshold HCRs often rely on biological reference points derived under steady-state assumptions, which may suffice for stable or slowly changing systems but can fail when confronted with rapid or environmentally driven spasmodic fluctuations in recruitment.

Populations that exhibit spasmodic recruitment, such as redfish (*Sebastes* spp.), hakes (*Merluccius* spp.), and mackerel species (*Trachurus* spp.), pose persistent challenges for fisheries management (Caddy and Gulland 1983; Spencer and Collie 1997). These species often violate the assumptions of steady-state HCRs prompting the development of alternative strategies better suited to the dynamic productivity regimes. Constant harvest rate HCRs have been proposed to maintain catch while reducing risk under fluctuating recruitment (Mildenberger et al. 2022; Free et al. 2023). Additional refinements, such as stability constraints, aim to limit abrupt changes in catch in response to recruitment pulses, while inventory-based strategies have been suggested as a means to buffer variability and sustain intermediate catch levels over longer periods (Licandeo et al. 2020).

Identifying species-specific management strategies (combinations of assessment methodologies and HCRs; MS) to promote continued fisheries sustainability is critical. To this end, management strategy evaluation (MSE) is a useful framework for evaluating the robustness of alternative MS to uncertainties regarding future population dynamics (e.g., recruitment, growth, movement), monitoring (e.g., changing survey effort), and management implementation (Punt et al. 2016). MSE has been used to identify MS that are robust to climate induced changes in recruitment in both US West Coast sablefish (*Anoplopoma fimbria*; Haltuch et al. 2019) and walleye pollock (*Gadus chalcogrammus*; A'mar et al. 2009), as well as assess the possible consequences of climate induced changes in movement of Pacific hake (*Merluccis productus*; Jacobsen et al. 2022). In Europe, MSE has also been used to evaluate the effects of environmentally driven productivity relationships on the economics of a mixed-species fishery in the North Sea (Kühn et al. 2023). Ultimately, MSE represents one of the most robust and widely accepted methods to develop and evaluate the performance of candidate MS, especially in the face of uncertain, climate-driven future population dynamics.

The Northeast Pacific Ocean is at the forefront of research to understand the impacts of changing environmental conditions on marine species because it is one of the most rapidly changing large marine ecosystems due to extensive marine heatwaves in recent years (Barbeaux et al. 2020). Fisheries management in the region faces increasing difficulty due to abrupt shifts in productivity, including recent population collapses (e.g., snow crab, *Chionoecetes opilio*; Litzow et al. 2024). In contrast, some species appear to be thriving under novel environmental and ecosystem conditions. This divergence in species responses poses additional challenges for management and stakeholders, particularly as they attempt to navigate species-specific dynamics alongside volatility in market conditions. One apparent climate "winner" is sablefish, which has experienced rapid increases in recruitment in recent years. Thus, sablefish offers a valuable case study for exploring the development of climate-resilient fisheries management frameworks, including HCRs that are robust to future recruitment uncertainty and variability.

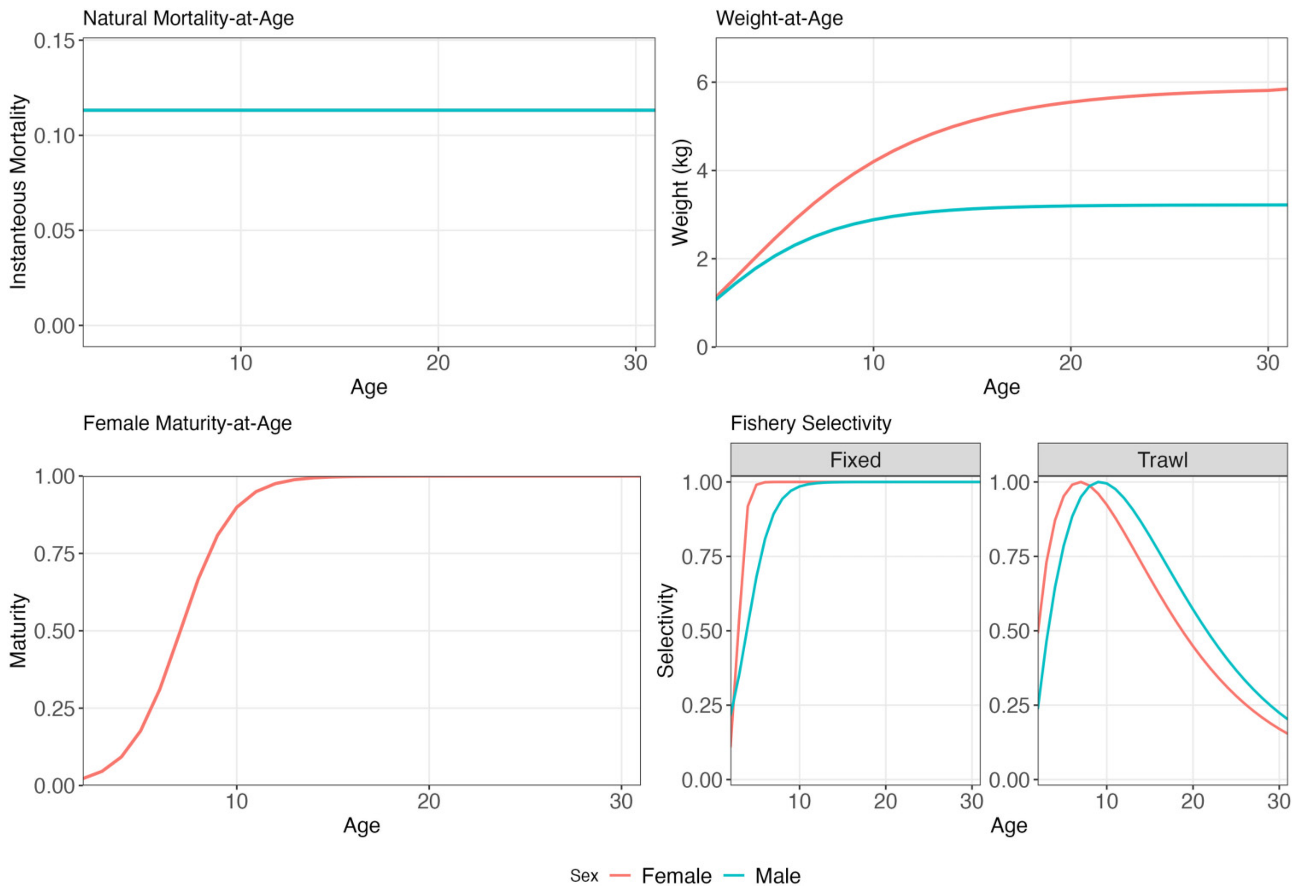
Sablefish are a long-lived, highly mobile groundfish species found throughout the Northeast Pacific Ocean, and are genetically homogenous across their range (Timm et al. 2024). A defining feature of sablefish population dynamics is spasmodic recruitment, likely linked with environmental variability (Goethel et al. 2023; Shotwell et al. 2023). Since 2014, the population has experienced a period of exceptionally strong recruitment, resulting in rapid biomass growth and a 325% increase in recommended acceptable biological catch (ABC), and substantial increases in landed catch (Goethel and Cheng 2024). However, this influx of supply has saturated markets, leading to steep declines in sablefish prices and reduced socioeconomic performance. These trends have raised concerns among stakeholders regarding the ability of existing management policies to deliver desirable fishery outcomes (Goethel et al. 2025). Conservation concerns persist due to the species' spasmodic recruitment variability, a long-term declining biomass trend, and pronounced age truncation, which is particularly problematic for a long-lived species (Goethel and Cheng 2024). The continued use of a generic ramped-threshold HCR (e.g., an F40% policy) applied across many Alaskan species, including sablefish, may no longer be appropriate given the observed diversity in life histories and species-specific responses to recent environmental changes observed across the region.

To address stakeholder and management concerns, an MSE framework was developed to explore the performance of alternative harvest strategies for sablefish in Alaskan waters. A suite of existing and novel HCRs was tested, incorporating fishery stakeholder input on combinations of biological reference points, catch stability constraints, and quota caps. Participants in the MSE process represented the major gear sectors in the sablefish fishery and self-identified based on their interest in the MSE process. Stakeholder feedback on MSE design, HCR specifications, and performance metrics was collected through a series of three workshops held between June 2024 and April 2025. The goal of the study was to evaluate the trade-offs among management strategies across a range of fishery and conservation performance metrics under scenarios of extreme recruitment variability, future recruitment uncertainty (e.g., due to climate impacts), or a prolonged recruitment failure. By evaluating both widely used and novel HCRs, this study aims to identify management strategies that are robust to recruitment dynamics, thereby informing climate-resilient fisheries management for sablefish.

Methods

MSE tools consist of a closed-loop simulation framework, in which an operating model (OM) simulates the underlying true population dynamics and generates future monitoring data. A management feedback loop is incorporated, wherein the MS (comprised of an estimation model, EM, that estimates stock status and an HCR that determines the management response) calculates the allowable catch in the following year. This catch is then removed from the OM population, completing the feedback cycle (Punt et al. 2016). The sablefish MSE tool was developed in the R programming language using the *afscOM* R package (Zahner et al. 2024). The OM was conditioned to reflect current understanding of sablefish population dynamics in Alaskan waters, using parameters derived from the operational stock assessment model (Goethel et al. 2023). A detailed description of the OM can be found in Supplement A. The estimation method (EM) is an age- and sex-

Fig. 1. Natural mortality, weight-at-age, maturity-at-age, and fishery selectivity-at-age used within the OM. Values of natural mortality are assumed to be the same between sexes (single line shown). Maturity-at-age is shown for females only.



structured stock assessment model, implemented in TMB, that emulates both the operational assessment (Goethel et al. 2023) and the core dynamics of the OM.

The MSE framework consisted of two phases: a conditioned historical period (1960–2014), during which no management feedback was applied, and a 75-year projection or feedback period (2014–2090), during which full management feedback loops were simulated. Historical recruitment dynamics were fixed to the most recent estimated recruitment time series from the operational stock assessment (Goethel et al. 2023). To explore the implications of future productivity, three alternative recruitment scenarios were implemented for the feedback period (2014 onward). These scenarios captured a range of plausible future dynamics based on historical patterns, expert judgement, and potential extremes (e.g., a recruitment crash). Ten alternative MSs were evaluated. These included MSs currently used for sablefish across the Northeast Pacific (Kapur et al. 2024), approaches proposed for other species with spasmodic recruitment (e.g., Licandeo et al. 2020), and novel strategies developed through stakeholder engagement. For each combination of OM and MS, 200 stochastic replicates were conducted to reflect variability in observation and process error. Performance was evaluated across a suite of fishery and conservation metrics to assess trade-offs among MSs under different recruitment regimes.

Operating model

Simulations were conducted using an age- and sex-structured OM assuming a panmictic population across Alaska. Most age and sex-specific demographic rates (e.g., natural mortality, weight-at-age, and maturity) were time-invariant in the feedback simulation period and parameterized based on estimates from the operational stock assessment model (Goethel et al. 2023). Natural mortality (M) was fixed at 0.11 year^{-1} for both sexes. Growth was sex-specific, with females assumed to grow faster and attain a larger asymptotic size than males. Female maturity was modeled as a logistic function, with 100% sexual maturity by age-14 (Fig. 1).

Across simulations, three primary sources of observational data were generated at each time step and passed to the EM: (1) fishery landings, (2) survey indices of abundance and biomass, and (3) age composition data from the fishery and surveys. Landings were simulated for two fishery fleets: a fixed gear fleet and a trawl fleet. The primary directed fishery is the fixed gear fleet, which historically utilized longline hooks, but shifting to pots after 2017 to reduce whale depredation (Cheng et al. 2024). Fleet-specific annual removals were apportioned according to the Alaska Groundfish Fisheries Management Plan (NPFMC 2020), with 85% allocated to the fixed gear fleet, and 15% to the trawl fleet. Consistent with the sablefish operational stock assessment, selectivity for the fixed-gear fleet was modeled as a logistic function, while trawl fleet was assigned dome-shaped selectivity using a gamma function (Goethel et al. 2023). Instantaneous fishing mortality rates (F) were derived using Baranov's catch equation (Baranov 1918) to ensure that each fleet-specific total catch matched the projected annual catch (i.e., as based on the Acceptable Biological Catch (ABC); see "Harvest control rules" section).

The OM also simulated the dynamics of two surveys: the National Oceanic and Atmospheric Administration (NOAA) Alaska Longline Survey and Gulf of Alaska Bottom Trawl Survey. These surveys provide indices and age-composition datasets using in the EM. The Alaska Longline Survey produces an abundance index, while the Gulf of Alaska Bottom Trawl produces a biomass index. Both survey indices were assumed to represent the entire sablefish population across Alaskan waters and were simulated annually from a lognormal distribution with CV = 0.10 (see Supplement). Survey-specific catchability coefficients, q, were fixed to values estimated in the most recent assessment.

Sex-specific age composition data were generated for both fishery and survey fleets. Age composition observations were generated as random multinomial draws about the true, selected population numbers-at-age. To reflect differences in data quality, an input sample size of 50 was used for the fixed-gear fishery and longline survey, while a lower sample size of 30 was used for the trawl-gear fishery and bottom trawl survey. This reduction in input sample size was intended to reflect the limited availability of age data from the trawl fishery and bottom trawl survey in operational management, which primarily rely on length composition data.

Initialization

The OM was initialized (conditioned) by simulating the population forward from 1960 to 2014 (the historical period) using fixed, input demographic rates (e.g., annual recruitments and fishing mortality) from the operational stock assessment (Goethel et al. 2023). These rates were held consistent across all simulation runs and scenarios, ensuring that the OMs first 54 years were conditioned to replicate the historical time series of fishing mortality and SSB. The feedback period, or feedback phase, began in the year 2015 (year 55 of the OM) and incorporated alternative recruitment scenarios and MSs applied annually through the feedback loop. This phase was initialized using the numbers-at-age vector from the final year of the historical period. Notably, the simulation was initiated prior to the emergence of recent large recruitment events to ensure the projection did not begin from an anomalously high abundance state.

Recruitment scenarios

Recruitment is the primary source of stochastic process variation among simulations, and the only process for which alternative states of nature are considered. Sablefish exhibit highly variable recruitment, with annual events ranging from 5 to 95 million (mean of 25.8 million recruits; Goethel et al. 2023). Large recruitment events often occur in rapid succession over several years, typically uncoupled from population size, and are interspersed between multiple decades of lower recruitment.

Given this variability in recruitment and uncertainty regarding future recruitment dynamics, three alternative models describing potential future recruitment patterns were developed (Fig. 2; Table 1). In all scenarios, simulated recruitment began in the first year of the feedback period (year 55), corresponding to the calendar year 2015.

(1) *Random recruitment*: Recruitment is randomly resampled with replacement from the time series of estimated recruitments (e.g., Punt and Methot 2005) from the operational assessment (Goethel et al. 2023). This "random" scenario emulates the historical variability in sablefish recruitment, which is not well represented by a simple statistical distribution. Temporal autocorrelation between recruitment events is not included or replicated in this scenario.
(2) *Beverton–Holt regime recruitment:* This scenario assumes the existence of two unique Beverton–Holt (BH) stock-recruitment relationships (Beverton and Holt 1957; Mace and Doonan 1988) representing alternating high and low recruitment regimes. Both relationships share the same steepness parameter (h = 0.85), but differ in their unfished equilibrium recruitment values, R_0, and consequently in unfished SSB, S_0 (see Table 1). The scenario begins with a 20-year period of "low" recruitment (R_0 = 12.5 million), followed by a 5-year period of "high" recruitment (R_0 = 50 million). These regimes alternate with the same periodicity throughout the projection period. The magnitude of difference between regimes was chosen such that the mean recruitment over the full feedback period approximates the average historical recruitment since 1960. The "BH Regime" scenario aims to replicate the cyclical and spasmodic nature of sablefish recruitment, while maintaining a functional link between spawning biomass and recruitment. This ensures that recruitment declines if spawning biomass becomes extremely low (Goethel et al. 2023).
(3) *Crash recruitment:* This scenario incorporates a recruitment collapse during the first 20 years of the feedback period, where recruitment is assumed to follow a lognormal distribution centered on the lowest single-year recruitment estimate from the historical time series (4.7 million recruits) with CV = 0.1. For the remainder of the projection period, recruitment is randomly resampled from the historical time series of estimated recruitment. The "Crash Recruitment" scenario was designed to evaluate the robustness of MSs in the wake of a climate-related recruitment collapse.

Estimation method

The EM was an integrated age- and sex-structured stock assessment model developed in template model builder (TMB; Kristensen et al. 2016). The EM assumed a single sablefish population consistent with the operational assessment model (Goethel et al. 2023) and matched the primary under-

Fig. 2. Simulated time series of recruitment (millions of recruits) for each of the three OM recruitment scenarios for five randomly selected iterations (colored lines). The black line indicates the median recruitment in each year across all 200 simulations. Numbers in the top-right of each panel and horizontal dashed lines indicate the simulated median recruitment level for each scenario across years and replicate simulations.

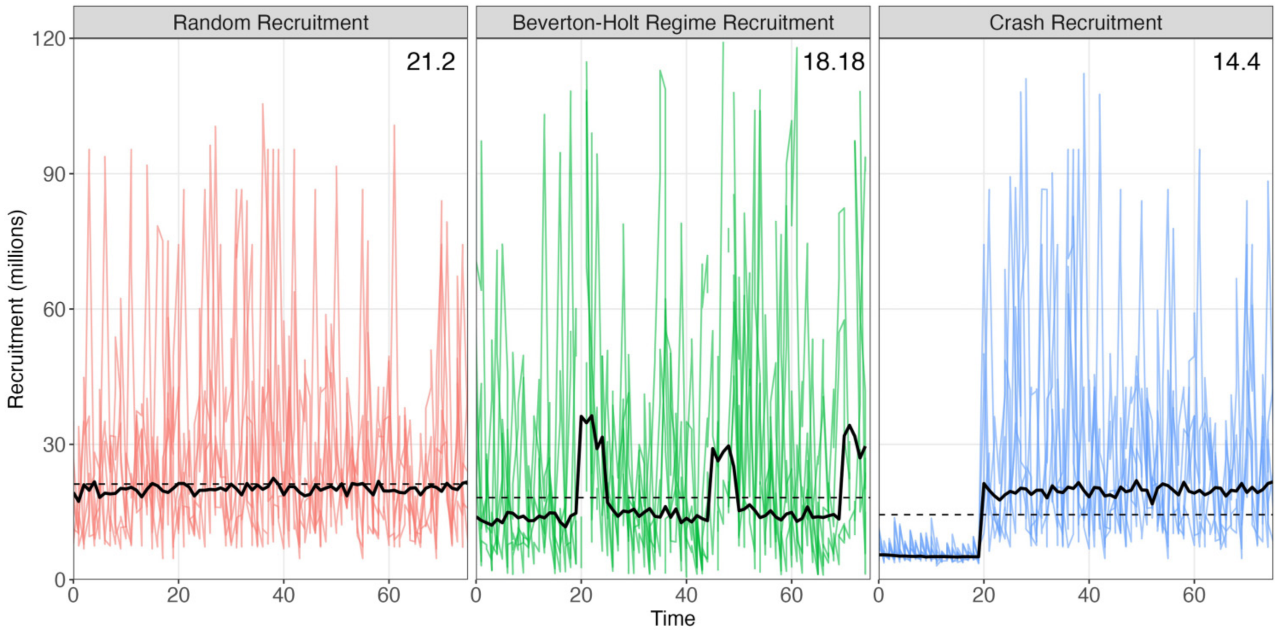


Table 1. Descriptions and parameterizations of the three recruitment scenarios.

Name	Description	Additional parameters
Random	Random resampling with replacement from the historical recruitment timeseries.	
BH regime	Alternating high and low regime Beverton–Holt stock recruitment relationships with different R_0s.	$h = 0.85$ $R_0^{\text{low}} = 12.5$ million recruits $R_0^{\text{high}} = 50.0$ million recruits $\sigma_R = 1.20$ Regime length: 20 years (high), 5 years (low)
Crash	For the first 20 years of the simulation feedback period recruitment is assumed to be in a "crashed" state, then for the rest of the time series recruitment is randomly resampled from the historical recruitment time series.	$\bar{R}_{\text{crash}} = 4.70$ million recruits Crash length: 20 years Crash start year: 55

Note: See the supplemental material for stock-recruit equations used for the "BH Regime" scenario.

lying dynamics of the OM. Similar to the OM, the EM explicitly modeled two fishery fleets (fixed gear and trawl) and two survey fleets (longline and trawl). The EM was fit to the various simulated data sources, including time series of catch data from both fishery fleets, survey abundance indices from both survey fleets, and age-composition data from fisheries and surveys. The EM was fit to pseudo-data simulated by the OM, including observation error in every simulation year.

Although the EM closely followed the structure and data inputs of the operational assessment model, several key differences existed. Notably, the operational assessment fits the length composition data from the trawl fleet and survey; however, these data were not simulated by the OM and thus not used in the EM. Instead, age composition data were simulated from a multinomial distribution with a low input sample size (30 samples) and used as a proxy for the length compositions. Additionally, the one-year lag in availability of age composition data to the operational assessment was not incorporated into the EM. The EM also fit age composition data in a sex-disaggregated manner using a "split" approach (Cheng et al. 2025*b*), assuming a fixed 50–50 sex ratio at recruitment. This contrasts with the operational assessment, which fits to a combination of sex-aggregated age composition and sex-disaggregated length composition data. To improve model stability in the MSE framework, strong priors were placed on the catchability coefficients for both the longline and trawl surveys in the EM.

Estimates from the EM (e.g., selectivity, SSB, recruitment, and numbers-at-age) in the terminal year were used by the HCRs to determine the fishing mortality rate and total catch to recommend for the following year (see "Catch projection and OM feedback" section below). These estimates were up-

Fig. 3. Relationship between relative spawning stock biomass (SSB/B_{40}) and relative fishing mortality (F/F_{40}; solid lines) or catch (dotted lines) under each of the 10 management strategies (MS). Note that the annual stability constraints that differentiate the F40, F40 ± 5%, and F40 ± 10% MS are not shown.

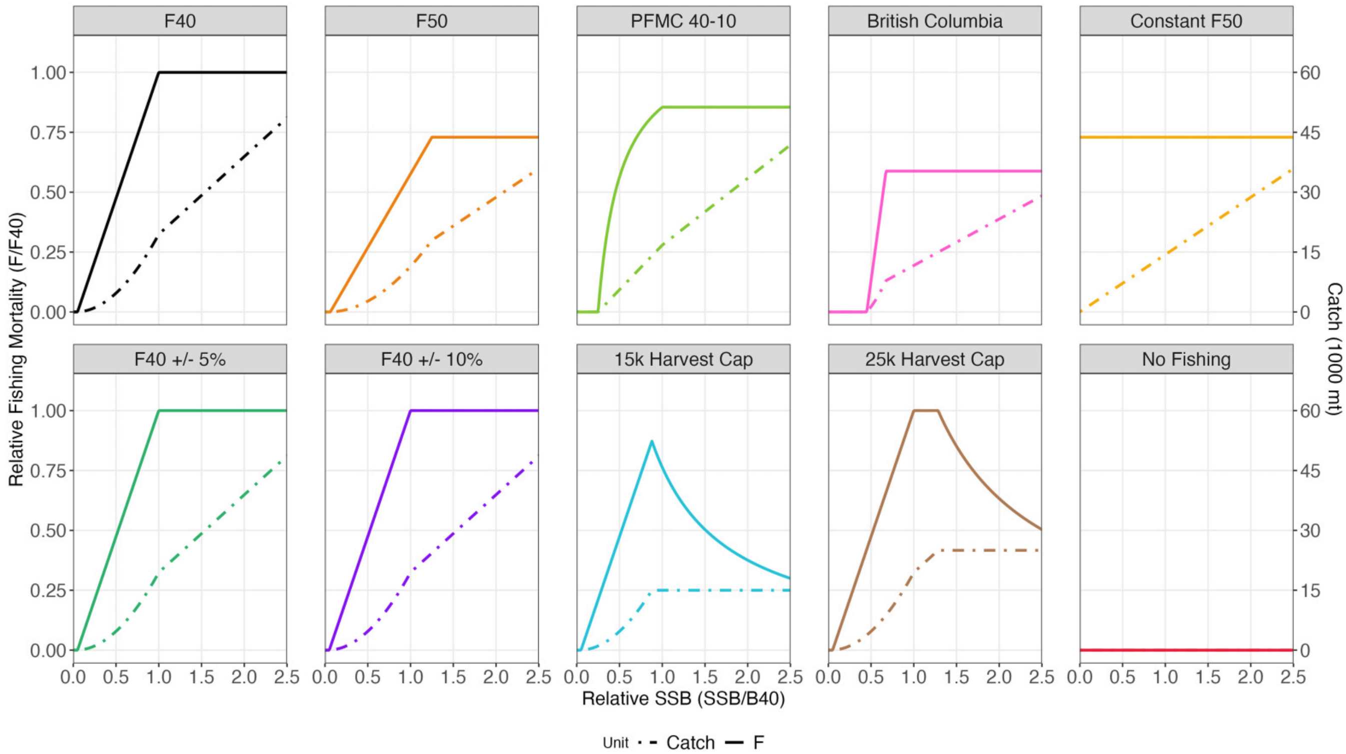


Table 2. Harvest control rule (HCR) specifications.

Name	BRP	Limit BRP	FRP	Constraints	Rationale
F40	B_{40}	$0.05B_{40}$	F_{40}		Current NPFMC rule (NPFMC 2020)
F50	B_{50}	$0.05B_{40}$	F_{50}		Conservative F to promote age structure expansion
PFMC 40-10	$0.40B_{100}$	$0.10B_{100}$	F_{45}		Current PFMC rule (PFMC 2023)
British Columbia	$0.60B_{45}$	$0.40B_{45}$	0.055		Rule used in British Columbia, Canada, through 2022 (DFO 2023)
Constant F_{50}	n/a	None	F_{50}		Shown to enhance catch volumes for highly variable populations compared to threshold strategies (Mildenberger et al. 2022; Free et al. 2023)
F40 ± 5%	B_{40}	$0.05B_{40}$	F_{40}	≤5% annual change in ABC	Decrease market volatility and promote socioeconomic stability
F40 ± 10%	B_{40}	$0.05B_{40}$	F_{40}	≤10% annual change in ABC	
15k Harvest cap	B_{40}	$0.05B_{40}$	F_{40}	≤15 000 mt ABC	Maximize long-term yield by "banking" fish during high productivity periods
25k Harvest cap	B_{40}	$0.05B_{40}$	F_{40}	≤25 000 mt ABC	
No fishing	n/a	None	0		Baseline for comparison

Note: Reference points (BRP and FRP) are SPR based quantities (e.g., F_{40} is the fishing mortality required to reduce SPR to 40% of unfished SSB). Limit BRP indicates the SSB level below which fishing mortality is set to 0.

dated in each feedback year to re-calculate reference points and inform catch advice based on current stock status and the applied HCR.

Harvest control rules

Ten alternative HCRs were implemented, some of which were identified through consultation with stakeholders in the Alaskan sablefish fishery (Fig. 3; Table 2). These HCRs were designed to achieve a range of conservation and fishery performance objectives, many inspired by HCRs previously used for sablefish in other regions or for other species exhibiting high recruitment variability. Deviations from the currently utilized HCR (F40, see below) fell into three main categories: (1) use of alternative reference points, (2) constraints on interannual changes in allowable catch, and (3) imposition of maximum quota caps.

Most HCRs were described by a ramped-threshold functional form (Deroba and Bence 2008; Free et al. 2023), parame-

Table 3. Fishing and biomass reference point values used to parameterize the different harvest control rules (HCRs) across the three recruitment scenarios.

Reference point	Random recruitment	Beverton–Holt regime recruitment	Crash recruitment	HCR
F_{40}	0.0935	0.0935	0.0935	F40, F40 ± 5%, F40 ± 10%, 15k Harvest Cap, 25k Harvest Cap
B_{40}	103.61	126.25	89.74	F40, F40 ± 5%, F40 ± 10%, 15k Harvest Cap, 25k Harvest Cap
F_{50}	0.0682	0.0682	0.0682	F50
B_{50}	129.51	157.81	112.17	F50
F_{45}	0.0799	0.0799	0.0799	PFMC 40-10, British Columbia
B_{45}	116.56	142.04	100.96	PFMC 40-10, British Columbia
0.60 B_{45}	69.93	85.22	60.58	British Columbia
0.40 B_{45}	46.62	56.19	40.38	British Columbia
B_{100}	259.03	315.64	224.36	PFMC 40-10
0.4 B_{100}	103.61	126.25	89.74	PFMC 40-10
0.1 B_{100}	25.90	31.56	22.44	PFMC 40-10

Note: Values are indicative of the reference points calculated based on the estimation model outputs in the terminal year of the simulation period.

terized by a fishing reference point (FRP) and a biomass reference point (BRP). The FRP is the level of fishing mortality that reduces spawning biomass per recruit to *x*% of its unfished value (spawning potential ratio) and is referred to as $F_{x\%}$. The BRP, or target BRP, is the SSB that results from fishing at the FRP, assuming future recruitment remains at the long-term average. This biomass threshold is referred to as $B_{x\%}$. Long-term average recruitment was defined as the average recruitment since the start of the historical period (year 1), and was updated annually as new recruitment events were estimated by the EM. Recruitment time series, and therefore average recruitment, differed across the various recruitment scenario, leading to different BRPs across recruitment scenarios. Some HCRs also included a second BRP (a limit BRP) below which fishing mortality is 0. Two tested HCRs tested (the PFMC 40-10 and the British Columbia rule, described below) used reference points based on maximum sustainable yield (MSY), specifically F_{MSY} and B_{MSY}. However, under the "Random" and "Crash" recruitment scenarios, where no stock recruit relationship (SRR) exists, MSY-based reference points could not be directly estimated. In these cases, F_{45} and B_{45} were used as proxies for F_{MSY} and B_{MSY}, consistent with the Pacific Fishery Management Council Groundfish Management Plan (PFMC 2023). All reference points were recalculated in each EM feedback year based on updated estimates of selectivity-at-age and average recruitment (Table 3).

The 10 HCRs (Fig. 3) were:

(1) *F40*: A threshold strategy using $F_{40\%}$ and $B_{40\%}$ as reference points. Fishing mortality is set to $F_{40\%}$ when SSB $\geq B_{40\%}$, and linearly declines to 0 as SSB declines below $B_{40\%}$. Fishing mortality is 0 when SSB < $0.05B_{40\%}$. This rule is the operational strategy used by the NPFMC for groundfish management (NPFMC 2020).

(2) *F50*: A threshold strategy identical in structure to the F40 HCR but using more conservative $F_{50\%}$ and $B_{50\%}$ reference points. These more precautionary targets may be more appropriate for long-lived species like sablefish, supporting a broader age structure and reducing risk of quota inflation following large recruitment events.

(3) *PFMC 40-10*: A threshold strategy using $F_{45\%}$ as the fishing mortality reference point, and $0.4B_{100\%}$ and $0.1B_{100\%}$ as the target and limit BRPs, respectively. When SSB < 0.4%, catch declines linearly until SSB < 0.1%, below which no catch is allowed. This rule, used for sablefish management on the U.S. West Coast (PFMC 2023), differs from other threshold strategies in that catch, rather than fishing mortality, is reduced linearly. The relatively high limit BRP provides stronger precautionary protection during extended recruitment downturns and subsequent declines in SSB.

(4) *British Columbia:* A threshold strategy that uses $F = 0.055$ as the maximum fishing mortality rate when SSB $\geq$ 0.60%, and linearly declines to F = 0.0 when SSB < 0.40 B_{45}. This rule is similar to that used in British Columbia, Canada through 2022 (DFO 2023), but uses percent as a proxy for B_{MSY} as was done for the PFMC 40-10 strategy. The low FRP (~60% of the FRP from the F40 HCR) and a high BRP make this strategy highly precautionary, potentially better suited for sustaining populations through extended low recruitment periods.

(5) *Constant F50*: A constant fishing mortality strategy using $F_{50\%}$ as the FRP. Constant harvest rate strategies have been shown to enhance catch volumes without increas-

Table 4. Summary of performance metrics used to compare management strategies.

Metric name	Short name	Description	Equation
Average annual catch	Average catch	Average annual landed catch in metric tons.	$\bar{C} = \frac{\sum_{y=1}^{Y} C_y}{Y}$
Average annual catch variation	AAV	Average variation in catch in successive years.	$\overline{\text{AAV}} = \frac{\sum_{y=1}^{Y} \frac{\lvert C_y - C_{y-1} \rvert}{\bar{C}}}{Y}$
Average annual SSB	SSB	Average annual population spawning stock biomass in metric tons.	$\overline{\text{SSB}} = \frac{\sum_{y=1}^{Y} \text{SSB}_y}{Y}$
Average annual population age	Population age	Average age of a female individual in the population.	$\overline{N_\text{A}} = \frac{\sum_{y=1}^{Y} \frac{\sum_{a=2}^{A} a N_{y,a}}{\sum_{a=2}^{A} N_{y,a}}}{Y}$
Proportion of years SSB $< B^*_{35}$	Years of SSB $< B^*_{35}$	The proportion of years in which of SSB $< B^*_{35}$. $B^*_{35} = 105,000$ and is constant across scenarios (Goethel and Cheng 2024).	$P = \frac{\sum_{y=1}^{Y} \begin{cases} 1, & \text{SSB} < B^*_{35} \\ 0, & x \geq B^*_{35} \end{cases}}{Y}$

Note: $C_{y,a}$ is the landed catch in year y (in metric tons), SSB_y is spawning stock biomass (1000 mt) in year y, and $N_{y,a}$ is number of individuals (millions) of age a in year y. Y indicates the total number of years in the simulation period (75), and $\bar{C}$ is the average catch across the simulation period.

ing conservation risks for widely fluctuating populations as compared to threshold strategies.

(6) *F40 ± 5%*: The F40 strategy modified to include a catch stability constraint, limiting year-to-year changes in recommended catch to no more than ±5%. Stability constraints are often requested by stakeholders to reduce market volatility and improve socioeconomic performance (Hilborn 2007).

(7) *F40 ± 10%*: The F40 strategy but including a stability constraint that restricts changes in recommended catch advice in successive years to a maximum of ±10%.

(8) *15k Harvest cap*: The F40 HCR with a hard cap limiting annual catch to a maximum of 15 000 mt. Quota caps serve as inventory control tools, allowing surplus fish from productivity years to support catches during less productive years (Licandeo et al. 2020). A 15 000 mt cap was reflects the average harvest level from 2000 to 2014.

(9) *25k Harvest cap*: The F40 strategy but including a maximum annual catch limit of 25 000 mt. A 25 000 mt cap was selected to reflect the average catch under the F40 HCR assuming future recruitment remains near its long-term mean.

(10) *No fishing*: A zero-catch strategy used as a baseline to understand population dynamics under different recruitment scenarios in the absence of fishing pressure.

Catch projection and OM feedback

For each MS (combination of EM and HCR), the terminal year estimates from the EM are used to perform short-term catch projections based on the HCR. Because the EM is applied in every feedback year, catch projections only occur for a single year. In these projections, recruitment is assumed to be equal to the average recruitment across the entire EM time series, consistent with the assumption used to calculate biomass-based BRPs. Terminal year estimates of selectivity are used to project fishery dynamics, aligning with the assumptions used in calculating the FRP. Using the terminal numbers-at-age, the assumed recruitment, and the stock status determination (if required by the HCR), the HCR is applied to calculate the appropriate fishing mortality rate. The population is then projected forward one year to determine the ABC. The assumed ratio of catch among fleets is held constant and matches the OM assumption. All MS are implemented at the ABC level, with no management implementation uncertainty simulated. The total allowable catch (TAC) is assumed to be equal to the recommended ABC in all years, and realized landings are assumed to match the TAC exactly. The resulting ABC is then passed back to the OM, which uses it to derive the realized fishing mortality rate for the following MSE simulation year. Any discrepancies between the EM and OM (i.e., estimation bias) may lead to differences between the fishing mortality projected to achieve the ABC and the actual fishing mortality realized in the OM.

Replication and uncertainty

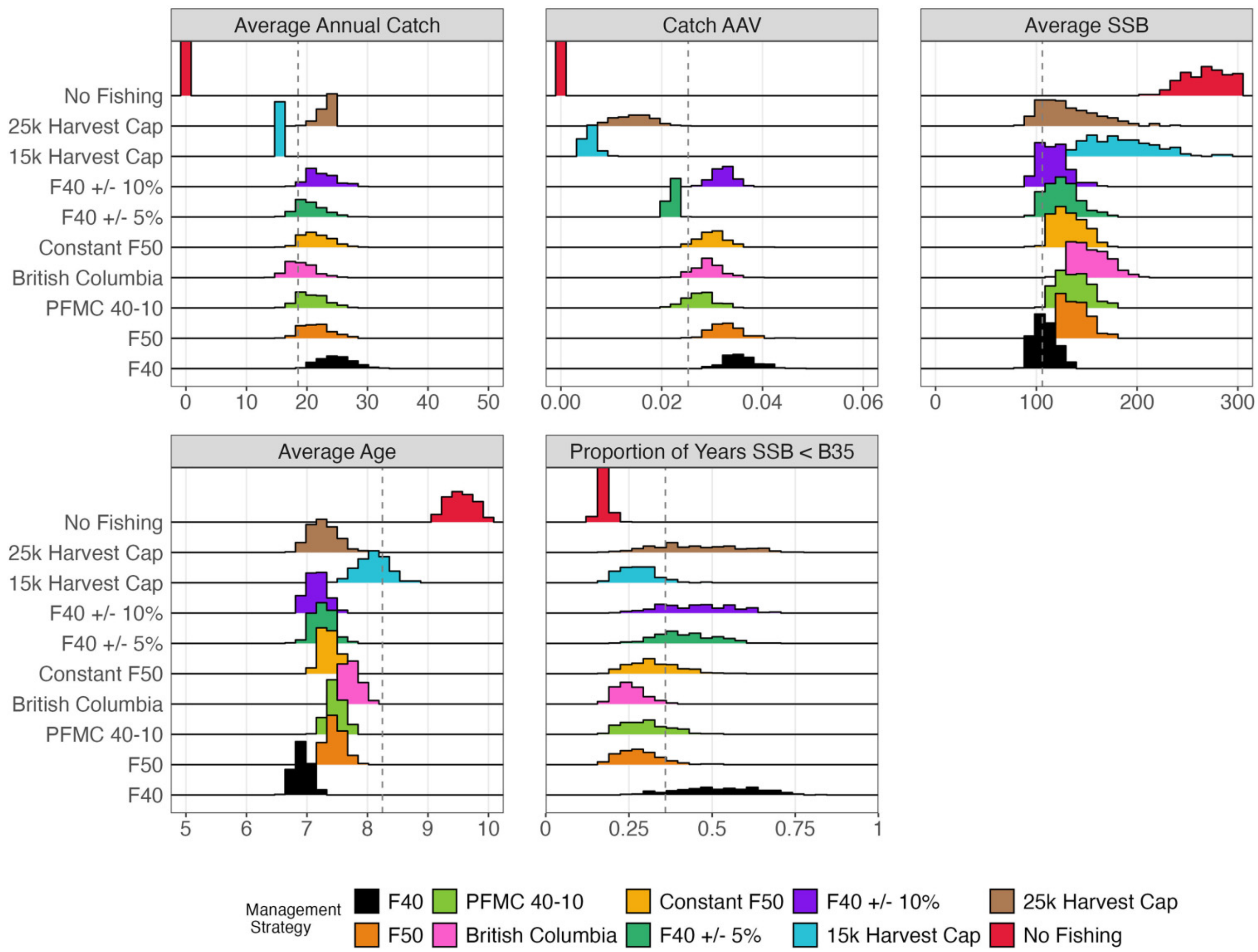
Recruitment was the sole source of process variation in the MSE loop, with a distinct recruitment time series being used in each replicate simulation. Observation error was also incorporated into the OM-generated data provided to the EM. Specifically, survey indices were simulated using random draws from lognormal distributions, while age-composition data were drawn from multinomial distributions. To ensure comparability across simulations, identical random number seeds were used across all OM–MS.

A total of 200 replicate simulations were conducted for each OM–MS combination to account for uncertainty in recruitment and observation processes. EM convergence was evaluated based on the presence of a positive-definite Hessian matrix. Any replicate in which the EM failed to converge in one or more simulation years was discarded for every OM–MS combination and replaced with a new replicate. All EM time-steps (75 per combination of MS, OM, and replicate) successfully converged.

Performance metrics

The performance of alternative MS for each recruitment scenario was compared using five performance metrics (Table 4):

Fig. 4. Histograms of median performance metric values by management strategy (MS) aggregated across all operating model (OM) recruitment scenarios and replicates. Dashed vertical lines indicate (1) the median ABC from 2014–2023 (18 358 mt), (2) the median average annual catch variation across all simulations, (3) the most recent operational stock assessment estimate of B35 (105 935 mt; Goethel and Cheng 2024), (4) the average age of the female population in the historical period, and (5) the proportion of years in the historical period that SSB < 105 000 mt.

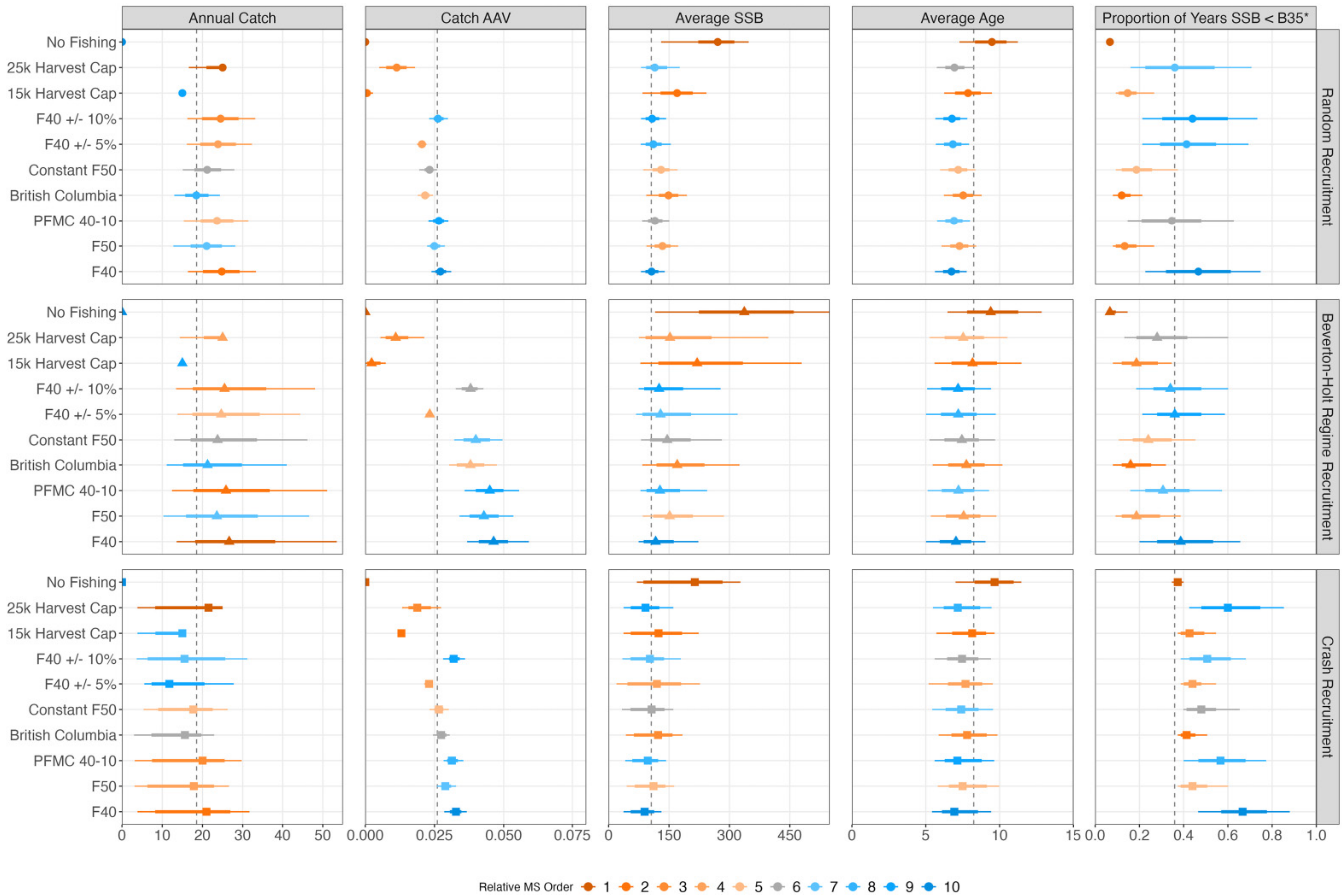


1. average annual catch,
2. average annual catch variation (AAV),
3. average annual SSB,
4. average annual population age, and
5. the proportion of years in which SSB $< B^*_{35}$.

The threshold B^*_{35} was fixed at 105 000 mt for all OM–MS combinations to provide a consistent reference point and was taken from the most recent stock assessment (Goethel and Cheng 2024). These performance metrics were calculated across the full 75-year feedback period and were intended to quantify tradeoffs between conservation and fishery performance under scenarios of extreme recruitment variability. Specifically, the metrics reflect the overall magnitude of catch (economic yield), variability in catch (market stability), spawning potential (biological sustainability), age diversity of the population (linked to fishery value due to size-based pricing), and the risk of population depletion (management concerns). While a broad set of metrics was initially explored, the final five were selected to simplify interpretation. Several alternative metrics demonstrated similar patterns and provided overlapping insight (e.g., average age of catch metric was excluded due to near identical results to average population age). It is important to note that AAV is artificially reduced in this framework due to the absence of implementation and management errors, which would typically introduce greater variability in a real-world setting. Performance metrics are reported as medians, 50th, and 80th percentiles across the 200 stochastic simulation replicates. Distributions of performance metrics were found to be stable after said number of replicate simulations.

Additionally, under the "Crash" recruitment scenario, two supplementary resilience metrics were calculated: "crash time", the number of years required for SSB to decline below $0.5 * B^*_{35}$ (52 500 mt) following the onset of a recruitment crash, and "recovery time", the number of years required for SSB to rebound above B^*_{35} (105 000 mt) after the end of a crash period. These metrics provide insight into the pop-

Fig. 5. Median, 50th (thick colored lines), and 80th percentiles (thin colored lines) of performance metrics (columns) across management strategies (MS) and operating model (OM) scenarios. Colors indicate relative order of each MS for each metric within each scenario. Coloration is reversed for the catch AAV and proportion SSB < B35 metric to reflect a preference to minimize these values. Dashed vertical lines indicate (1) the median estimate of ABC from 2014–2023 (18 538 mt), (2) the median average annual catch variation across all simulations (0.0206), (3) the most recent operational assessment estimate of B35 (105 935 mt; Goethel and Cheng 2024), (4) the median age of the female population in the historical period (8.25 years), and (5) the proportion of year in the historical period that SSB < 105 000 mt (0.359).



ulation's resilience to adverse recruitment conditions under different MS. The crash threshold ($0.5 * B^{*}_{35}$) represents the SSB level that would require the development of a rebuilding plan for the stock (NPFMC 2020). The recovery threshold (B^{*}_{35}) denotes the SSB level at which the population is considered rebuilt. As with other B^{*}_{35}-based metrics, the reference value of 105 000 mt is derived from the most recent operational stock assessment model (Goethel and Cheng 2024).

The following qualitative descriptors are used to characterize the magnitude of difference in median performance among alternative management strategies: "very similar" (<|5%|), "slightly lower/higher" (<|10%|), "lower/higher" (<|20%|), and "much lower/much higher" (>|20%|). Because the primary objective of this study was to evaluate the relative performance of MS under conditions of extreme recruitment variability, no formal utility function was developed to rank or identify a single "best" MS across all performance metrics.

Results

Fishery performance

Average annual catch across all OM scenarios was approximately 19 200 mt, with considerable variation among MS (15 000–24 800 mt; Fig. 4). The F40 strategy produced the highest average annual catch levels across all OM scenarios (24 800 mt), closely followed by the 25k Harvest Cap strategy, which performed very similarly (Fig. 4). In contrast, the F50, constant F50, PFMC 40-10, and British Columbia strategies all resulted in lower to much lower catch levels compared to the F40 strategy. The stability constraint strategies (F40 ± 5% and F40 ± 10% strategies) yielded similar to very similar median average catch relative to the F40 strategy under the "Random" and "BH Regime" scenarios (Fig. 5), though with slightly differently shaped distributions (Fig. 4). However, under the "Crash" scenario, both stability constrained strategies produced much lower average annual catch, particularly during the population recovery phase (years 75–129; Fig. 5). This re-

Fig. 6. Landed catch (top) and spawning stock biomass (SSB; bottom) trajectories across management strategy (color) and OM scenario (columns). Lines represent the median annual catch and SSB in each simulation year across 200 replicate simulations. Dashed vertical line indicates the start of the simulation period when alternative management strategies are applied. Horizontal dashed reference lines indicate (1) the median ABC from 2014–2023 (18 358 mt; top row) and (2) the most recent operational assessment estimate of B_{35} (105 935 m; bottom row; Goethel and Cheng 2024).

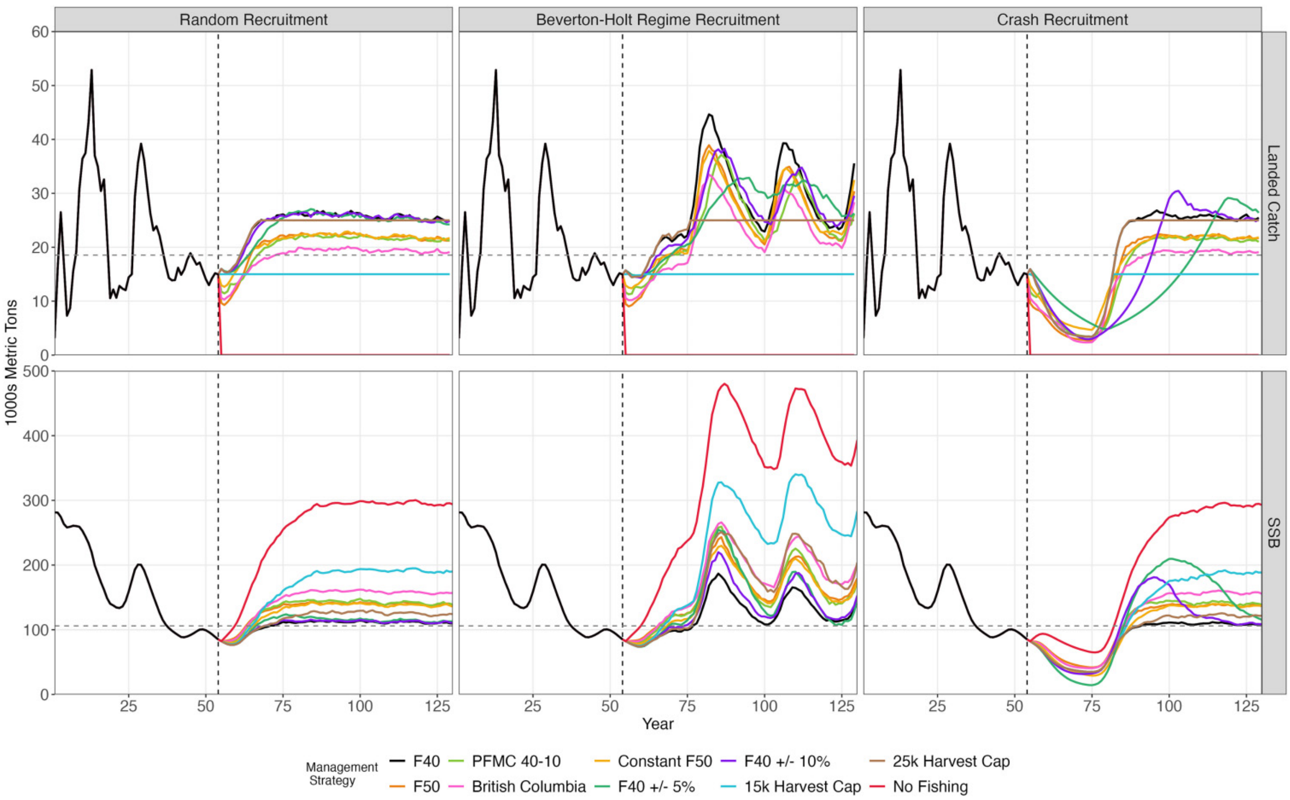


Table 5. Percentage of years (median and 80th percentiles across replicate simulations) in which the stability and harvest cap constraints were applied for the F40 ± 5%, F40 ± 10%, 15k Harvest Cap, and 25k Harvest Cap strategies.

	F40 ± 5%	F40 ± 10%	15k Harvest cap	25k Harvest cap
Random recruitment	66.7% (53.3–77.3)	20.0% (13.3–28.0)	98.0% (90.7–100.0)	59.3% (26.7–80.0)
BH regime recruitment	86.7% (75.9–93.3)	52.7% (37.3–68.0)	93.3% (78.7–100.0)	69.3% (41.2–85.5)
Crash recruitment	92.0% (85.3–96.0)	57.3% (49.3–65.3)	65.3% (61.3–68.0)	39.3% (16.0–58.7)

Note: Values reflect the frequency with which total annual catch was constrained by either the maximum allowable annual change constraint (for the two stability constraint rules) or by the maximum allowable annual catch constraint (for the two harvest cap rules).

duction was driven by the stability constraint limiting the rate at which catches could increase following the crash. The 15k Harvest Cap strategy consistently yielded the lowest average catch across all recruitment scenarios (15 000 mt as compared to 24 800 mt under F40; Fig. 6). In contrast, the 25k Harvest Cap strategy produced very similar catch levels to the F40 strategy under the "Random" and "Crash" scenarios, but lower catch under the "BH Regime" scenario (Figs. 5 and 6).

Across OM scenarios, AAV showed substantial variability, with the highest AAV observed under the "BH Regime" scenario and lowest under the "Random" scenario (Fig. 5). Within each OM scenario AAV generally increased in tandem with annual catch, with most MS exhibiting performance similar to the F40 strategy across both metrics (Fig. 5). Notable exceptions included the 25k Harvest Cap and F40 ± 5% strategies, both of which resulted in very similar annual catch levels to the F40 strategy but with much lower AAV across all recruitment scenarios. The degree to which AAV was reduced depended on the stringency and frequency of application of each quota constraint under different recruitment scenarios. For example, under the F40 ± 5% strategy, the 5% stability constraint was invoked in over 66% of years in all OM scenarios (Table 5), leading to much lower AAV than other MS. By comparison, under the F40 ± 10% strategy, the 10% stability constraint was triggered in only 20% of years under the "Random" scenario and 50%–60% of years in the other scenarios, resulting in limited improvement in AAV relative to the unconstrained F40 strategy. Similarly, the 15k harvest cap was invoked in more than 93% of years under the "Random" and "BH Regime" scenarios and in 65% of years under the "Crash" scenario, driving consistently low AAV. In contrast, the 25k harvest cap was invoked in only 40%–70% of years across the different scenarios, resulting in a moderate reduction in AAV relative to F40 (Table 5).

Conservation performance

Average annual SSB was 149 000 mt across all OM scenarios, the SSB under the "No Fishing" strategy was 287 000 mt (Fig. 4). The F40 strategy produced the lowest average SSB across all scenarios (108 000 mt. MS that applied lower fishing mortality rates (F50, 15k Harvest Cap, Constant F50, British Columbia) resulted in much higher average SSB (e.g., 135 000 mt under F50; Fig. 6). Under the "Random" recruitment scenario, the F40 ± 5% and F40 ± 10% stability constraint strategies yielded very similarly average SSB to F40. However, under the "BH Regime" and "Crash" scenarios these strategies produced higher and much higher SSBs, respectively. Under the "Crash" scenario, the stability constraint strategies resulted in lower minimum SSB levels at the end of the crash period due to their delayed reduction in recommended catch during population decline. However, these strategies also yielded higher post-crash SSB peaks as the recovering population grew faster than catch advice could increase. Over time, SSB levels for the stability-constrained strategies converged toward those under the F40 strategy (Fig. 6). Consequently, median SSB values over the full feedback period for the stability constant strategies were very similar to those of F40. Lastly, the 25k Harvest Cap strategy resulted in higher and much higher average SSB relative to the F40 strategy under the "Random" and "BH Regime" scenarios, respectively, but only slightly higher SSB under the "Crash" scenario (Fig. 5). Importantly, no MS-OM combination resulted in population extirpation, indicating that all strategies maintained the population above critical biological thresholds throughout the feedback period.

The average population age across all OM scenarios was 7.59 years, with limited variability across MS (excluding the "No Fishing" strategy) during the feedback period (6.92–8.10 years; Fig. 4). Under the "No Fishing" strategy, the average population age reached 9.55 years, reflecting the expected age structure in an unexploited population. The F40 strategy consistently resulted in the lowest average population age. Only the 15k Harvest Cap and British Columbia strategies produced higher average population ages, while all other rules resulted in slightly higher or very similar average ages compared to the F40 strategy (Fig. 5).

On average, SSB conditions < B^*_{35} occurred in 40% of simulated years across all OM scenarios. However, there was substantial variation across MS (Fig. 4). The F40 strategy resulted in the highest proportion years with SSB < B^*_{35}, occurring in 66% of simulated years. Strategies that applied more conservative FRPs (e.g., F50 and British Columbia strategies) resulted in lower to much lower proportion of low-SSB years (Fig. 5). The stability constraint strategies showed a lower to slightly lower proportion of years with SSB < B^*_{35} under the "Random" and "BH Regime" scenarios compared to the F40 strategy. Under the "Crash" scenario, however, these strategies showed a substantially lower proportion of low-SSB years. For instance, the F40 ± 5% strategy resulted in SSB < B^*_{35} in 45% of years, compared to the 67% under F40. The 15k Harvest cap strategy consistently yielded a much lower proportion of years with SSB < B^*_{35} across all recruitment scenarios (Fig. 6) relative to the F40 strategy, reflecting its strong conservation effect due to a hard cap on catch.

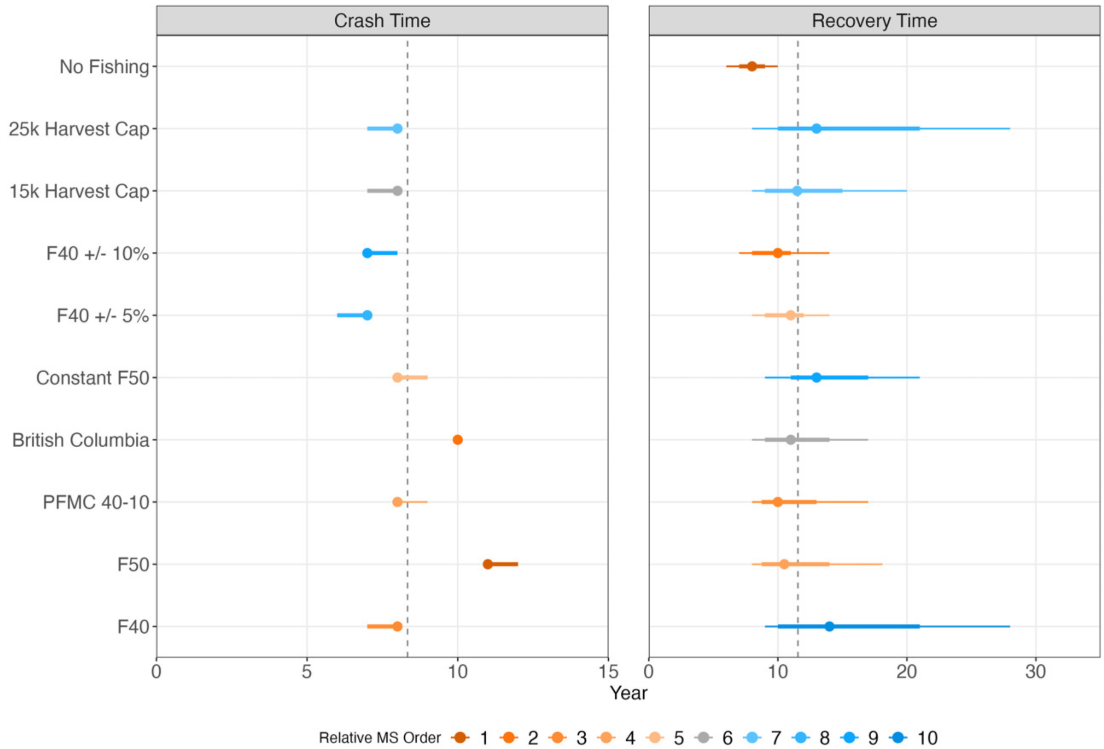
Population resilience

The "Crash" OM scenario was designed to evaluate the performance of alternative MS under a hypothetical, prolonged recruitment failure. No MS was able to prevent a decline in SSB below $0.50{*}B^*_{35}$ (the defined collapsed biomass threshold) during the 20-year crash period, with average collapse times ranging from 7–12 years (Fig. 7). MS that employed lower maximum fishing mortality rates (e.g., F50, British Columbia) or more conservative LRPs (e.g., PFMC 40-10 rule) were able to delay the onset of collapse. In contrast, MS with stability constraints resulted in slightly faster population crashes, due to their slower responsiveness to population downturns. Among all strategies, the F50 strategy was the most effective at mitigating collapse, with the population remaining above the threshold for 11 years. The F40 ± 5% strategy led to the fastest collapse, with the population falling below the threshold after just 7 years (Fig. 7). Under the "No Fishing" strategy, the population remained entirely above the collapse threshold. Despite these differences in collapse timing, all MS achieved recovery of the population above B_{35} within 20 years following the end of the crash. Most strategies required 10–12 years for recovery, with the F40 ± 10% and PFMC 40-10 strategy enabling the fastest recovery (10 years), and the F40, Constant F50, and 25k Harvest Cap strategy taking the longest (12 years). Substantial variability in recovery times was observed, with the 80th percentile ranging from 7 to 28 years across MS (Fig. 7).

Discussion

Our MSE illustrates how commonly used management options are expected to perform when confronted with uncertain and variable future recruitment dynamics, offering insights to support the development of climate-resilient and economically sustainable management approaches. While this work is specifically tailored to sablefish, a species characterized by spasmodic recruitment, our findings are likely generalizable to other species, including those with less dynamic recruitment patterns. In particular, the "Crash" scenario offers valuable insight into the potential consequences of persistent recruitment failure, highlighting the differential impacts of MS in terms of resilience and recovery. While species-specific outcomes will vary depending on environmental forcing and life history traits, the general patterns observed here remain informative. Overall, our results suggest that all MS evaluated are broadly robust to recruitment un-

Fig. 7. Distribution of years required for the population to crash (SSB $< 0.50 * B^*_{35}$; left) and subsequently recover (SSB $> B^*_{35}$; right) under the "Crash" operating model scenario by management strategy. Points are the median, thick bars the inner-50th percentile, and thin bars the inner-80th percentile across 200 simulations. The population never drops below the crash threshold under the "No Fishing" MS. Extremely skewed distributions of crash time reflect the limited variability in recruitment, and hence stock trajectory, during the period of the recruitment crash (years 55–75).



certainty, though they exhibit distinct tradeoffs between conservation performance and fishery outcomes. These tradeoffs emphasize the importance of clearly defining management objectives and tolerances for risk when selecting or designing MS under future uncertainty.

Management strategy performance

Threshold management strategies (e.g., F40, F50, PFMC 40-10, and British Columbia MS) are among the most commonly used HCRs for data-rich fisheries (Zahner 2023). A key benefit of threshold strategies is the use of a sloped HCR, which reduces fishing mortality as stock size declines, thereby theoretically improving resiliency to population crashes and helping avoid overfishing (NPFMC 2020; Free et al. 2023; PFMC 2023). As expected, threshold strategies with lower maximum fishing mortality rates (e.g., F50 and British Columbia rules) were more conservative of population biomass and overall catches than those with higher maximum rates, consistent with findings from other studies (Punt et al. 2008). Meanwhile, the inclusion of a higher LRP (e.g., the PFMC 40-10 strategy) had relatively minimal effect on catch and SSB performance metrics, likely due to the infrequency with which biomass fell below the LRP. Had more extreme poor recruitment scenarios that resulted in very low SSB levels been explored, the impact of higher (more conservative) LRPs may have been greater. A clear tradeoff emerged between catch and conservation objectives: as the FRP decreased, average catch declined, SSB levels increased, the population age structure became older, and the probability of SSB < B^*_{35} decreased (see Supplementary Material, Fig. S3). These trade-offs are consistent with expectations given typical age-structured population models. The Constant F50 MS performed very similarly to the threshold F50 MS across all performance metrics and recruitment scenarios. This is likely due to the infrequent occurrence of SSB < B_{50} and aligns with prior work suggesting that constant fishing mortality strategies can achieve comparable or higher catch, lower catch variability, and no substantial increase in conservation risk as compared to threshold strategies (Mildenberger et al. 2022; Free et al. 2023).

Catch stability constraints are commonly incorporated into MS to reduce interannual variability in allowable catch, thereby providing a more predictable supply of product to processors and markets, an objective often prioritized by fisheries stakeholders (Hilborn 2007). These constraints were originally intended to limit fluctuations in catch when monitoring data are highly variable or uncertain (e.g., de Moor et al. 2011; ICES 2023), rather than for stocks that experience large, natural fluctuations in biomass. For populations with spasmodic recruitment, such as sablefish, recruitment events are often not large or frequent enough to trigger high-end constraints (e.g., ±20%). This pattern was observed in our simulations; for example, the ±10% constraint was invoked in only 20%–50% of years, depending on the recruitment scenario (Table 5). This limited application helps explain the similar performance between the F40, F40 ± 5% and F40 ± 10% strategies, particularly under the "Random" recruitment scenario, when only 20% of years triggered the 10% constraint. While stability constraints had minimal impact on metrics such as average catch and average SSB, they introduced additional risk during periods of recruitment failure. Their slow response to declining stock size can delay necessary catch reductions, potentially increasing the risk of overfishing. One potential solution is to implement asymmetric stability constraints, applying them only to catch increases, a "slow up, fast down" approach. This allows for rapid reductions in catch during declines, while still smoothing interannual increases during periods of stock growth. Alternatively, stability constraints could conditionally apply only when the stock size is high, such as times of market saturation, mirroring the approach used for data-moderate stocks in Europe (ICES 2023). These refinements may improve the risk profile of stability constraints while retaining their intended economic benefits.

Harvest caps are another form of quota constraint shown to extend the duration over which moderate harvest can be sustained as seen in Acadian redfish, Pacific halibut, and Pacific hake (Clark and Hare 2004; Hicks et al. 2016; Licandeo et al. 2020). Our results support these findings, especially under the "BH Regime" scenario, where the 25k Harvest Cap MS yielded higher catches during low recruitment periods than many other MS (Fig. 5). However, harvest caps must be carefully calibrated through stakeholder engagement. If set too high, the cap may never be triggered, providing no benefit over uncapped strategies (Clark and Hare 2004). In our simulation the 25k quota cap MS performed similarly to the F40 MS in terms of average catch and SSB, suggesting that a higher cap would offer little improvement in yield or conservation. In contrast, the 15k quota cap MS led to substantially lower catch, indicating impaired fishery performance. Nonetheless, rapid quota increases following strong recruitment events have previously depressed sablefish market value, suggesting that a moderate harvest cap (between 15k and 25k) might help stabilize catch variability (i.e., reduce AAV) and preserve market value. Further economic analyses and stakeholder input are needed to identify a more effective harvest cap level. This should be paired with periodic evaluation to ensure the cap continues to support both economic viability and conservation objectives.

Implications of poor recruitment

Periods of poor recruitment are common in marine fish populations, particularly those with spasmodic dynamics, and pose significant challenges for fisheries management (Caddy and Gulland 1983; Spencer and Caddy 1997). Our results show that no MS tested could entirely prevent recruitment-driven declines in SSB when recruitment remains low for an extended period, as simulated in the "Crash Recruitment" scenario. However, more conservative strategies, such as those using lower maximum fishing mortality rate (e.g., F50, British Columbia MS) or a steeper fishing mortality ramp (e.g., PFMC 40-10 MS), were able to slightly delay population collapse, through higher noncrash biomass levels, or quicker reductions in fishing mortality at low biomass levels. By mitigating and postponing declines, these strategies can effectively "buy time", increasing the chance that recruitment or environmental conditions improve, and trigger a strong recruitment event. Delaying a collapse may also postpone the need for costly rebuilding plans (e.g., the Pacific groundfish fishery; McQuaw et al. 2021). In contrast, catch stability constraints performed poorly during recruitment crashes, as they delayed quota reductions, leading to faster and deeper SSB declines, particularly under the F40 ± 5% MS.

Although no MS could prevent population collapse during the "Crash Recruitment" scenario, all were able to rebuild the population within 8–12 years, assuming a return to typical recruitment conditions. Catch stability constraints and MSs with more conservative fishing mortality targets (e.g., F50), slightly shortened recovery times. These recovery periods are broadly consistent with Magnuson–Stevens Act rebuilding guidelines (10 years, unless unachievable). However, real-world complexities, such as data availability lags, structural uncertainty in assessment models, and implementation error, could extend actual recovery timelines beyond those observed in simulation. The limited differences in recovery time across MS suggests that, for sablefish, recruitment variability is a stronger driver of population recovery than management strategy itself.

Recommendations for Alaska sablefish management

The recent shift (approximately 2016) into a high recruitment regime for Alaska sablefish highlights the limitations of conventional management strategies when faced with spasmodic recruitment dynamics. Our MSE results show that while the existing F40 strategy is robust during prolonged low recruitment, it is vulnerable to rapid quota increases following sudden recruitment and population spikes (e.g., short-term increases, regime shifts, or boom-bust dynamics). Although no single alternative MS consistently outperformed others, combining elements across strategies may offer better resilience to uncertain recruitment futures. For instance, using a more conservative BRP (e.g., B_{50}), a larger limit BRP (e.g., PFMC 40-10), an intermediate harvest cap (e.g., 20k mt), and a "slow up, fast down" stability constraint could improve performance across both conservation and fishery objectives by buffering against both collapses and spikes. Given sablefish's spasmodic recruitment, it's critical to ensure that reference point calculations are robust to nonstationary dynamics. Additionally, MSs that explicitly integrate information on age structure (e.g., Griffiths et al. 2023), may help address concerns around age truncation in long-lived species, something not well captured in many contemporary threshold strategies like F40.

Future work

There are several avenues to extend this work for sablefish or other spasmodically recruiting species, including the development of more complex OM scenarios, the inclusion of additional HCR functional forms, and the integration of a bioeconomic model. For example, sablefish have been shown to exhibit ontogenetic movement and spatially variable harvest, creating complex spatiotemporal interactions among biological and fishery dynamics (Cheng et al. 2025*c*). To address stakeholder concerns, especially around spatial ABC apportionment, ongoing efforts are adapting the MSE to be spatially explicit, informed by a spatial research assessment model and long-term data tagging effort (Cheng et al. 2025*c*). Some studies have also suggested sablefish potentially exhibit density-dependent growth (Cheng et al. 2025*a*) and skip-spawning (Rodgveller et al. 2016), which could influence SSB and reference point calculations, with downstream effects on fishery yield and value. Age-structured MS would benefit from recognizing the differing conservation and economic contributions of older age classes. Finally, coupling a bioeconomic model would enable evaluation of fishery value under different management strategies by incorporating market dynamics and price variability. In fisheries like Alaska sablefish, where quotas are sometimes under-harvested in high productivity years, profit-optimizing strategies rather than fishery catch strategies may improve both fishery and conservation outcomes.

Conclusion

As with most fisheries management decisions, tradeoffs between conservation goals and socioeconomic outcomes are unavoidable. While no single HCR fully balanced these competing objectives, our results suggest that hybrid strategies drawing from multiple MS types may offer the best compromise. For instance, threshold rules are effective at reducing fishing mortality during population declines, while quota stability constraints can support recovery. Similarly, harvest caps help prevent quota creep common in threshold MS, and promote more stable, moderate catches that align with economic objectives. For sablefish, and other species with high recruitment variability, we recommend exploring combinations of threshold strategies with appropriate quota caps and "slow up, fast down" catch constraints to optimize both conservation and fishery performance. However, such approaches should be developed collaboratively with stakeholders and refined through extensive iterative MSE testing to ensure they address both biological and socioeconomic priorities. As fisheries management frameworks attempt to build climate resiliency and confront increasing uncertainty in a rapidly changing marine environment, broader use of MSE tools and stakeholder engagement processes will be essential to building resilient adaptive management frameworks that meet the needs of both the resource and its users.

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Data availability

The codebase used to run and analyze the simulations described here is available at https://doi.org/10.5281/zenodo.17081421. The operating model codebase is available at https://doi.org/10.5281/zenodo.17081537. The original model simulation data are available at https://doi.org/10.5061/dryad.q2bvq83zv.

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Daniel R. Goethel served as Associate Editor at the time of manuscript review and acceptance; peer review and editorial decisions regarding this manuscript were handled by another editorial board member.

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Competing interests

The authors declare there are no competing interests.

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Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/cjfas-2025-0115.

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