Canadian Journal of Fisheries and Aquatic Sciences

Research Article

Range-wide contrast in management outcomes for transboundary Northeast Pacific sablefish

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Abstract

Sablefish (*Anoplopoma fimbria*) of the Northeast Pacific support a highly mobile, valuable fishery resource currently managed as three separate populations. Recent work has shown sablefish to be genetically mixed; have high movement rates; and have synchronous biomass trends, including recent declines. A management strategy evaluation was developed with stakeholders and scientists from three regions to investigate whether spatially structured management paradigms might result in better conservation and economic outcomes. The management strategy evaluation includes a transboundary operating model to represent spatial population dynamics including movement and a delay–difference estimation method with varying spatial complexities and potential stratifications, and harvest control rules. Mismatches in the spatial scale of management and the underlying biological units pose a crucial risk of localized depletion in the southern U.S. West Coast. This study presents one of the first transboundary, spatially-explicit management strategy evaluations conditioned to actual data. These results underscore the importance of spatial management strategy evaluation tools and implications when regional management is conducted in isolation. Future work should incorporate additional spatial hypotheses and investigate the drivers of recruitment patterns range-wide.

Key words: harvest control rules, management strategy evaluation, sablefish, spatial modeling, stock assessment

1. Introduction

Stock assessment scientists and managers of commercial fisheries have long been concerned with spatial structure (e.g., Beverton and Holt 1957), because fish populations are not evenly distributed across the seascape, and many biological or fishery dynamics are driven by spatial processes (Lowerre-Barbieri et al. 2019). Numerous studies have illustrated that misspecifying spatial structure can undermine assessments of stock status, and the ability of management strategies (MS) to meet conservation and economic objectives (e.g., Ying et al. 2011; Thorson et al. 2015*b*). Moreover, spatial dynamics complicate the development of effective MS to meet conservation and economic objectives, given the unintuitive interactions between fish connectivity, dispersal, and management actions that span political boundaries (e.g., Bosley et al. 2019; Palacios-Abrantes et al. 2020).

Although spatial assessment approaches demonstrate improved performance over closed population models when spatial structure exists (Punt et al. 2015; Goethel et al. 2021), transitioning to a spatially structured paradigm of assessing or managing a fished population can be costly and uncertain. At a minimum, such efforts require an agreed-upon set of spatial areas, a reconfiguration of the input datasets to meet the new spatial stratification, and an approach for reconciling the outputs of the new assessment method with the specification of catch limits. It is therefore helpful to employ a management strategy evaluation (MSE) to assess the trade-offs associated with implementing spatial assessment and management frameworks because such changes add uncertainty, and can lead to dramatic changes to the perception of the status of a stock (Kerr et al. 2014; Szuwalski and Punt 2015) and of fishery yields (Ralston and O'Farrell 2008).

Management strategy evaluation is a modeling approach that simulates the effects of alternative management actions on a fish stock, has been applied successfully in several fisheries around the world, and has been shown to be an effective way to address the issue of spatial structure in fisheries management (Punt et al. 2016). The results from an MSE can help managers understand how changes in fishing practices and other factors will impact a stock, and identify the most effective MS, before making a formal change. Pacific hake (*Merluccius productus*) are managed as a single stock via international treaty across the US–Canada border, and recent MSE work has shown that ignoring climate-induced changes in the spatial structure of the stock can lead to lower catches (Jacobsen et al. 2022). Similarly, area-based management was shown to insulate commercial catches from climate-related range con-

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tractions of Atlantic surfclam (*Spisula solidissima*, Kuykendall et al. 2019).

Sablefish (*Anoplopoma fimbria*) in the Northeast Pacific have been identified as a species that warrants spatially-explicit MSE explorations, because a single genetic population exists (Jasonowicz et al. 2016; Timm et al. in review) across three management jurisdictions (i.e., Alaska, British Columbia, and the U. S. West Coast), each of which utilize different assessment and management frameworks. Moreover, the closed population stock assessments performed in each region have indicated spatially synchronous biomass trends, including a large-scale decline from 2010 to 2018 followed by rebuilding due to large year classes over the most recent few years. Recent work indicates that sablefish populations in the northeast Pacific are well-mixed, and tagging studies have shown that sablefish readily traverse the distance between southern Alaska and the middle of the U.S. West Coast within 1 or 2 years (Hanselman et al. 2014; Goetz et al. 2018). The movement dynamics of sablefish are assumed to involve high (10%-88%) annual movement rates out of the Gulf of Alaska, forming a large net subsidy of biomass from Alaska to British Columbia (B. Connors (Department of Fisheries and Oceans Canada, *personal communication* 2023)); there is assumed to be exchange in both directions across the U.S. West Coast–Canada border, and intra-regional movement to offshore sea mounts. The last synthesis of recruitment trends throughout the northeast Pacific, based upon recent assessments, also indicated that U.S. West Coast and British Columbia recruitment indices are more similar to one another than to Alaskan recruitments (Fenske et al. 2019). Recruitment indices for Alaska appear to lag those in the more southern regions by 1–2 years. In 2018, scientists from the U.S.A. and Canada began development of a transboundary MSE for sablefish. The principal goal of this effort was to investigate how ignoring the spatial dynamics of Northeast Pacific sablefish might affect management outcomes. This study is the culmination of a multi-year MSE endeavor, which included stakeholder input (Fenske et al. 2019; Kapur et al. 2021*a*). This study presents a novel, transboundary age-structured model conditioned to historical observations of sablefish catch, discards, survey biomass, and age compositions from 1960 to 2019. The model illustrates the plausibility of an interconnected transboundary sablefish stock that would result in the regional biomass trends estimated in the individual management models.

2. Methods

The MSE (Fig. 1) used an operating model (OM) of the population dynamics to project a population forward based on a set of management actions (total allowable catches, TACs). The OM is assumed to represent the truth regarding transboundary sablefish population dynamics and generates future data to inform TACs. The management actions for the model-based harvest control rules (HCRs) are based on the derived quantities from an estimation method (EM), which is fit to the historical and projected data from the OM for each year of the simulation period. We also investigated model-free HCRs based on recent survey abundance. TACs are determined by applying the HCRs to estimated quantities (current biomass and reference points) from the EM and are taken exactly (e.g., implementation error is not modelled). Therefore, the management strategy consisted of an optional EM and an HCR for setting catches in subsequent years.

2.1. Operating model

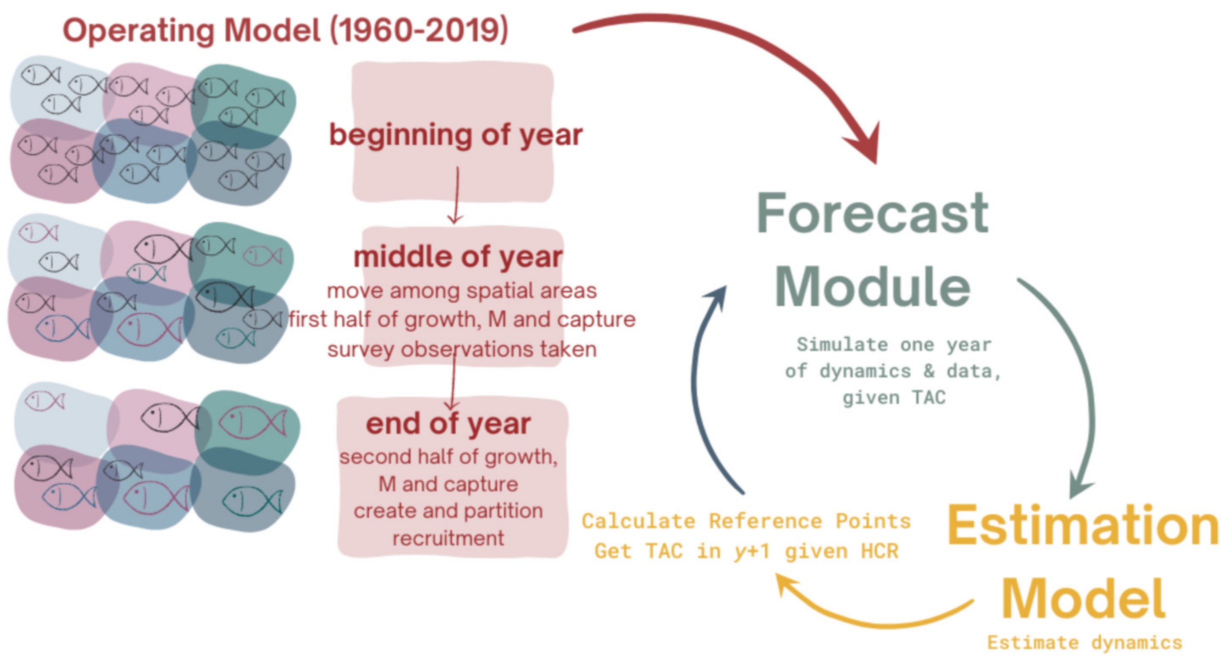
2.1.1. General structure

The OM is conditioned on observed data from 1960 to 2019, where key population parameters are first estimated by fitting the catch, survey biomass, age-composition, and discarding data from the entire domain using Template Model Builder (Kristensen et al. 2016). Fishing occurs in two time steps corresponding to the beginning and middle of the year. Then, estimated parameters are used to simulate data during a 21-year projection period. This timescale is appropriate given that sablefish reach maturity and are selected into the fishery for all regions by age 10 (Supplementary Figs. SB.5 and SB.20), and that the focus of this effort was near-term impacts of various MS. Each OM is projected forward 100 times to allow for stochastic process error. A detailed description of the OM, including equations governing the dynamics and the sensitivity analyses, is provided in the Supplementary Material.

The OM is a two-sex, age-structured, and spatially structured population dynamics model, with an annual time-step, and intra-year dynamics accounted for using three "seasons". In the OM, six spatial areas are modeled (Fig. 2A) representing the highest spatial resolution at which population and fishery dynamics are simulated. Next, a stock is defined by biological dynamics and represents fish with common demographic parameters, including growth and maturity. There are four biological stocks (stock 1: Southern U.S. West Coast, stock 2: Northern U.S. West Coast and Southern British Columbia, stock 3: Northern British Columbia and Gulf of Alaska, and stock 4: Bering Sea) in the OM defined by distinct demographic regimes (growth is described by Kapur et al. 2020), which can match the extent of spatial areas or extend across multiple spatial areas. Fish that move to a new stock assume the demographic characteristics of that stock and contribute only to the biomass for that stock.

The stock structure defined in the OM follows from the analysis in Kapur et al. (2020), and the concept of the Bering Sea/Aleutian Islands (area west of 145°W) as a separate marine ecosystem from that of the Gulf of Alaska (Cleaver and Evans 2019). The US West Coast is modeled consistent with recent empirical analyses indicating that the area south of Monterey Bay (36.6°N) exhibits distinct sablefish recruitment dynamics from the northern area (Tolimieri and Haltuch 2023). Finally, the population of British Columbia is considered a highly connected component of the overall population, generally dependent on subsidies from Alaska to meet catch quotas and fit survey indices. It is clear that the movement rates and the location and structure of density-dependence (recruitment) remain crucial uncertainties to evaluating the population status of long-lived, highly mobile species such as sablefish, echoing suggestions from simulation work (Goethel et al.

Fig. 1. (Top) Schematic of the management strategy evaluation framework. The operating model (OM, red text) is conditioned to observed data from 1960 to 2019 and is used to determine unfished recruitment, the biomass and age structure at the start of 2020, and terminal year movement and selectivity. Stock-specific recruitment deviates are drawn for each of 21 projection years for all OM replicates; these determine variability in the simulated dynamics during the projection period. Each annual projection step updates the OM by 1 year given the fishery-specific catches during year *y* and provides these catches and observed survey biomass data to the management strategy. The management strategy consists of an estimation method (EM) and a harvest control rule, and is used to calculate total annual catches (TACs). This cycle is repeated for 21 projection years for each simulation experiment. (Bottom) Schematic of the order of events in the OM. Fish are subject to movement, half of growth, natural mortality (*M*) and capture by fisheries in the first "season". Fish then undergo the second half of growth, movement, and capture. The resultant biomass is used to calculate the expected recruitment for the start of the following year. This recruitment may be split among multiple spatial areas if a given stock is comprised of more than one area.



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2011) and applications to other groundfish species (Jacobsen et al. 2022; Mazur et al. 2023).

Density-dependence in recruitment follows a Beverton–Holt stock–recruitment relationship and occurs at the stock level (i.e., local density-dependence is assumed). The proportion of recruits assigned to each area within a stock (when a stock is distributed across multiple areas) is defined by an apportionment parameter that varies for each stock and each year. Movement rates are specified among spatial areas based on the results of a tag-recapture study (Rogers et al. in preparation, Fig. 2). Each replicate consists of a unique time series of deviations from expected recruitment for each of the four stocks across the projection period. These future recruitment deviations are simulated to retain the variation within and spatial autocorrelation among stocks as determined from the conditioned OM (see Supplementary Material B). These correlations are highest, in an absolute sense, between adjacent stocks in the US and Canada, with a 57% correlation between stock 2 (the U.S. West Coast and southern British Columbia) and stock 3 (northern British Columbia/the Gulf of Alaska), and a correlation of −57% between stocks 3 and 4 (northern British Columbia/the eastern Gulf of Alaska and the western Gulf of Alaska/Bering Sea/Aleutian Islands, Supplementary Fig. SB.12). The positive correlation between stocks 2 and 3 is likely caused by the high level of mixing between the four areas composing these two stocks, and because there is a single survey for British Columbia that straddles both stocks. The negative correlation across the 145°W line (splitting the eastern Gulf of Alaska from the western Gulf of Alaska, Bering Sea, and Aleutian Islands) is consistent with the ecological perception of those areas as separate, large marine ecosystems (Cleaver and Evans 2019).

2.1.2. Data generation

Actual observed data for the historical period are unchanged across replicates. Projection involves generating future survey estimates of abundance but not future discard nor length- nor age-composition data, because these data types are not used by any management strategy. The future survey observations (Supplementary Fig. SA.1) occur at the same frequency as the historical surveys. Survey estimates of biomass are generated by assuming that they are lognormally distributed about their expected values (proportional to the biomass vulnerable to each fishery in the middle of the year), with variances corresponding to the survey-specific input variance used in the terminal year of the conditioning model (2019). The future catches returned from the

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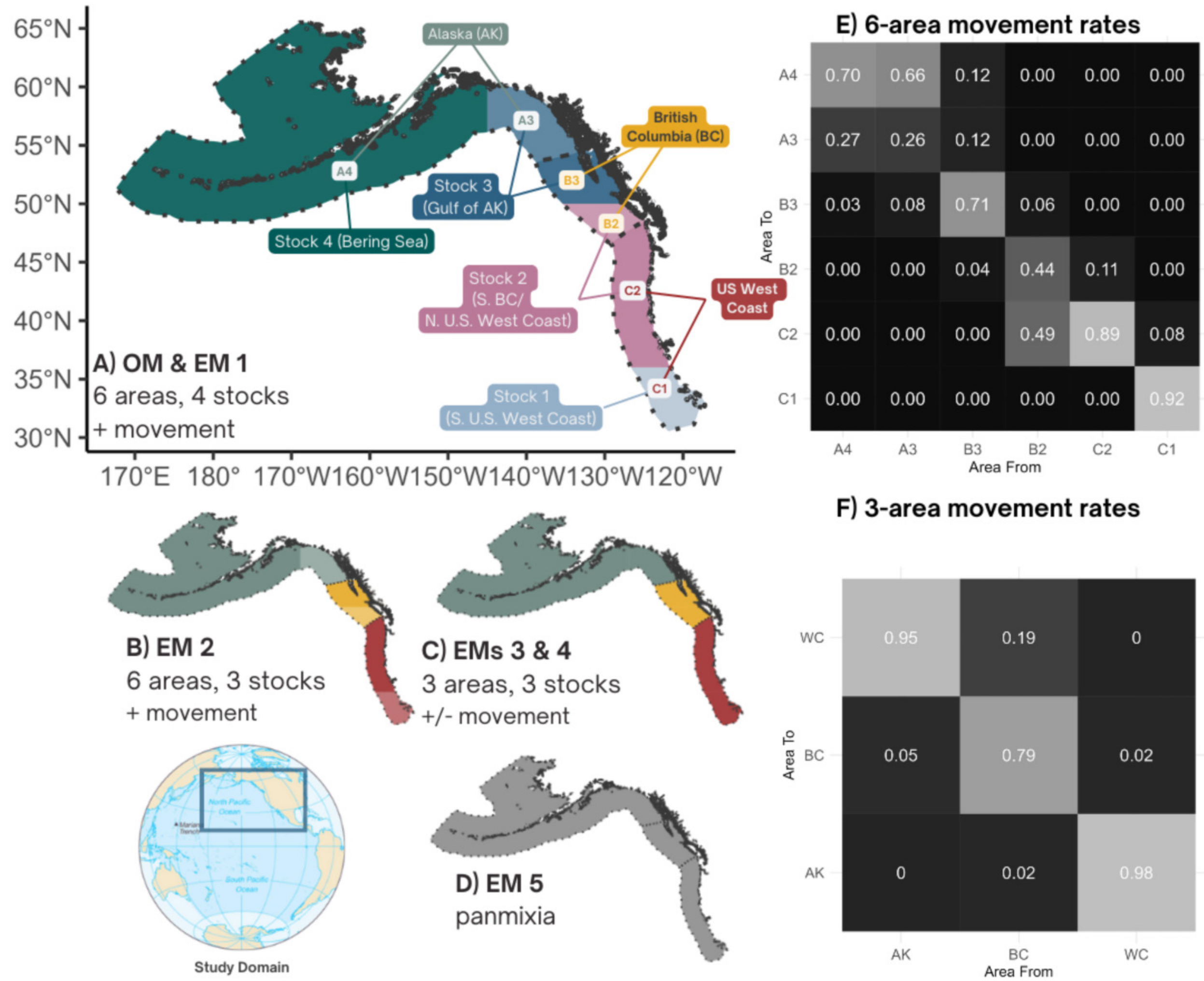
Fig. 2. (A–D) Maps depicting spatial structure in the management strategy evaluation (MSE) scenarios. In all scenarios, management actions occur at the three political levels (dotted lines). (A) Spatial structure in the operating model (OM) and estimation method (EM) 1. There are six modeled spatial areas (colors) within which population dynamics are tracked; fish move among spatial areas. These spatial areas are each nested within a single demographic area or "stock", indicated by shading of colors (green, blue, pink, and gray). (B) Spatial structure for SixAreaThreeStockMove. There are six spatial areas with movement among them, and the three stocks in the EM coincide with the management regions. (C) Spatial structure for ThreeAreaThreeStockMove. There are three spatial areas, with (ThreeAreaThreeStockMove) or without (ThreeAreaThreeStockNoMove) movement among them, and the three stocks in the EM coincide with the management regions. (D) Spatial structure for Single Area. There is one stock, hence no movement, and one management region. (E) Movement rates for the 6-area EMs. (F) Movement rates for the 3-area EM (lighter gray tiles indicate higher movement rates).



management strategy are assumed to be taken exactly; the harvest rate is calculated to fully realize these catches from the vulnerable biomass in the OM.

2.2. Management strategies

Five of the seven MS consist of an EM (a stock assessment method with an assumption about the spatial structure of the population), and all seven include an HCR applied to the quantities estimated using the EM, or estimates of recent survey biomass, or average catches (Table 1). The MS are specified to provide TACs for the appropriate regions, as defined by the HCR(s).

2.2.1. Estimation method/EM

The EM is a state-space delay–difference model (Schnute 1985) with spatial structure characterized by a set of spatial areas (see Supplementary Material A for more details). It does not consider age nor size structure and is not sex-specific. This provides a computationally efficient means of estimating population dynamics for the scale of this exercise; most pre-existing modeling frameworks such as Stock Synthesis also preclude the representation of regional (vs. global) density-dependence, an important consideration for our research question. Furthermore, the only MSE presently used for tactical management advice (for British Columbia)

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Table 1. Components of the management strategies.

Management strategy	Harvest control rule			EM spatial areas	EM demographic areas (stocks)	EM movement
	U.S. West Coast	*British Columbia*	*Alaska*			
1: SixAreaFourStockMove	PFMC "40–10" rule *(Terms of Reference for the Groundfish Stock Assessment Review Process for 2023–2024, 2022)*	U_{MSY}-based rule, without buffers (Cox et al. 2011)	NPFMC Harvest control rule (Cleaver and Evans 2019)	6	4	Yes
2: SixAreaThreeStockMove	"	"	"	6	3	Yes
3: ThreeAreaThreeStockMove	"	"	"	3	3	Yes
4: ThreeAreaThreeStockNoMove	"	"	"	3	3	No
5: Single Area	"	"	"	1	1	n/a
6: Empirical HCR	Mean slope of the logarithms of the most recent 5 years of survey observations within the management region, multiplied by mean fishery catches during 2009–2019			No EM	n/a	n/a
7: Mean Catch 2000–2019	Mean fishery catch by fisheries in the management region during 2000–2019			No EM	n/a	n/a

Note: Each estimation method (EM; rows, top half of table) is combined with the "status quo" control rule (HCR) for a total of seven management strategies.

similarly uses a simplified, surplus production model that ignores age-composition data and models the stock biomass as an aggregated total. The spatial areas may or may not coincide with the boundaries of a demographic stock, depending on the management strategy. Fish may move between spatial areas and assume the demographic characteristics (growth rates and stock recruitment parameters) of their present spatial area. The EM requires a time series of survey biomass and catches (1960 onward) for each fishery. The biomass in each spatial area is defined by the proportion of fish that stay, immigrate, and survive capture and natural mortality in that spatial area; this biomass grows and contributes to the expected Beverton–Holt recruitment for the applicable stock for the following year. Detailed descriptions, including equations of the EM dynamics, parameterization, and objective functions, are provided in Supplementary Material A.

The first five MS each involve one of five EMs. These methods are defined by their spatial stratifications and whether fish are assumed to move among spatial areas. There are two EMs with six spatial areas, two with three spatial areas, and one with a single-area EM (Fig. 2).

Parameters estimated using the EMs include: a time series of stock-specific recruitment deviates and the standard deviation thereof (as random effects), the unfished recruitment in numbers for each stock, and the proportion of recruits from each stock that are partitioned into each constituent spatial area for each year (assuming stock k is comprised of more than one spatial area). Parameters that were not estimated in using the EMs include: natural mortality (set to values from the OM), Berverton—Holt steepness, growth parameters (see below), and movement rates (set to values from the OM, when applicable). Estimation is performed using marginalized maximum likelihood, implemented in Template Model Builder (Kristensen et al. 2016). The EM assumes that annual recruitment represents female sablefish at age 10 because the biomass estimates from the delay–difference model are used as proxies for fully selected vulnerable biomass and stock biomass. In the OM, 10 years is the age at which 100% of fish in each stock are assumed to be mature, fish are fully selected, and after which (where applicable) movement rates are unchanged. The values for Ford-Brody demographic parameters concerning the weight of recruits and annual growth rate are estimated externally to the EM at the appropriate spatial stratification using simulated length- and weight-at-age data of age-10 female sablefish from the OM. This is achieved by first randomly sampling 5000 observations of female length-at-age from the OM from each of the six spatial areas shown in Fig. 2A. This ensures that the relative proportion of sampled fish roughly matches the abundance of fish in each area and influences the growth estimates accordingly. These data are then aggregated at the appropriate stock stratification for the EM in question (either the four stocks in Fig. 2A, three stocks as in Figs. 2B–2C, or a single stock Fig. 2D). The parameters of the von Bertalanffy growth curve (asymptotic length, growth rate, and age at length zero) are estimated for each stock using nonlinear minimization, and then used to calculate the parameters of the Ford–Walford growth model, which approximates weight-at-age (as in Thorson et al. 2015*a*; see Supplementary Material A).

For all EMs, the initial harvest rate is set to 0.01 to avoid confounding with initial estimates of recruitment (earlier attempts to condition on catch resulted in unreliable estimates of initial and unfished recruitment). Natural mortality and steepness are set to the stock-specific values used in the OM. For the EM with a single area, these parameters are set to the means of the values used in the OM. An analysis of 30 years of tag-recapture data (Rogers et al. in prep) provided time-invariant movement rates among the six spatial areas, as in SixAreaFourStockMove and SixAreaThreeStockMove, as well as among the three management regions for ThreeAreaThreeStockMove. Movement rates are not estimated within the EMs. Attempts to estimate the spatial apportionment of recruits as random effects were intractable. Initial runs of the EM revealed very little (<5%) change in recruitment apportionment across years within stocks (Supple-

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mentary Table SB.17) so this parameter is assumed to be time-invariant.

Before performing the MSE, EMs for each of the five spatial scenarios were evaluated based on their ability to fit the historical survey data, realize the historical catches, and return a time series of biomass estimates for recent years of the same order of magnitude as the recent regional assessments. The study design is balanced so that the same unique replicates were used for all MS. Replicates were discarded for all strategies if any EM failed to minimize (achieve an invertible Hessian matrix) for any year during the projection period. This meant that many more than 100 replicates were produced for the analyses, but results were truncated to only include the same 100 replicates that successfully minimized for all EMs; the proportion of attempted replicates that minimized for each EM was recorded.

Five EMs represent the five spatial scenarios evaluated (Fig. 2; Table 1). These range from complex, biologically representative configurations (spatial and stock structure determined by demographic analysis) to approximations of the status quo (spatial and stock structure determined by political boundaries, with or without movement among spatial areas). The final scenario is a panmictic EM (no spatial structure). Stock- or spatial area-specific parameters are estimated at the stratification applicable to the EM scenario. The five spatial EMs are embedded within the first five MS; all MS are as follows, with the name used to refer to each in italics:

- Management Strategy 1: *SixAreaFourStockMove*. This mimics the spatial structure of the OM, in that there are six spatial areas, with movement among them, and four stocks. Two of the stocks are each comprised of two spatial areas and straddle an international boundary (Fig. 2A).
- Management Strategy 2: *SixAreaThreeStockMove*. Management as stocks, with six spatial areas and movement. This EM has the same six spatial areas as the OM, with movement among them. Instead of four stocks, demographic parameters are instead shared only within the three management regions, each of which is comprised of two spatial areas (Fig. 2B).
- Management Strategy 3: *ThreeAreaThreeStockMove*. This is a three-area EM with movement among the three spatial areas. The spatial areas reflect the political borders of the United States and Canada (British Columbia, BC). As in SixAreaThreeStockMove demography is shared within each of the three spatial areas, which are now each comprised of a single, coincident spatial area. This represents the current spatial stratification of sablefish assessment models for the region (though movement is not part of the current management paradigm). The observed survey abundances specific to the six OM areas ($B^{f}_{obs,y}$) and their uncertainties area summed into the appropriate management region (Fig. 2C).
- Management Strategy 4: *ThreeAreaThreeStockNoMove*. This is identical to *ThreeAreaThreeStockMove*, but there is no movement among the three spatial areas (Fig. 2C).
- Management Strategy 5: *Single Area*. This panmictic EM treats the entire region as a single stock, with a single set of demographic parameters. The data from the fisheries and survey observations are summed into a single fishery and survey, assumed to act throughout the assessed area (Fig. 2D).
- Management Strategy 6: *Empirical Harvest Control Rule*. This strategy does not use an EM, and instead uses the slope of recent survey observations multiplied by recent average catches to define catches (see details below).
- Management Strategy 7: *Mean Catches 2000–2019*. This strategy does not use an EM, and instead applies the average fleet-specific catches from 2000 to 2019 for each projection year.

2.2.2. Stock status and harvest control rules

Reference points

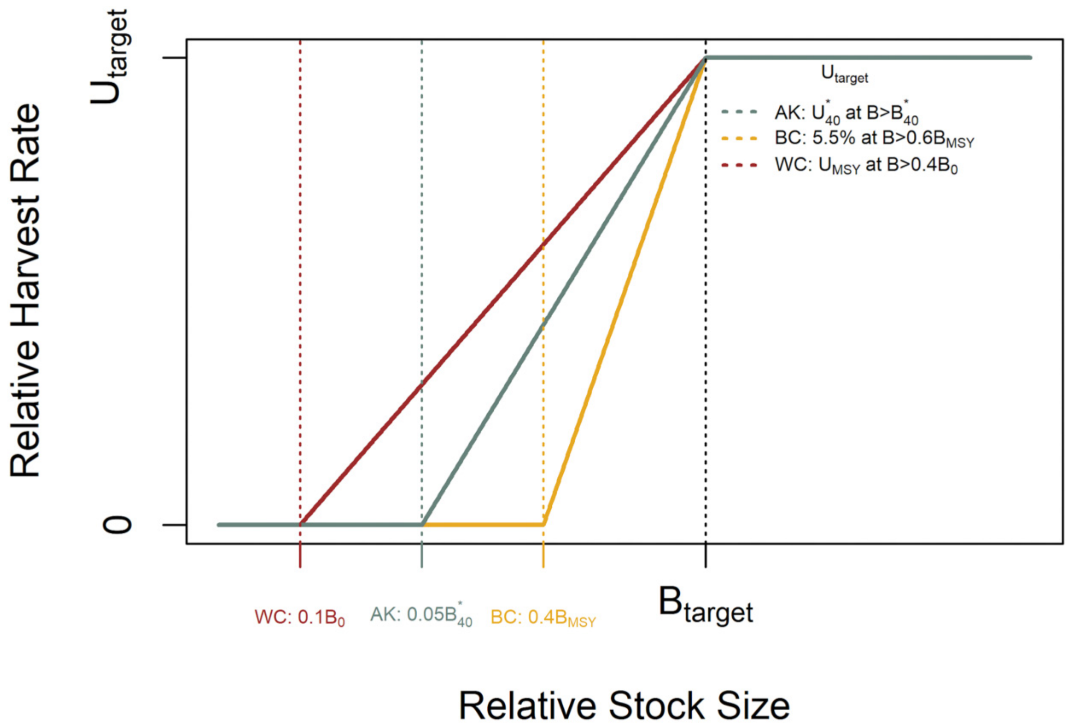
Several of the HCRs considered in the MSE require estimates of the reference points MSY and B_{MSY}, which are computed using the EM for each stock. However, the calculation of equilibrium reference points for spatially structured models is an open area of research (Kapur et al. 2021). Because the MS explored here already differ substantially from the current management paradigm (both in terms of model type and spatial structure), the reference points are calculated using equilibria that do not consider movement among areas. This provides reasonable confidence that differences in performance among MS can be attributed to the management strategy (HCR and EM) itself. Details on the region-specific reference points are provided in Supplementary Material A.

Harvest control rules

Catch limits are set on a per-management-area basis using HCRs, which may or may not be unique to each management region. The actual observed catches are used for year 2020. There are three sets of HCRs (Fig. 3; Table 1). The first set includes those currently used in each management region. Generally, these are recti-linear algorithms that ramp harvest rates up or down between two pre-specified limits and scale to the current estimated biomass from the EM (B_y). The principal difference among the regions' HCRs are that the U.S. West Coast and British Columbia use an equilibrium-based harvest level (or fraction thereof), U_{MSY}, as their target, while for Alaska, % is used as a proxy for U_{MSY}, where % is harvest rate associated with a spawning potential ratio of 40%. % is then the maximum harvest rate applied when biomass is at or above % (the long-term average biomass that would be expected under average recruitment and $U =$ %). The yield corresponding to U_{MSY} is %. Target harvest levels are identified using a search algorithm. Biomass-based reference points need to be computed for TAC setting purposes at the scale of the management regions, but the boundaries of the modeled stocks do not always match those of the management regions. For these cases, the biomass reference point for a given management region is computed by the weighted sum of the estimated total biomass in each constituent stock within the management region. Details of and equations pertaining to all HCRs are provided in Supplementary Material A.

The second HCR is an empirical HCR that considers the slope of a regression of the logarithms of survey observations in each management region during the most recent 5 years.

Fig. 3. Schematic of "status quo" harvest control rules (HCRs) for the three management regions (U.S. West Coast, WC; British Columbia, BC; Alaska, AK), which specify the harvest rate *U* as a function of the stock size relative to reference points specific to each region. Vertical lines indicate the start of the ramp, below which *U* is zero. Note that the figure is not to scale and cannot be used to make conclusions about the relative conservatism of the given HCRs in each management region (as the measures on the *x* axis differ among regions).



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The TAC is then the proportional increase or decrease based on the slope (or mean of slopes, if more than one active survey) multiplied by the mean catch from 2009 to 2019. The final HCR also does not consider the outputs of the EM, and instead sets the catch for each fishery to the corresponding mean of the 2000–2019 catch to introduce some contrast between this and the empirical HCR. The first set of HCRs is combined with each of the five EMs to create the first five MS (Table 1); the other two HCRs do not require outputs from the EM and are treated as standalone MS, for a total of seven MS.

For all HCRs, TACs are apportioned from management regions to fishery based on the proportion of the total 2019 catch taken by each fishery by weight. This retains the current apportionment paradigm used in each region for the duration of the projection period. TAC setting occurs at the management level and TACs are allocated to fisheries within each management region. The MSE assumes that TACs are fully realized by all fisheries in all management regions, whereas it has been common, particularly off the U.S. West Coast, for TAC attainment to be low (on the order of 15% south of 36°N, often due to bycatch avoidance; Somers et al. 2023).

2.2.3. Performance Metrics

Two types of metrics are used to quantify the performance of each management strategy: those related to biological and economic objectives (Table 2). These objectives were taken directly and/or adapted from those determined during a series of stakeholder workshops held during April 2021 (Kapur et al. 2021*a*). The biological performance metrics (PMs) associated with these objectives include the following: the number of years during which the stock biomass is above the overfished limit (see below); the number of years during which the stock biomass is above a general precautionary limit, defined here 40% of unfished biomass; and the mean fish length during the first 10 years of the projection period. These metrics were evaluated for each of the four biological stocks in the OM (Fig. 2A). Economic metrics included the following: the average catch during the first and last 5 years of the projection period, the total catch during the entire projection period, the average annual variability in the catches, and how often that annual variability exceeds 15% (a threshold selected by stakeholders). The catch metrics are evaluated for each of the three management regions (Fig. 2A). The PMs were weighted equally.

In practice, the definition of overfished varies by management region: for sablefish in waters off the U.S. West Coast, this occurs when the ratio of stock biomass in year *y* to unfished stock biomass is less than 0.25; for sablefish off the coast of British Columbia, it occurs when the stock biomass falls below B_{MSY}; for sablefish off the coast of Alaska, it occurs when the ratio of stock biomass to the stock biomass at maximum sustainable yield falls below 0.5. For this study, the U.S. West Coast definition is applied to all three re-

Table 2. Objectives and performance metrics identified during the 2021 stakeholder workshop (Kapur et al. 2021*a*).

Objective	Performance metric(s)	Equation
Minimize risk of stock being overfished	Proportion of years during the projection period that the stock biomass *B* is above 25% of unfished biomass[a]	$P\left(B^m_{2020-2040} > 0.25B^m_0\right)$
Avoid depleted populations	Proportion of years during the projection period that the stock biomass is above 40% of unfished biomass	$P\left(B^m_{2020-2040} > 0.40B^m_0\right)$
Maintain minimum catch level	Whether the proportion of projection years in which the catch *C*is greater than the lowest historical catch is at least 0.5	$P\left(C^m_{2020-2040} > min\left(C^m_{1960-2019}\right)\right) > 0.5$
Minimize annual catch variability	Average annual variation (AAV) in catch over the projection period*	$AAV^m_y = \frac{\sum_{2021}^{2040}\left\lvert C^m_y - C^m_{y-1}\right\rvert}{\sum_{2021}^{2040} C^m_{y-1}}$
	Proportion of years* during projection period that the average annual proportional change in catch does not exceed 0.15	$P\left(AAV^m_{2021-2040} \leq 0.15\right)$
Maximize catch in the near- and long- term	Average catch during the first* and last 5 years of the projection period	$\frac{\sum_y^{y+4} C^m_y}{5}$
	Total catch during the projection period*	$\sum_{y=2021}^{2040} C^m_y$
	Positive catch trend over the projection period* in each management region	$P\left(S^m_{2021-2040}\right) > 0$, where S^m is the slope of a linear model fit to the catches in region *m* during the projection period
Maximize long term profitability	Mean fish length over a ten-year period, by management region (see supplementary material for notation)	$\frac{\sum_{2020}^{2029} N^m_y \bar{l}^m_y}{\sum_{2020}^{2029} N^m_y}$

Notes: Equations are provided for how the metric was calculated from the OM during the projection period. When applicable, metrics are first computed for an individual replicate and then averaged across replicates. *These calculations begin in 2021 as actual catches are used for 2020 and do not vary among strategies. Years with zero catch are excluded from this calculation. [a]The definition of "overfished" used to calculate performance metrics is based on a threshold of 25% of unfished biomass; it is undesirable to conflate management performance with the complex, and unresolved, problem of calculating equilibrium reference points (e.g., B_{MSY}) from a spatially structured operating model (Kapur et al. 2021). Similarly, the application of management region-specific thresholds would have over-complicated the interpretation of management performance. Future explorations of this system could choose to focus on economic outcomes, such as the percentage of years the fishery would be closed, using region-specific thresholds.

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gions. This avoids the uncertainties associated with calculating equilibrium-based reference points (i.e., B_{MSY}) from a spatial OM, and eases interpretation of performance for stocks that straddle management regions (as the regional definitions of overfished would vary among adjacent spatial areas within British Columbia).

The PMs are calculated on a per-replicate, per-strategy basis, which becomes the raw score. Equal weight is applied to all performance metrics. For summarization, scores are adjusted such that a high value always reflects a positive outcome: e.g., the complement of average annual variability in catch is used so that scores closer to one correspond to lower variability. Then, scores for each performance metric are scaled to the maximum for each unique performance metric-area combination, such that a score of 1 represents the highest score obtained for each stock or management region for a given metric across all MS. The sum of the medians of the scaled scores for each performance metric is used to compare across strategies within each spatial unit (either stocks, for biological metrics, or management regions, for economic metrics). The median raw scores (i.e., actual catches obtained in t) are used to evaluate the relative performance and describe trade-offs among strategies.

The performance of each strategy is also evaluated by qualitative fits to the historical and projected survey and catch data. The mean relative error (MRE) in key derived quantities (unfished stock size and depletion) is summarized to aid investigation of the impacts of spatial misspecification on estimation performance.

3. Results

3.1. Conditioning the Operating Model

The scale of the OM in terms of unfished spawning stock biomass S_0 were comparable to those from recent regional stock assessments (Supplementary Fig. SB.24). S_0 in the conditioned OM were 256 011, 106 928, and 169 608 metric tons (t) for Alaska, British Columbia and the U.S. West Coast, respectively. The recent regional assessment estimates of S_0 were 295 351, 56 560, and 168 875 t, respectively. The trend in biomass fell within the confidence interval for most of the period after the onset of survey and compositional data for Alaska and the U.S. West Coast, whereas the trend for British Columbia matched that of the regional assessment although higher in magnitude (Supplementary Fig. SB.24). OM depletion was above the overfished cut off at the end of the historical period, but was close to the threshold in Alaska (0.31). Because the OM did not fit the unprecedented high survey biomasses observed in the terminal years for Alaska nor British Columbia, the simulated survey observations for the projection period were more in line with observations for

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earlier years (Supplementary Fig. SA.2). A detailed description of the conditioning results and projected data are provided in the Supplementary Material.

3.2. Estimation method performance

All EMs fit the historical and projected survey data well and fit the high survey observations in the late 2010s better than the OM (Supplementary Fig. SA.2 vs. Supplementary Fig. SB.15), with the peak observation at the end of the historical time series for Alaska best fit by the three-area models. SixAreaFourStockMove, ThreeAreaThreeStockNoMove, and Single Area have the highest proportion of models with invertible Hessian matrices (96%, 99%, and 100%, respectively), followed by SixAreaThreeStockMove (84%) and ThreeAreaThreeStockMove (11%, Supplementary Table SA.1). The proportions of simulations with invertible hessian matrices did not vary greatly among years and were not used to discard model runs, as this is not often used as a criteria for estimators in an MSE context (e.g., Punt et al. 2016; Heller-Shipley et al. 2021). Results shown here correspond only to simulations that successfully converged based upon the maximum gradient being below 1e−6 (but did not necessarily produce an invertible Hessian matrix) for all projection years.

Strategies that treated Alaska as a single area (ThreeAreaThreeStockMove and ThreeAreaThreeStockNoMove) estimated the population to be overfished in 2% (ThreeAreaThreeStockNoMove) to 9% (ThreeAreaThreeStockMove) of simulations during the first 5 years of the projection period (Supplementary Fig. SA.3); the median estimated depletion during this period ranged from 31% to 38%. The stock was estimated to be overfished in fewer than 2% of simulations for Alaska thereafter. The British Columbia population was not estimated to be overfished during any projection year for any simulation under the spatially structured EMs (Supplementary Fig. SA.3). *SixAreaThreeStockMove* and *ThreeAreaThreeStockMove* estimated the population off the U.S. West Coast to be overfished at least once in 62% of simulations (Supplementary Fig. SA.3), and ThreeAreaThreeStockNoMove estimated the population to be overfished at least once in 94% of simulations; the median estimated depletion for the entire projection period for the U.S. West Coast ranged from 21% (ThreeAreaThreeStockNoMove) to 32% (SixAreaFourStockMove, Supplementary Fig. SA.3).

Estimated B_0 did not vary greatly among years or MS (Fig. 4; Supplementary Fig. SA.4). Median estimated B_0 for Alaska ranged from 299 to 305 kt (Fig. 4 and SA.4); the OM value was 256 kt for British Columbia, B_0 estimates did not vary by more than 100 t across estimators (Fig. 4 and Supplementary Fig. SA.4). Median estimated B_0 for the U.S. West Coast ranged from 172 to 192 kt (Fig. 4 and Supplementary Fig. SA.4); the OM value is 170 kt. In comparison to the OM, the EM estimates of unfished biomass were slightly higher for Alaska and the U.S. West Coast, and lower for British Columbia (where the median estimate of B_0 across all years and strategies was 61 kt, roughly half the value in the OM and more similar to the estimate from the recent, regional assessment, Supplementary Figs. SA.4 and SB.24). The median estimate of B_0 from the panmictic EM was 575 kt, slightly higher than the sum of the three management from the OM (∼531 t, Supplementary Fig. SA.4).

Estimation uncertainty, represented by the variance of the estimated biomass across all replicates and years during the projection period, was lowest under ThreeAreaThreeStockNoMove (Fig. 4). Variance in estimated biomass was largest for Alaska under ThreeAreaThreeStockMove, and for British Columbia and the U.S. West Coast under SixAreaFourStockMove (Fig. 4). The panmictic model exhibited very little among-simulation variability on a year-to-year basis (Fig. 4), given that there are simply fewer data points fit to for each year and the whole of the population is well-represented by the aggregated data.

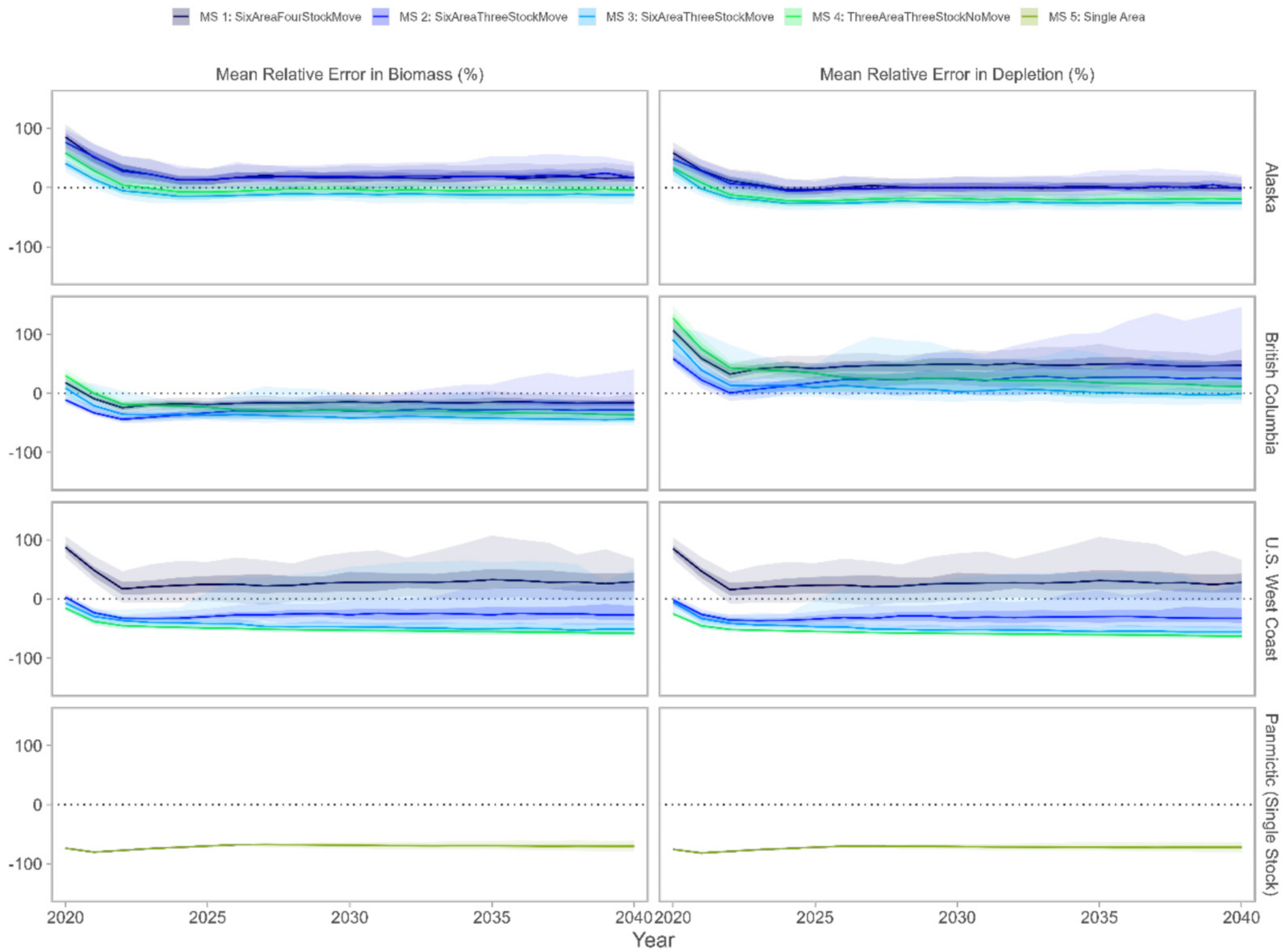
The MRE for both model outputs was the most positive for all regions and EMs in the first projection year, after which MRE in stock biomass and depletion declined and stabilized (Fig. 4). The MRE trajectories for biomass and depletion in Alaska were virtually identical for SixAreaFourStockMove and SixAreaThreeStockMove. The MRE trajectories for biomass in British Columbia were all negative, while the MRE trajectories for depletion in British Columbia were positive. The least-biased depletion trajectory for British Columbia occurred for ThreeAreaThreeStockMove, where the median MRE across all projection years was 6%. SixAreaFourStockMove was the least biased for the U.S. West Coast in terms of stock biomass (average MRE across all projection years = 27%, Fig. 4) and depletion (average MRE across all projection years = 26%); all other spatially structured EMs resulted in negative median relative errors for the entire projection period for the U.S. West Coast (Fig. 4). ThreeAreaThreeStockNoMove was the most biased for both model outputs for the U.S. West Coast (median MRE across all projection years was −52% for stock biomass and −58% for depletion). The panmictic EM led to the largest discrepancy of all estimators, with a median MRE for stock biomass of −70% and depletion of −72%.

All spatially structured MS estimated at least one large recruitment event in all areas during the late 2010s followed by a period of low recruitment leading into the start of the projection period, and relatively stable recruitment deviations thereafter (Fig. 5). The large late-2010s recruitment pulse occurred in 2017 for stocks 1 and 2, in 2016 and 2019 for stock 3, and 2016 and 2019 for stock 4 by SixAreaFourStockMove (Fig. 5). EMs with three stocks all placed this event in 2016 for the U.S. West Coast and British Columbia, and 2015 for Alaska (with a secondary pulse in 2018 or 2019, Fig. 5). In the OM, the largest recruitment event occurred during 2016 for stock 1, in 2017 for stocks 2 and 3, with no large recruitment event in stock 4. Under SixAreaFourStockMove, recruitment deviations were negative for the entire projection period for stock 1 and near zero for stock 2. Estimates of the recruitment deviations from the single-area EM were nearly flat and slightly negative for the entire projection period, with no large recruitment event in the late 2010s and very little variability among simulations (Fig. 5).

3.3. Management strategy performance

The highest overall scaled score in terms of biological (conservation) metrics was achieved by Single Area (panmictic es-

Fig. 4. Mean relative error in biomass (left column) and depletion (B/B_0, right column) from five management strategies (colors) by management area (rows) during the projection period. Only management strategies that included spatial dynamics and the status quo harvest control rule (HCR) are shown. The solid line is the median, the darker shaded area represents the 25th to 75th quantile, and the lighter shaded area represents the 5th and 95th quantiles for 100 replicates. For the panmictic stock (yellow values), errors are calculated against the sum of OM biomass values for all spatial areas. Time series of estimated quantities indicate the estimates for each year based on the assessment conducted in that year.



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timation model) for all stocks (Table 3; Supplementary Table SA.2). For both stocks within Alaska (stocks 3 and 4), the empirical harvest strategy (Empirical Harvest Control Rule) achieved the same total score for the biological PMs as ThreeAreaThreeStockMove, tying for second place. There is greater variation in biological performance among strategies for more southerly stocks (e.g., stocks 1 and 2, Fig. 2), where total biological scores varied by up to 60% (Table 3), than northerly stocks, with total scores ranging by only 16% (Table 3). SixAreaFourStockMove was the lowest- or second-lowest performing strategy for biological metrics for all stocks.

The highest overall scaled score in terms of harvest (catch) metrics was achieved by the panmictic strategy (Single Area) for British Columbia, by the empirical HCR (Empirical Harvest Control Rule) for the U.S. West Coast and by SixAreaFourStockMove for Alaska (Table 4; Supplementary Table SA.3). SixAreaFourStockMove had a nearly-equivalent total score as SixAreaThreeStockMove for catch metrics in Alaska. The mean catch strategy (Mean Catches 2000–2019) was the second best performing for U.S. West Coast in terms of catch metrics (Table 4). Single Area was the lowest-performing strategy for catch metrics for Alaska, while ThreeAreaThreeStockMove was the lowest-performing for British Columbia and the U.S. West Coast (Table 4).

Median depletion for stocks 3 and 4 were at or larger than 40% in at least 50% of simulations, for all MS except SixAreaFourStockMove and SixAreaThreeStockMove (Table 3). Mean length during the first 10 projection years varied by 2 cm at most within stocks among MS (Supplementary Fig. SA.5). No strategies resulted in a median stock status in any year across all replicates for stocks 3 or 4 below the overfished threshold (Fig. 6; Table 3). Stock 1 was overfished for 64% of SixAreaFourStockMove simulations (Table 3; Fig. 6). The probability that the stock was above $B_{40\%}$ during the projection period was the most variable biological performance metric, both within stocks and among strategies (Table 3). The

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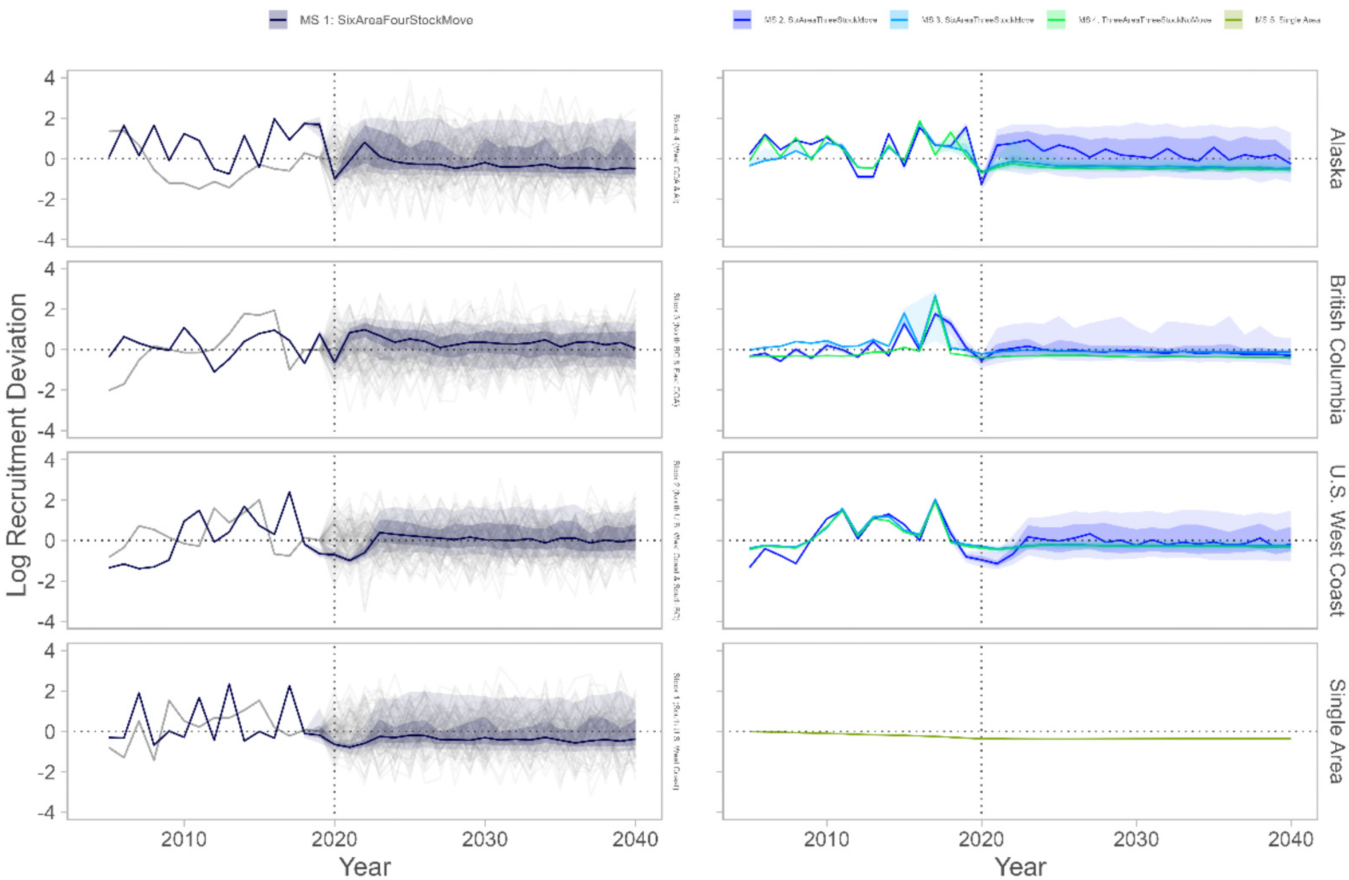
Fig. 5. Estimated 2005–2040 recruitment deviations by stock for the five estimation methods (EMs), based on the assessment conducted in that year; historical values are from the 2020 EM (i.e., left of the vertical dotted line). SixAreaFourStockMove (left column) has the same four stocks as the operating model (OM); historical OM recruitment deviations are shown as gray points, with vertical gray bars indicating the 5th and 95th simulation interval. All other EMs (right column) assume biological stocks coincide with management areas (EMs 2–4) or that there is single panmictic stock (Single Area). The solid line is the median, the darker shaded area represents the 25th to 75th quantile, and the lighter shaded area represents the 5th and 95th quantiles for 100 replicates.



populations in stocks 1 and 2 were never above $B_{40\%}$ under SixAreaFourStockMove, Empirical Harvest Control Rule, nor Mean Catches 2000–2019 (Table 3; Fig. 6).

In all regions, the strategies that scored highest overall on economic metrics were distinguished by high catches, low annual average variability in catch, and many years with average annual variation (AAV) in catch below the 15% threshold identified by stakeholders (Table 4; Supplementary Fig. SA.5). The spatially structured strategies did not result in positive catch trends for British Columbia, and only SixAreaThreeStockMove resulted in a positive catch trend for the U.S. West Coast; all spatially structured strategies resulted in a positive catch trend for Alaska (Table 4; Supplementary Fig. SA.5). All strategies resulted in catches above the historical minima in at least 50% of projection years (Table 4), although Single Area had periods of very low catch during the early portion of the projection period (Supplementary Fig. SA.5). SixAreaFourStockMove had the second-lowest AAV (10%) of the strategies based on an EM for Alaska, and the second-highest catches overall (360 kt, Table 4; Supplementary Fig. SA.5). The strategy with the highest total Alaskan catches (SixAreaThreeStockMove) had a higher overall AAV (13%) and AAV was below 15% in only two-thirds of the projection years (Table 4). SixAreaFourStockMove and SixAreaThreeStockMove had nearly equivalent overall scores for catch metrics in Alaska (Table 4). The best-performing strategy for British Columbia in terms of catch (Single Area) had low AAV during the projection period (7%, Table 4) and AAV fell below the 15% threshold in 74% of projection years (Table 4). Single Area dominated the mean catch strategy for British Columbia because the catch levels were higher. The Empirical Harvest Control Rule outperformed all other strategies for the U.S. West Coast, though the total catch was identical to the mean catch strategy and about 10% lower than under SixAreaFourStockMove (Table 4).

The strategy most similar to the current management paradigm (ThreeAreaThreeStockNoMove) was among the top three performers in terms of biological metrics for all stocks, resulting in biomass levels above $_{40\%}$ in at least three-fourths of simulations for all stocks (Table 3). This strategy resulted in the lowest or second-lowest catches for the U.S. West Coast in the first and last 5 years of the projection period (6–

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Table 3. Median (across replicates) raw scores for the biological performance metrics (columns) for the seven management strategies (rows) and four stocks (panels).

Stock	Management strategy	$P(B>0.40B_0)$	$P(B>0.25B_0)$	Mean Length (cm)	Total (scaled)
Stock 4 (West GOA & AI)	MS 7: Mean Catch 2000-2019	0.81	0.90	56.71	2.87
	MS 6: Empirical HCR	0.81	0.90	56.79	2.88
	MS 5: Single Area	0.86	0.90	57.72	2.95
	MS 4: ThreeAreaThreeStockNoMove	0.76	0.90	56.62	2.82
	MS 3: ThreeAreaThreeStockMove	0.81	0.90	56.79	2.88
	MS 2: SixAreaThreeStockMove	0.38	0.90	56.41	2.37
	MS 1: SixAreaFourStockMove	0.48	0.90	56.53	2.48
Stock 3 (North BC & East GOA)	MS 7: Mean Catch 2000-2019	0.86	1.00	49.06	2.82
	MS 6: Empirical HCR	0.90	1.00	49.18	2.88
	MS 5: Single Area	0.90	1.00	49.96	2.89
	MS 4: ThreeAreaThreeStockNoMove	0.86	1.00	49.10	2.82
	MS 3: ThreeAreaThreeStockMove	0.90	1.00	49.17	2.88
	MS 2: SixAreaThreeStockMove	0.62	1.00	48.95	2.56
	MS 1: SixAreaFourStockMove	0.57	1.00	48.87	2.50
Stock 2 (S. B. C. & N. U.S. West Coast)	MS 7: Mean Catch 2000-2019	0.00	1.00	42.19	1.89
	MS 6: Empirical HCR	0.00	1.00	42.33	1.89
	MS 5: Single Area	0.86	1.00	43.75	2.92
	MS 4: ThreeAreaThreeStockNoMove	0.81	1.00	43.47	2.86
	MS 3: ThreeAreaThreeStockMove	0.76	1.00	43.22	2.80
	MS 2: SixAreaThreeStockMove	0.60	1.00	43.10	2.60
	MS 1: SixAreaFourStockMove	0.00	0.62	41.22	1.48
Stock 1 (South U.S. West Coast)	MS 7: Mean Catch 2000-2019	0.00	0.86	34.07	1.71
	MS 6: Empirical HCR	0.00	0.93	34.14	1.78
	MS 5: Single Area	0.81	1.00	35.40	2.88
	MS 4: ThreeAreaThreeStockNoMove	0.81	1.00	35.22	2.88
	MS 3: ThreeAreaThreeStockMove	0.76	1.00	34.79	2.81
	MS 2: SixAreaThreeStockMove	0.43	1.00	34.76	2.40
	MS 1: SixAreaFourStockMove	0.00	0.36	33.10	1.18

Notes: The rightmost column indicates the total of the scaled median scores. Color intensity corresponds to the ranking of each management strategy within each management region, where darker green is the best performing, and lighter green is the worst performing.

11 kt, Table 4) and overall (36 kt, Table 4; Supplementary Fig. SA.5). Catches under ThreeAreaThreeStockNoMove were in the middle of the range for Alaska (330 kt overall) with similar AAV to SixAreaFourStockMove (10%, Table 4; Supplementary Fig. SA.5). Total catches under ThreeAreaThreeStockNoMove were 37 kt for British Columbia, roughly at the middle of the range among strategies (32 kt under ThreeAreaThreeStockMove to 81 kt under Single Area). This strategy performed second best in terms of economic metrics out of the five EM-based strategies for British Columbia (Table 4).

4. Discussion

4.1. Summary

The benefit of spatial EMs is nuanced and varies whether management performance is measured at the stock or management unit level. The simple delay–difference modeling approach can capture the general population trajectory and fit the data, presenting a promising, simple way to incorporate spatial structure that could be applied within or across management regions. The EMs evaluated here represent a gradient of spatial complexity, ranging from the hypothesized demographic structure of the sablefish population to full panmixia. The HCRs include the true model-based rules currently used in each region and model-free rules that use either empirical observations (survey data) or the mean catches for recent years. Empirical harvest control rules are of interest when considering spatial misspecification as they bypass the challenge of deriving reference points from spatially explicit models. The results illustrate the trade-offs between assuming, simplifying, or ignoring spatial structure in a management context and how these trade-offs might vary by management region.

In relative and absolute terms, the differences among MS are far less pronounced for Alaska and the Alaskan stocks than for the U.S. West Coast and stocks therein (Tables 3 and 4). This is likely a result of the interaction between movement paradigms, the specification of stock structure and how the management-region-specific HCRs respond to changes in stock structure and size (discussed below). Findings suggest that Alaska may obtain better catch outcomes under MS that consider connectivity between areas than those that do not, or those that do not use an EM, though the difference in near-

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Table 4. Median raw scores (across replicates) for the economic performance metrics (columns) for the seven management strategies (rows) and three management regions (panels).

	Catch in first 5 proj. yrs	Catch in last 5 proj. yrs	Total Catch, all proj. yrs	AAV in Catch	P(AAV < 15%)	P(Catch Trend is positive)	P(C>Historical Min)>50%	Total Score (Scaled)	Region
MS 7: Mean Catch 2000-2019	70,000	70,000	280,000	0.00	1.00	0.00	1.00	4.42	Alaska
MS 6: Empirical HCR	67,000	64,000	260,000	0.02	1.00	0.00	1.00	4.29	Alaska
MS 5: Single Area	8,300	30,000	96,000	0.07	0.74	1.00	1.00	4.06	Alaska
MS 4: ThreeAreaThreeStockNoMove	71,000	88,000	330,000	0.10	0.79	1.00	1.00	5.29	Alaska
MS 3: ThreeAreaThreeStockMove	66,000	85,000	320,000	0.13	0.68	1.00	1.00	5.06	Alaska
MS 2: SixAreaThreeStockMove	88,000	97,000	380,000	0.13	0.66	1.00	1.00	5.38	Alaska
MS 1: SixAreaFourStockMove	84,000	90,000	360,000	0.10	0.79	1.00	1.00	5.43	Alaska
MS 7: Mean Catch 2000-2019	14,000	14,000	57,000	0.00	1.00	0.00	1.00	5.16	British Columbia
MS 6: Empirical HCR	11,000	11,000	44,000	0.05	1.00	1.00	1.00	5.55	British Columbia
MS 5: Single Area	2,700	27,000	81,000	0.07	0.74	1.00	1.00	5.61	British Columbia
MS 4: ThreeAreaThreeStockNoMove	9,400	9,200	37,000	0.05	0.95	0.00	1.00	4.26	British Columbia
MS 3: ThreeAreaThreeStockMove	7,700	8,000	32,000	0.11	0.79	0.00	1.00	3.71	British Columbia
MS 2: SixAreaThreeStockMove	6,900	8,900	34,000	0.08	0.84	0.00	1.00	3.82	British Columbia
MS 1: SixAreaFourStockMove	8,700	8,400	35,000	0.04	1.00	0.00	1.00	4.20	British Columbia
MS 7: Mean Catch 2000-2019	27,000	27,000	110,000	0.00	1.00	0.00	1.00	4.48	U.S. West Coast
MS 6: Empirical HCR	25,000	27,000	110,000	0.04	1.00	1.00	1.00	5.36	U.S. West Coast
MS 5: Single Area	1,500	19,000	54,000	0.09	0.68	0.00	1.00	3.13	U.S. West Coast
MS 4: ThreeAreaThreeStockNoMove	6,600	11,000	36,000	0.10	0.79	0.00	1.00	3.11	U.S. West Coast
MS 3: ThreeAreaThreeStockMove	11,000	15,000	53,000	0.36	0.34	0.00	1.00	2.50	U.S. West Coast
MS 2: SixAreaThreeStockMove	13,000	23,000	81,000	0.21	0.42	1.00	1.00	4.12	U.S. West Coast
MS 1: SixAreaFourStockMove	39,000	25,000	120,000	0.24	0.42	0.00	1.00	3.81	U.S. West Coast

Notes: Scores have been rounded to two significant digits. The rightmost column indicates the total of the scaled median scores. Color intensity corresponds to the ranking of each management strategy within each management region, where darker green is the best performing, and lighter green is the worst performing (for example, higher raw values of average annual variability are lighter in color).

term catch across strategies is less than 10%. The U.S. West Coast has the largest range in catches and resultant depletion across strategies (Fig. 6 and Supplementary Fig. SA.6). Crucially, southerly stocks encompassing this management region are the only stocks for which biomass was never above 40% of unfished biomass (with median depletion as low as 21% for the southern U.S. West Coast under the four-stock strategy, Fig. 6; Table 3), an important threshold for fishery management in that region. This may indicate a higher-than-acceptable probability of impairment for this region, and the U.S. West Coast must carefully consider the interaction between movement rates, stock structure, and the allocation of catches south of 36°N to avoid localized depletion.

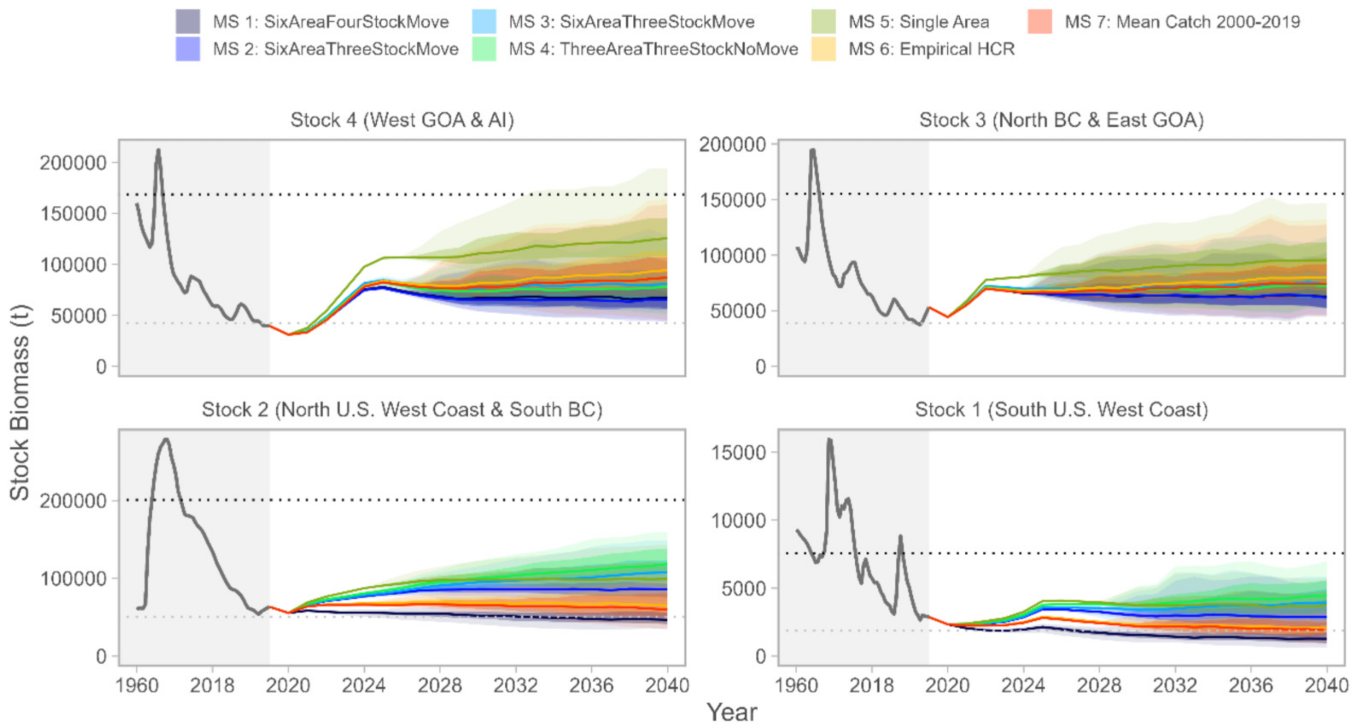
4.2. What drives differences in management performance across regions?

The results indicate trade-offs between economic and conservation performance, with more pronounced discrepancies among MS in the southern regions. Additionally, several EM-based MS involve a mismatch between the scale of the conservation unit (stocks) and the management paradigm (three political areas); such incoherence has been shown to lead to undesirable outcomes, particularly when demographic parameters vary among modeled areas (Berger et al. 2020). The sensitivity of southerly regions to the spatial misspecification in MS corroborates warnings from simulation studies that such mismatches can mask localized depletion of small stock units (Bosley et al. 2019; Okamoto et al. 2020).

Economic and biological outcomes do not vary greatly among strategies in Alaska (aside from the *Panmixia* strategy), with total catches ranging from 260 to 380 kt (Table 4; Supplementary Fig. SA.5), and median depletion in the two northern stocks from 45% to 58% (Fig. 3). This effect is compounded by the fact that estimated biomass in Alaska is similar across MS (Fig. 4), although estimation uncertainty is higher in the spatially structured models than the single-area model, as expected (Punt 2019*a*). The consistency in estimated stock biomass is attributable to high mixing rates within the Alaskan spatial areas, while emigration to British Columbia amounts to 4% or less of Alaskan biomass (Fig. 2*e*). This means that the movement paradigms examined here do not lead to large differences in the estimated stock biomass for Alaska among strategies. Future research should investigate movement rates, potentially using tag-integrated assessment models, to confirm whether emigration across the Alaska–Canada border is indeed low and assess how estimation of these rates might impact management performance; such efforts are underway in Alaska (D. Goethel (Alaska Fisheries Science Center, *personal communication* 2023).

Conservation and economic objectives were met in British Columbia by several MS, with strategies SixAreaThreeStockMove, ThreeAreaThreeStockNoMove, and EmpiricalHCR leading to positive outcomes for both performance categories for this region (Tables 3 and 4). Two mechanisms likely contribute to the apparent insensitivity of British Columbia populations to the spatial structure of the management

Fig. 6. Operating model trajectories of stock biomass for four biological stocks (panels) for seven management strategies (colors), which are combinations of estimation methods (EMs) and harvest control rules (HCRs). The *x* axis is condensed during the historical period (1960–2019, gray rectangle). The solid line is the median, the darker shaded area is the 50% simulation interval, and the lighter shaded area is the 90% simulation interval. The horizontal dotted lines indicate the unfished biomass (black) and 25% of unfished biomass (gray).



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strategy used: firstly, the target harvest rate used in British Columbia is set to 5.5%, lower than what the MSY-based target harvest rate would be for this region given the demographic values used in this study (18%, Supplementary Table SA.4). This results in a narrow range of catches under the first four MS (Supplementary Fig. SA.6), all below the EM-free strategies, leading to less-depleted populations (Fig. 6). Secondly, OM movement rates assume British Columbia to be highly dependent on biomass subsidies from other management areas, whereby ∼26% of Canadian biomass is a result of immigration on an annual basis (Figs. 2*e* and 2*f*). Simulation work has indicated that recruitment estimates for smaller stocks (such as British Columbia) are sensitive to mixing with larger stocks (Cadrin et al. 2019).

Estimated recruitment deviations for British Columbia were negative for most of the projection period for SixAreaThreeStockMove, ThreeAreaThreeStockMove, and ThreeAreaThreeStockNoMove, where British Columbia is treated as an independent stock; when assumed to belong to two shared stocks (SixAreaFourStockMove), estimated recruitment deviations applicable to British Columbia are positive for the entirety of the projection period (Fig. 5). This is consistent with the observation that under the movement and recruitment paradigm specified in the OM and SixAreaFourStockMove, the British Columbia population exports recruits and/or biomass to adjacent areas, as evidenced by the posterior estimates for the ratio of recruits that settle in each spatial area, τ Supplemetary Fig. SA.7). Revisions to the movement–density dependence paradigm, particularly were they to suggest that British Columbia is less connected to other stocks, might lead to less-desirable depletion outcomes (as in the southern part of the US, discussed below). Managers in British Columbia might not need to consider the feasibility of moving toward a spatially structured EM, considering that it appears that outcomes are fairly consistent regardless of the movement paradigm used (given the range of movement rates explored here) and the considerable overhead involved in constructing a spatial model. The authors anticipate application of the transboundary OM to investigate bio-economic topics that may be of interest to this region, and be more sensitive to spatial dynamics.

The U.S. West Coast and stocks therein exhibit much more variation in economic and biological performance among MS than other areas. This is likely the result of the movement–recruitment paradigm used within the EMs, and how the HCR applied in this region is sensitive to spatial misspecification in the management model. For stocks 1 and 2, SixAreaFourStockMove leads to much higher total catches (130 kt vs. 110 kt or less for the other strategies, Table 4; Supplementary Fig. SA.5) at the expense of much lower depletion in stock 1 (24% median across all projection years for all simulations, Fig. 6). This exemplifies the well-documented concern from simulation work (e.g., Goethel and Berger 2016) that even when the EM faithfully matches the spatial structure of the population, an HCR that aggregates biomass across biological boundaries

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can still produce undesirable management outcomes; this is particularly pronounced when such HCRs are biomass-based. Had the U.S. West Coast instead implemented the Alaskan SPR-based HCR, target harvest rates would have been lower overall (11% vs. 14% under SixAreaFourStockMove) and would have changed less dramatically among strategies (Supplementary Table SA.4), potentially avoiding the "overfished" outcomes for stocks 1 and 2 under SixAreaFourStockMove. However, recent examinations of Atlantic groundfish indicate that unintended overfishing driven by misperceptions of stock status might be more influential to overall management strategy performance than the control rule used (Mazur et al. 2023).

The undesirable biological outcomes under SixAreaFourStockMove for stocks off the U.S. West Coast illustrate several important considerations for the impact of spatial dynamics on management outcomes. The EM used in SixAreaFourStockMove starts with large positive bias for stock biomass in 2020 (Fig. 4), corresponding to the high estimate of the 2016/17 recruitment event also captured in the regional assessment (Fig. 5, Kapur et al. 2021*b*). The estimated biomass quickly declines, as does the MRE in depletion, to near-zero, where it remains for the first half of the projection period (Fig. 4). Around 2030, the MRE in biomass becomes more positive for this strategy, even though estimated biomass has decreased slightly (Fig. 4), suggesting that the EM has failed to accurately perceive a decline in biomass in this region, likely due to the absence of age-composition data since the "missing fish" are not selected by the survey (at 8 years) given the projection period used here.

The OM and SixAreaFourStockMove has six connected subareas nested within four independent "stocks" (Fig. 2). Two of these stocks are each comprised of a single sub-area, one of which (the area south of 36°N on the U.S. West Coast, "C1") receives no immigration from northerly regions (Fig. 2*e*). The survey estimates of biomass for C1 are of similar magnitude to those for British Columbia, about 25% of the total for the U.S. West Coast region, and do not exhibit similar trends to the northerly population (remaining mostly flat as northern stocks increase and decrease, Supplementary Fig. SB.2). These ecological characteristics render the area south of 36°N a strong candidate for localized depletion due to its small size and unidirectional movement northward (Fig. 2*e*, Ying et al. 2011; McGarvey et al. 2017).

Empirical analyses have suggested that the area south of Monterey Bay (36.6°N) exhibits different sablefish recruitment dynamics from the northern area (Tolimieri et al. 2018); the recruitment paradigm in the northern region appears to be strongly linked to sea-level height (Tolimieri and Haltuch 2023). This is represented by the near-zero correlation in recruitment deviations between these two areas (Supplementary Fig. SB.13). In the OM, 80% of estimated recruitment and 90% of mature biomass off the U.S. West Coast comes from the area north of 36°N, consistent with the posterior estimates of τ (Supplementary Fig. SA.7) and relative survey biomasses (Supplementary Fig. SA.2) for this region. Indeed, the biomass decline in the OM is pronounced in this southern area (Supplementary Fig. SB.6). A slight decline in estimated biomass is evident for the U.S. West Coast during the last 3 years of the projection period when the southern US is treated as an independent stock (Supplementary Fig. SA.3). Given that the HCR acts at the management level (even though assessments are conducted at the stock level), managers must consider the risks of missing undesirable population trends at small spatial scales inherent in using simplified EMs (e.g., Okamoto et al. 2020). Future work could explore alternative TAC-setting and/or apportionment procedures that consider local dynamics, given that this analysis provides information on survey biomass in each area that could be considered in catch allocation.

4.3. Limitations and future work

Results should be considered given several limitations of the study design; these are discussed below and in greater detail in Supplementary Material A.

The variety of data used when conditioning the OM led to compromises in how well the OM fitted to individual data sources: it fails to fit the terminal year survey observations for Alaska and British Columbia (Supplementary Fig. SB.15), which are much larger than those for the preceding years, although it does estimate an increase in observed biomass during the early projection period (Supplementary Fig. SA.2). This pre-determines that the EMs (which fit all survey observations) anticipate higher biomasses than the OM during the early years of the projection period. This should not be a factor in relative management strategy performance because this effect (better fits to survey data) was consistent across all EMs. The delay–difference approach is computationally faster than a statistical catch-at-age model, and is also able to fit all survey data from all regions even in the presence of complex spatial structure (SixAreaFourStockMove), whereas the OM could not reconcile the high-terminal survey observations in Alaska and British Columbia with compositional and discard data, and was computationally intractable to implement as an estimator. Future work could explore methods to incorporate age structure within the estimation framework.

An important next step for this work would be to synthesize the drivers of recruitment dynamics for the sablefish population coast-wide to (i) confirm or modify the structural assumptions present in the OM, and (ii) allow for exploration of how oceanic conditions might lead to changes in the recruitment paradigm for sablefish, and effects on management performance. This analysis could inform the development of additional OMs that explore the interaction of climate change and spatial uncertainty for high-value species such as sablefish. Potential climate linkages, particularly between sablefish recruitment dynamics and sea surface temperature (Tolimieri and Haltuch 2023), form a promising avenue for which this tool could be informative. Future phases of this work could also integrate economic models to investigate PMs such as fishery profits, or allocation questions, both of interest to stakeholders (Kapur et al. 2021*a*). Finally, the MSE can be used as a tool to explore additional hypotheses about the ecological and bioeconomic implications of transboundary sablefish management.

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5. Conclusions

Introducing spatial structure into the data collection, assessment, and management process is an immense undertaking for any fishery. Transboundary stocks present the additional challenge of formal, political barriers to constructing a mathematical representation of fish populations throughout their range (Palacios-Abrantes et al. 2020). This study presents an MSE for a valuable groundfish in the Northeast Pacific and finds that spatial models of intermediate structural complexity, including those that match the current assessment and management paradigm in terms of having three modeled areas, can satisfy stakeholder objectives, and avoid negative outcomes for the sablefish fishery. Management strategies that include movement between regions allow for better economic outcomes for the U.S. West Coast and Alaska, with trade-offs in catch variability. Accounting for mixing with adjacent regions does not result in large differences in management performance for British Columbia, given the range of movement rates explored here. A strategy where the three management regions are treated as separate, unconnected stocks—the closest to the current approach—did not rank highest for any region, but does not result in catastrophic outcomes for any performance metric. The mismatch in the spatial scale of the HCRs and the conservation units poses a crucial risk of "cryptic" or localized depletion in isolated stocks in the southern U.S. West Coast.

The motivation for this work, and others like it, lies in the observation that population demography varies greatly throughout a stock's range (Berger et al. 2020), and it is the specification of demography (including the structure of stock units and movement among them) that most heavily influences the relative performance of each management strategy. Though this work implements many of the best practices in spatial modeling for design (Punt 2019 and Punt 2023) and specification of the operating models and EMs, it is clear the mixing rates and the location and structure of density-dependence (recruitment) remain crucial uncertainties for evaluating the population status of long-lived, highly mobile species such as sablefish. This study presents one of the first transboundary, spatially explicit MSEs conditioned to data. These results highlight the importance of spatial MSEs to understand the consequences of regional management conducted in isolation. Future work should incorporate additional spatial hypotheses and investigate the drivers of recruitment patterns range-wide. These findings underscore the influence of movement rates on management performance (Goethel et al. 2011) and suggest that allowing for simultaneous estimation of movement (via the construction of tag-integrated models, perhaps on the scale of management regions) would be worthwhile for confirming the magnitude of movement effects, particularly for Alaska and British Columbia.

Acknowledgements

The authors thank D. Goethel and K. Johnson for thoughtful reviews of an early manuscript. We also acknowledge the helpful feedback received from fishery stakeholders, scientists, managers, and non-governmental organization staff at the April 2021 Transboundary Sablefish Management Strategy Evaluation workshop.

Article information

History dates

Received: 9 January 2024
Accepted: 29 February 2024
Accepted manuscript online: 12 March 2024
Version of record online: 4 June 2024

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Data availability

Code to conduct the analyses presented here is available at github.com/mkapur/sab-mse. Some datasets, such as catch records, are subject to confidentiality agreements and will be made available upon request.

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Competing interests

The authors declare there are no competing interests.

Funding information

MSK and AEP were [partially] funded by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative agreement No. NA15OAR4320063, Contribution No. 2019-1030. MSK was partially funded by Sea Grant project number R/E/I-33.

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Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/cjfas-2024-0008.

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