Received: 7 March 2019 | Revised: 15 August 2019 | Accepted: 29 August 2019
DOI: 10.1111/faf.12409

ORIGINAL ARTICLE

FISH and FISHERIES WILEY

Attending to spatial social–ecological sensitivities to improve trade-off analysis in natural resource management

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Funding information
Pew Charitable Trusts; David and Lucile Packard Foundation; Florida State University

Abstract

Balancing trade-offs amongst social–ecological objectives is a central aim of natural resource management. However, objectives and resources often have spatial dimensions, which are usually ignored in trade-off analyses. We examine how simultaneously integrating social–ecological benefits and their spatial complexities can improve trade-off analysis. We use Pacific herring (*Clupea pallasii*, Clupeidae)—an ecologically important forage fish with social, cultural and economic value to communities and commercial fisheries—as a case study. By combining spatial management strategy evaluation with social benefits analysis, we illustrate when policies aimed at aggregate stocks versus spatially segregated substocks of fish fail to balance trade-offs amongst social–ecological objectives. Spatial measures (e.g. area-based closures) may achieve some objectives but produce alternative trade-offs that are sensitive to assumptions about fish population dynamics and social complexities. Our analyses identify policies that are inefficient (e.g. yielding economic costs without producing social or ecological gains), highlight management strategies that generate trade-offs and indicate when costs are distributed unequally for different user groups. We also point to strategies with outcomes that are robust to spatial uncertainties and reveal research priorities by identifying which performance metrics exhibit sensitivity to spatial ecological assumptions. Collectively, our analyses demonstrate how incorporating social objectives and spatial dynamics into management strategy evaluation can reveal trade-offs and the implications of management decisions.

KEYWORDS

fisheries, management strategy evaluation, metapopulations, social–ecological systems, spatial planning, trade-offs

1 | INTRODUCTION

Natural resource management has historically been driven by a one-dimensional notion of sustainability that is rooted in the ecological concept that the ability of a population to withstand harvest is equal to its growth rate. This perspective of sustainability neglects diverse economic, social–cultural and ecological objectives (i.e. the "triple bottom line"—Elkington, 1994; Mangel et al., 1996). Simply obtaining maximum sustainable yield (MSY) or its derivatives will not maximize the economic value of fisheries (Hilborn et al., 2015), nor does it attend to ecological or social and cultural objectives (Marshall & Levin, 2017). Moreover, adjusting harvest rates (Pikitch et al., 2012), altering thresholds at which fisheries are closed (Pikitch et al., 2012), or imposing explicit spatial regulations (Edgar et al., 2014) to achieve MSY can lead to trade-offs, inefficiencies or inequalities amongst ecological, social–cultural and economic objectives (Halpern et al., 2013; Voss et al., 2014).

Trade-offs occur when gains in one objective lead to losses for another objective. Strategies are inefficient when an alternative strategy can make improvements in one or more objectives without commensurate costs to other objectives, and inequalities occur when benefits or costs are not equally distributed amongst individuals or sectors. Numerous approaches for trade-off analysis have been developed and applied for optimization in conservation and management (e.g. Hoekstra, 2012; Mangel & Dowling, 2016; Nelson et al., 2009; Watts et al., 2009); however, quantifying trade-offs, inefficiencies and inequities amongst multiple objectives in social–ecological systems can be difficult because dynamics that control outcomes are often non-commensurate (Daw et al., 2015; but see Mangel & Dowling, 2016), poorly understood or spatially heterogeneous (Ban et al., 2013; Brown et al., 2001; Epstein et al., 2018; Halpern, White, Lester, Costello, & Gaines, 2011; Pomeroy & Douvere, 2008).

Many fish populations exhibit spatial structure, as do the food webs and fishing communities that rely on them (Martin & Hall-Arber, 2008; Sanchirico & Wilen, 2005). Thus, benefits of fish to ecosystems (including humans) are often spatially structured and asymmetric amongst user groups. While spatial dynamics likely affect management outcomes (Dowling, Hall, & McGarvey, 2004; Pomeroy & Douvere, 2008; Wright, Christensen, Régnier, Rindorf, & Deurs, 2019), many trade-off analyses ignore space because of logistical and knowledge constraints (Koehn, Reineman, & Kittinger, 2013). For example, quantifying and forecasting fish movement is notoriously difficult (Payne et al., 2010; Waples, 1998). Trade-off analyses also often omit social or cultural (e.g. community cohesion) dimensions owing to their complexity and limited information (Chan et al., 2012; Pascoe et al., 2014; Plagányi et al., 2013). Recent work in fisheries has begun integrating space or social–ecological benefits into trade-off analysis (Daw et al., 2015; Dowling et al., 2004; Halpern et al., 2011; Lester et al., 2013; Mangel & Dowling, 2016; Pascoe et al., 2019; Plagányi et al., 2013; Plagányi, Skewes, Murphy, Pascual, & Fischer, 2015; Punt, MacCall, et al., 2016b). Far fewer studies directly address the intersection of how management strategies affect resources in space and time and how those outcomes affect diverse, spatially explicit social–ecological benefits.

Pacific herring (*Clupea pallasii*, Clupeidae) present a case study of how spatial dynamics can underlie conflict in the form of disputes over management practices (Levin, Francis, & Taylor, 2016). In British Columbia (BC) and Alaska, herring are valued by commercial fleets (Cleary, Hawkshaw, Grinnell, & Grandin, 2018), indigenous peoples (Brown & Brown, 2009; Jones, Rigg, & Pinkerton, 2017; McKechnie et al., 2014; Thornton & Kitka, 2015) and predators (Surma, Pakhomov, & Pitcher, 2018a; Surma, Pitcher, et al., 2018b). Indigenous harvest of herring and herring roe provides cultural, spiritual, nutritional and local economic benefits (Jones et al., 2017; Thornton & Kitka, 2015) and traces back thousands of years (McKechnie et al., 2014). Non-indigenous commercial fishing in BC began largely in the 1930s, collapsed from intense overfishing and weak year-classes in the 1960s (Hourston & Haegele, 1980) and recovered sufficiently to reopen at more conservative harvest levels (Cleary et al., 2018). Recent events catalysed efforts to rethink herring management (Brown & Brown, 2009; Cleary, Cox, & Schweigert, 2010; Jones et al., 2017; Kronlund, Forrest, Cleary, & Grinnell, 2018; von der Porten, Lepofsky, McGregor, & Silver, 2016); namely, periods of low productivity and biomass in the 2000s for three of the major BC stocks (Cleary et al., 2018), followed by partial recoveries and reopening of fisheries in one of these stocks.

Discordant perceptions about stock dynamics and management approaches have arisen in part from collapse of important spawning areas at substock scales and differential spatial access to the resource for indigenous versus industrial commercial fishers (Brown & Brown, 2009; Cleary et al., 2010; Levin et al., 2016; von der Porten et al., 2016). Indigenous fishers are often constrained to fishing in traditional areas and have called for finer scale spatial management and spatial closures (Admin Alaska. Code., 2019; Thornton & Kitka, 2015). In contrast, mobile commercial fishers may care more about regional-scale abundance for maintaining stable livelihoods. As a result, evaluation of alternative management options requires an understanding of how benefits to indigenous communities, commercial fishers and ecosystems arise from interactions between management strategies and spatial dynamics of herring and people.

We illustrate how trade-off analysis can improve conservation policy by considering spatially explicit resource dynamics and social–ecological benefits informed by a diverse group of fishery participants. Specifically, we explore how variation in Pacific herring (a) commercial harvest rates, (b) fishery closure thresholds and (c) spatial closures affect trade-offs amongst ecological, social–cultural and economic objectives. For simplicity, we focus on integrating spatial and social–cultural considerations, but acknowledge that a diversity of other factors are important (i.e. predators and market dynamics.). We explore the value of integrating spatial dynamics and social–cultural information, rather than provide explicit management advice. Our approach is flexible and generalizable to other resource contexts.

2 | METHODS

We conducted numerical experiments on Pacific herring fisheries within a closed-loop management strategy evaluation framework (MSE—Bunnefeld, Hoshino, & Milner-Gulland, 2011; Punt, Butterworth, Moor, Oliveira, & Haddon, 2016a) to examine how management strategies affect the triple bottom line. Our models are inspired by the social–ecological system in Haida Gwaii, BC. Following standard practice in this region (Department of Fisheries & Oceans, 2015b), we use a harvest control rule for herring that includes a target harvest rate, a lower biomass threshold for fishery closures and quota tapering to zero as biomass nears the threshold (Figure S1). To evaluate trade-offs amongst social–ecological objectives of alternative management strategies, we examine four combinations of target harvest rates, three biomass thresholds and two spatial closures. Additionally, we evaluate the impacts of various assumptions about spatial dynamics in herring populations.

2.1 | MSE framework

Our MSE framework includes: (a) a simulated management strategy to regulate the commercial fishing fleet, (b) an operating model describing herring population dynamics, the commercial fishing fleet and simulated scientific data on the fish populations and (c) a non-spatial statistical catch-at-age stock assessment model. Using these three elements in a feedback loop, we simulate alternatives under various biological assumptions. The Appendix S1 and Tables S1-S3 provide a full description of the model equations and parameter values.

The herring operating model is age-structured, with six spatially segregated spawning locations, emulates life history of herring and incorporates uncertainties about spatial dynamics of the fish and fleet (Figure 1, see Appendix S1 for more details). For generality, the model is simplified compared to empirical fisheries in a variety of ways. Simplifications include an assessment model with information not normally available (e.g. known mortality) and ignoring potentially important biological non-linearities (e.g. predator-prey interactions and Allee effects.). We use a baseline 20% stochastic

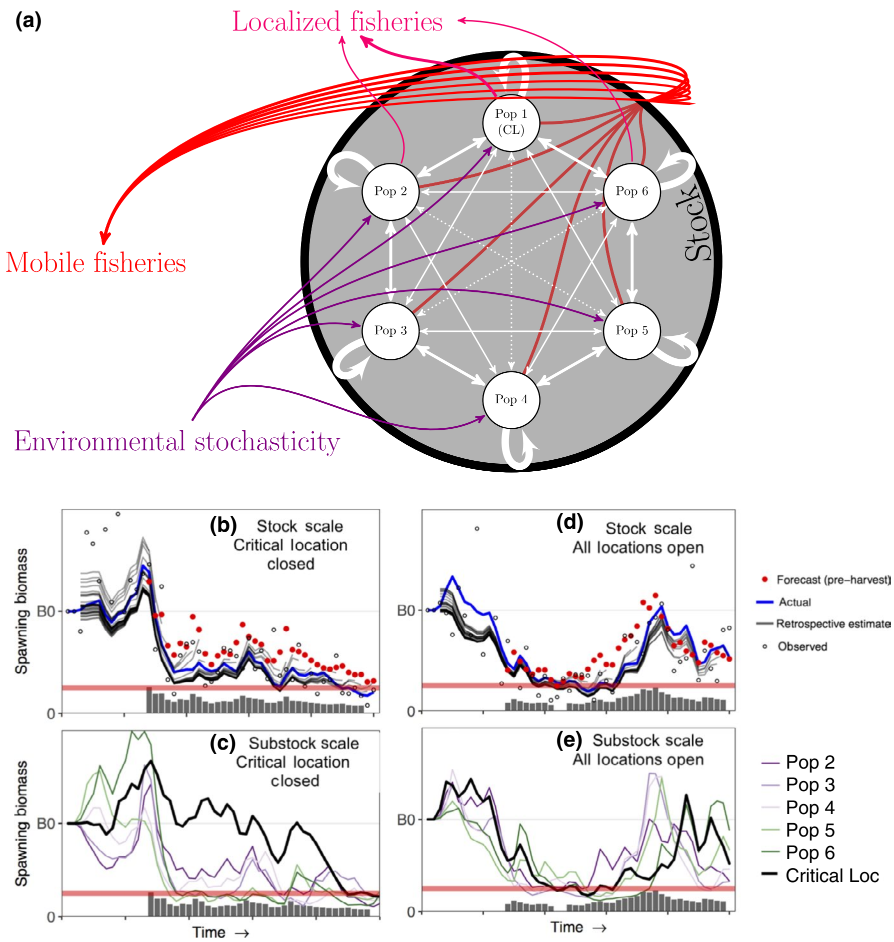

FIGURE 1 (a) Hypothetical herring fisheries and example simulations. Heuristic layout of subpopulations, migration amongst subpopulations, extraction from available subpopulations by mobile fisheries and extraction from a subset of three subpopulations by localized (indigenous) fisheries, including a critical traditional use spawning location (CL). Example simulations with 20% adult and juvenile migration under 20% target harvest rate and a 25% B_0 threshold at the stock-scale (b and c—sum of biomass across all spawning subpopulations) or at the subpopulation scale (d and e—biomass from individual spawning subpopulations). b and d) Dark blue line the sum of post-harvest spawning biomass across all spawning subpopulations; Thin black lines—individual stock assessment estimates for post-harvest spawning biomass for each year; Red points—forecast spawning biomass prior to harvest; Grey bars—catch summed across all spawning subpopulations; Horizontal pink line—true 25% B_0 closure threshold (B_0 is estimated in each year, but annual estimates are not shown for simplicity). (c and e) Thick black line— biomass at the spawning subpopulations designated as the CL which is either closed (c) or open to non-traditional use commercial harvest (e); individual coloured lines—biomass at other spawning subpopulations. Example simulation runs are shown for illustrative purposes. For comparison in performance amongst management strategies see Figures 2–4 and Appendix S1. Results shown are for a base case of 20% adult and juvenile diffusive migration

migration rate (for results with 1%, and 70% migration or density dependent migratory behaviour of MacCall et al. (2018), see Appendix S1). The non-spatial aspects of the fish population dynamics model (growth, mortality, productivity) are tuned to estimated properties (Department of Fisheries & Oceans, 2015b). We make simple assumptions about migration rates, migratory behaviour and productivity and conduct sensitivity analyses by varying fish migratory dynamics and spatial productivity amongst scenarios.

2.2 | Triple bottom line objectives and performance metrics

Simulation outputs are evaluated using nine performance metrics (Table 1) to represent standard fisheries metrics, ecological considerations and human well-being associated with harvest (Appendix, Table S3). Fisheries metrics include average herring roe yield from the commercial fishery and proportion of years the fishery is open and catch stability. We estimate catch stability as the inverse of the average annual variation in catch, which is the mean of the absolute value of first differences in catch divided by the mean catch. Ecological metrics include the proportion of total spawning biomass comprised of older (age 4+) fish, biomass depletion and the probability of falling below 20% of unfished biomass. We present outcomes for three important human well-being metrics out of nine that were created through social benefits surveys (see below). We selected these three for simplicity and in part because of outcome redundancy. Metrics are scaled from 0 to 1 for the sake of comparison, with higher values representing a more positive outcome for that metric. Scaling

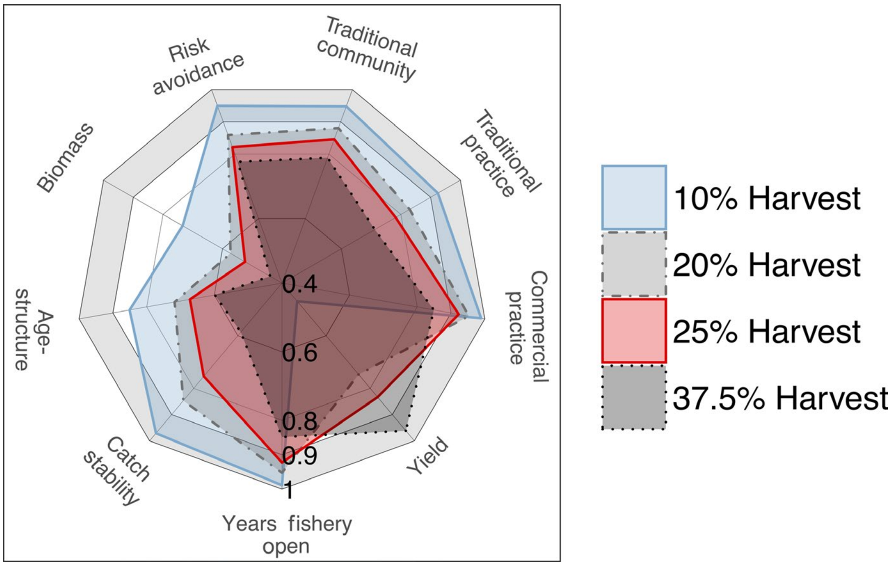

FIGURE 2 Comparison outcomes for the three target harvest rates for a base case of 20% adult and juvenile diffusive migration and a 30% lower closure threshold. Full results, including for different migration scenarios and closure thresholds, are shown in Table S1. Axes show standardized forms of performance metrics (scored 0–1—where 1 is the theoretical or observed maximum benefit) with polygons connecting individual management scenarios. Trade-offs occur when management choices lead to increases in one or more performance metrics with commensurate decreases in others; inefficiencies occur when scenarios decrease one or more performance metrics without commensurate increases in other. Clockwise from the bottom: yield (for the commercial for fishery) is scaled to the maximum across all simulations. Years fishery open is the proportion of years the fishery is open. Catch stability is the inverse of average annual variation in catch, divided by the maximum of the inverse. Age-structure is the ratio of the biomass of age 4+ fish in the population to total biomass. Biomass is the mean proportion of total spawning biomass relative to B_0. Risk avoidance is the mean of 1 minus the risk of collapse (<20% B_0) at across spawning subpopulations. Social benefits metrics are naturally scaled from 0 to 1. Note the axis ranges from 0.4 to 1 to illustrate the range of observed responses

factors are either a) the theoretical maximum when one exists (e.g. yield is scaled to maximum sustainable yield, MSY) or b) scaled to the observed maximum across all scenarios.

2.3 | Social benefits surveys

The impacts of Pacific herring management on the social objectives are explored by linking model outputs to social benefits potentially accrued by herring user groups. We explore benefits to: (a) indigenous harvesters who practise a culturally important traditional harvest for food, social and ceremonial use of herring roe on kelp or tree branches (known as *k'aaw*, in Haida) and (b) mobile commercial seine or gillnet fishers who target pre-spawning aggregations of adult herring in major stock areas. Evaluating the distribution of social benefits across these two groups enables analysis of social differentiation and equity.

The social benefits used in the present analysis were identified through extensive traditional knowledge studies in Haida Gwaii (Haida Marine Traditional Knowledge Participants et al., 2011; MP unpublished data; Jones, 2005), producing a more comprehensive typology of herring-associated social and cultural benefits. We identified a subset of these benefits for use in our case study: (a) ability for the commercial fleet to practise harvest, (b) ability for the indigenous Haida to practise harvest and (c) indigenous Haida community and social relationships (Appendix, Table S3). This subset of social benefits was selected through a consensus process by an expert cross-disciplinary working group (the Ocean Modelling Forum Pacific Herring working group, oceanmodelingforum.org/working-groups/pacific-herring/). Criteria used in selecting these social benefits include: universal applicability to each sector/group, relevance to management objectives (Council of the Haida Nation, & Her Majesty the Queen in Right of Canada, 2018; Marine Planning Partnership Initiative, 2015), and bundled and derivative co-benefits such that accrual of one benefit includes additional services (e.g. ability to practise the harvest is interconnected with transmission of fishing knowledge and maintaining cultural identity—Klain, Satterfield, & Chan, 2014). For details, equations and parameter values see Appendix S1.

2.4 | Management strategies

2.4.1 | Harvest rates

Target harvest rates used in the simulations include 10%, 20%, 25% and 37.5% (corresponding to 20%, 40%, 50% and 75% of the theoretical equilibrium F_{MSY}—fishing rate that produces maximum sustainable yield—given the operating model). The latter two rates are recommended for forage fish when there is relatively high knowledge about population dynamics, status and trends, and dependent predators (Pikitch et al., 2012), and the former two are implemented for BC herring stocks (DFO, 2015a). Harvest rates are applied to

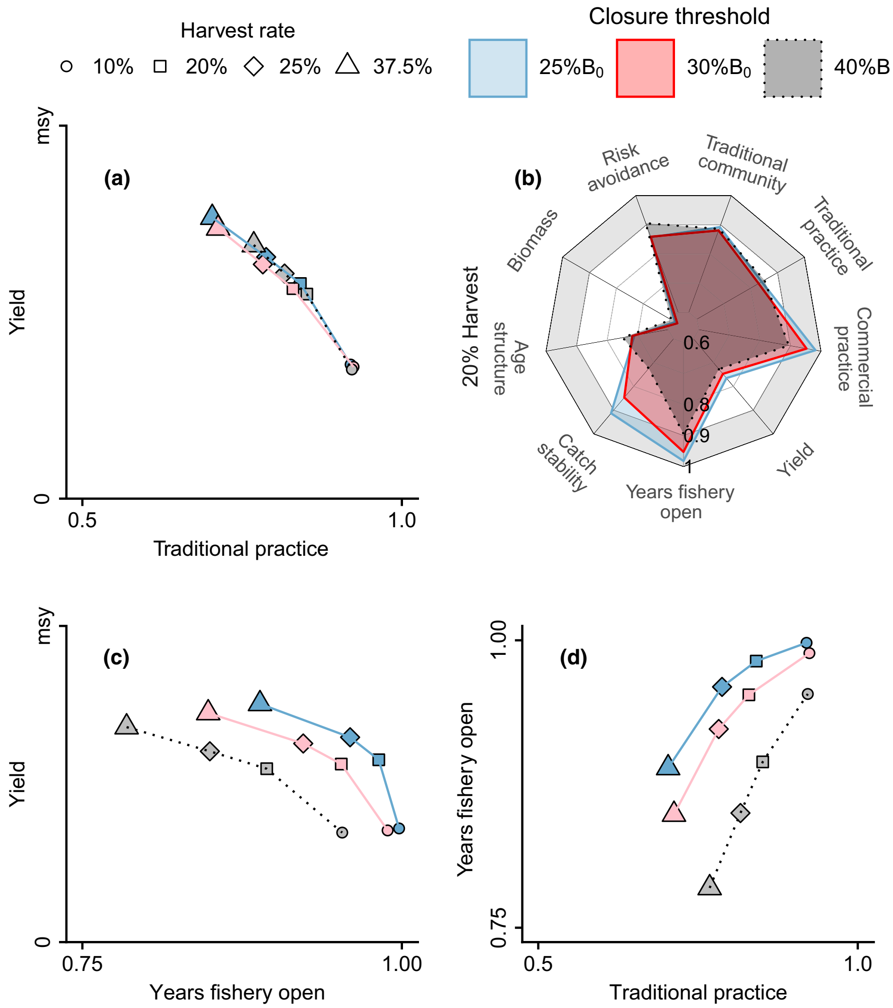

FIGURE 3 Comparison of performance metrics for the three lower closure thresholds. Axes show standardized forms of performance metrics (scored 0–1—where 1 is the theoretical or observed maximum benefit) with polygons connecting individual management scenarios. (a) Effect of thresholds (different colours and lines) and harvest rate (different shapes) on the trade-off between yield (for the commercial roe fishery) and traditional practice. (b) Outcomes for the suite of performance metrics for the three closure thresholds at a 20% harvest rate. (c) Effect of thresholds (different colours and lines) and harvest rate (different shapes) on the trade-off between (b) yield (for the commercial roe fishery) and catch stability (years the fishery is open). (d) Effect of thresholds and harvest rate on the bivariate outcome of catch stability and traditional practice. For each bivariate comparison, the inefficient outcomes are those with a reduction in one axis without change in the other (i.e. thresholds are inefficient for circles and squares in (c) because they create a cost to fishery openings without a benefit to traditional practice or yield). Full results, including for different migration scenarios and target harvest rates, are shown in Appendix S1. Note the axis in (a) ranges from 0.4 to 1 to illustrate the range of observed responses and responses are either naturally scaled 0–1 or scaled by their maximum across all simulations. Results shown are for a base case of 20% adult and juvenile diffusive migration

biomass forecasts using a stock assessment model (i.e. effectively no "in season" adjustments of the quota).

2.4.2 | Thresholds

The three lower limit thresholds for fishery closure used in the simulations (all based on estimated "unfished biomass",$\hat{B}_0$) are 25% $\hat{B}_0$ (DFO, 2015a), 30% $\hat{B}_0$ (Pikitch et al., 2012) and 40% $\hat{B}_0$ (recommended by Pikitch et al., 2012). In line with current practices for herring, these strategies close the fishery when biomass is forecasted to be below a proportion of $\hat{B}_0$. Thus, the decision to open the fishery requires an estimate for $\hat{B}_0$ in each year and a forecast given the results of a statistical catch-at-age stock assessment model. Specific mathematical details are given in Appendix S1.

2.4.3 | Spatial closures

We simulated a commercial harvest closure on a single spawning location of high value for cultural and traditional use by indigenous groups (hereafter, "critical location"). In these closure simulations, the total fishery quota is either (a) the same quota as without spatial closures but only extracted from the open locations or (b) reduced by the proportion of pre-harvest biomass observed in the critical location in the prior year.

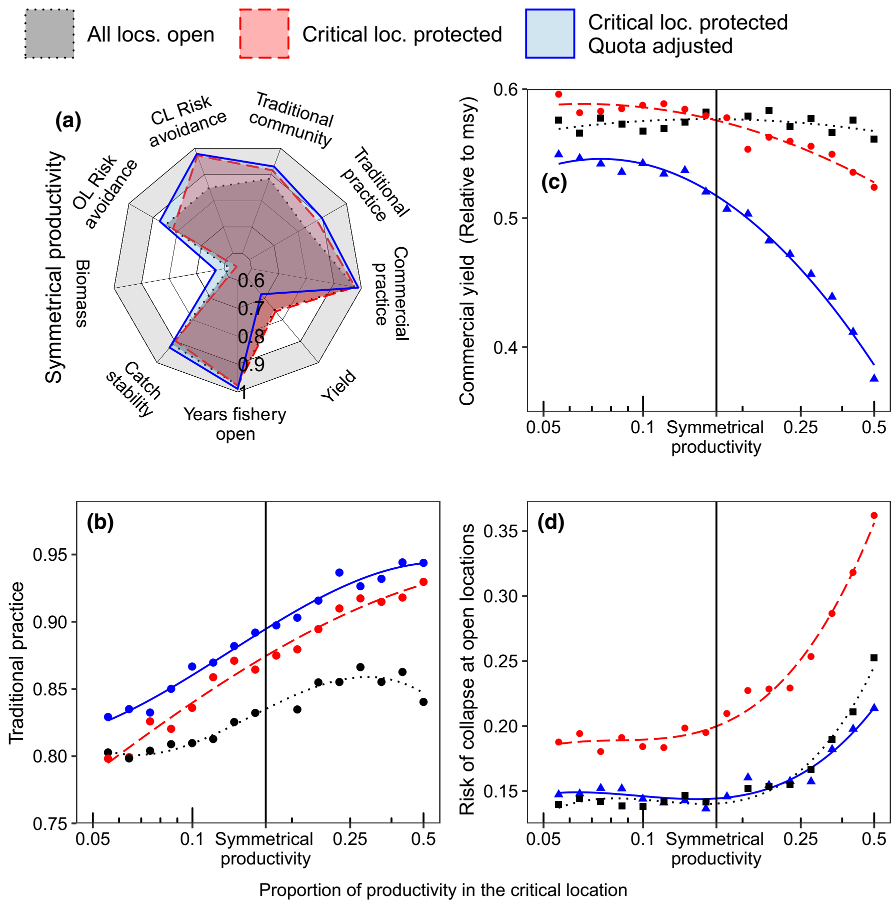

FIGURE 4 Comparison of performance metrics for the spatial management scenarios at a 20% (~40% F_{MSY}) target harvest for (a) all performance metrics with no spatial asymmetry in fish productivity and (b-c) sensitivity of select performance metrics to assumptions about critical location productivity (source [high] to sink [low]). Black dotted lines—all sites are open; red dashed lines–the critical site is closed but the harvest quota is not adjusted; blue solid lines—the critical site is closed and the harvest quota is adjusted for the spawning biomass in the closed area in the prior year, crossed with different spatial productivity and recruitment behaviour. Note the axis in (a) ranges from 0.5 to 1 to illustrate the range of observed responses and responses are either naturally scaled 0–1 or scaled by their maximum across all simulations. In contrast, the axis in (c) is relative to MSY. OL and CL risk avoidance in (a) represent 1 minus the risk of collapse at the open locations or the critical location. Results shown are for a base case of 20% adult and juvenile diffusive migration. See Appendix Figure S2 for results with different migration rates and Figure S3 for results with non-linear recruitment behaviour

3 | RESULTS

3.1 | Target harvest rates

Varying harvest rates generally led to a trade-off between commercial yield and all other metrics. While yields increased with harvest rate, these came at the cost of other economic, social and ecological benefits (Figure 2). The most conservative harvest rate (10%) resulted in high scores for all metrics except commercial yield, which was reduced by 37%, 44% and 54% compared with harvest rates of 20%, 25% and 37.5%, respectively (Figure 2). Migration rates and closure thresholds did not change the rank order of results. Importantly, the status quo harvest rate (20%) is well below the theoretical equilibrium F_{MSY} value from the operating model but still has noteworthy impacts on traditional practice (~10 unit decline from the 10% harvest rule) and commercial catch stability (~12 unit decline from the 10% harvest rule). The trade-off between yield and traditional practice was consistent regardless of the closure threshold (Figure 3a).

3.2 | Thresholds

Elevating thresholds for fishery closures reduced commercial sector benefits without providing substantial increases in indigenous social benefits. For a given harvest rate, elevating fishery closure thresholds above the status quo created inefficient management strategies. Specifically, higher thresholds (for a given harvest rate) increased the frequency of closures (Figure 3b,c) and slightly reduced average commercial yield (Figure 3b,d), but did not increase traditional practice benefits (Figure 3). For example, with a harvest rate of 20%, elevating closure thresholds from 25% to 40% of B_0 increased closure frequency more than fivefold without meaningful benefits to ecological or traditional user group performance metrics (Figure 3b). Moreover, setting both target harvest rates and closure

TABLE 1 Performance metrics in the MSE

Metric	Type	Description	Normalization Factor
Yield	Economic	Average herring roe catch in tonnes per year	MSY ~ 5.5 (×1,000 tonnes)
Years fishery open	Economic	Frequency of years herring roe fishery is open	1
Catch stability	Economic	Inverse of the average annual variation in herring roe catch (aav)	min aav = 0.16
Age truncation	Ecological	Average ratio of biomass of age 4+ herring to total spawning biomass	1
Depletion	Ecological	Average ratio of herring biomass to "virgin biomass"	1
Local risk avoidance	Ecological	Average frequency of years location-specific herring spawning biomass is above 20% location-specific virgin biomass.	1
Traditional practice	Social	Ability of indigenous fishers to participate in the traditional herring roe on kelp fishery	1
Commercial practice	Social	Ability of commercial seine/gillnet fishers to participate in the herring roe fishery	1
Traditional community	Social	Indigenous community social relationship benefits associated with herring	1

Note: Normalization factors are the maxima used to scale values to a maximum of 1 (see Appendix S1 for definitions).

thresholds at high levels (target harvest >20% and threshold ≥25% B_0) exacerbated these inefficiencies by creating more frequent closures, lower stability of the commercial harvest and reductions in traditional fishing benefits (Figure 3b,d).

Increases in ecological and social metrics under scenarios of higher closure thresholds were not discernable except with higher harvest rates (i.e. 37.5%—Figure 3b–d). Even in these cases, improvements in social benefits such as traditional user groups' ability to practise the fishery, while measureable, were small and still left these metrics well below values attained with other strategies (Figure 3b); moreover, those marginal improvements came at the expense of reduced catch stability and yields (Figure 3c,d). In contrast, elevating closure thresholds at lower harvest levels did not guarantee persistent access to spawn in places that matter for indigenous fishers. At a 20% harvest rate for example, all closure thresholds yielded >10% risk of collapse (Figure 3b). Assumptions about adult migration altered the magnitude of effects of higher closure thresholds. Increased migration rates with higher closure thresholds produced greater ecological and social benefits but still resulted in reduced catch stability and yield (Appendix—Figure S2).

3.3 | Spatial closures

Spatial closures resulted in a trade-off amongst commercial yield, traditional users' ability to practise and the risk of collapse at open locations (Figure 4a). A spatial closure improved traditional users' practice (Figure 4a,b) and community social relationship benefits (Figure 4a). These benefits came at the cost of either (a) higher risk of collapse at remaining open sites when quotas were not adjusted for the biomass isolated in the closure area or (b) a reduction in quota and average commercial yield when quotas were adjusted (Figure 4a).

The nature and magnitude of these trade-offs were dictated in part by (a) whether the closed area was a source or sink of fish productivity (Figure 4b–d) and (b) and whether recruits were attracted to spawning areas with higher biomass of older fish (Appendix Figure S3). Closing an unproductive critical location (a sink population) to commercial fishing without adjusting quotas (Figure 4b–d, blue vs. red lines) increased the risk of collapse at fished sites without providing substantial social benefit, and imposed costs to commercial yield. This occurred because increased fishing on source populations reduced overall productivity. However, adjusting the quota (Figure 4b–d, black vs. blue lines) reduced yield while also reducing risk of collapse and increasing social benefits. As the critical location became more productive, the tripartite trade-off between ecological risk, commercial yield and traditional practice was exacerbated.

4 | DISCUSSION

By integrating spatial social–cultural and ecological metrics into management strategy evaluation, we show how policies that seem optimal at one scale can be ineffective in achieving triple bottom line objectives over multiple scales. In doing so, we show how such an approach can identify key trade-offs and management scenarios that minimize inequalities. As a result, such analyses highlight inefficiencies, ineffectiveness or key sensitivities in the context of ecosystem-based management.

In many natural resource settings, non-spatial management policies are used with the hope that they will achieve a particular spatial objective (Halpern et al., 2011). When we considered non-spatial management alternatives (target harvest rates and biomass thresholds), they were generally inefficient or produced direct trade-offs. For example, only the lowest rate of commercial harvest used here maximized traditional practice and community social benefits and minimized risk of stock collapse at local scales. Yet, this harvest rate dramatically reduced commercial yield.

Policies that rely on the logic of "a rising tide lifts all boats" can cost the commercial fleet substantially without the guarantee of social benefits to place-based harvesters. Higher closure thresholds can generate more frequent commercial fishery closures, lower yields and decreased economic stability, while still allowing localized collapses that negatively affect traditional place-based users and ecosystems. Thus, when the resource is spatially structured, simply altering harvest rates and closure thresholds has potential to lead to inequitable and/or inefficient outcomes.

Spatial closures, on the other hand, lead to an alternative set of trade-offs. Implementing commercial spatial closures without adjusting quotas can yield ecological and economic costs without substantial social benefits. This occurred in our simulations because fishing in connected populations, despite spatial closures, can still have similar negative impacts on closed areas. The magnitude of such trade-offs, as with non-spatial policies, depends on fish behaviour and dynamics. Commercial spatial closures will not always ensure sustained traditional harvest practices or improved conservation outcomes. In BC, indigenous groups traditionally travel to several locations depending on spawn timing and weather (Appendix, Table S3); however, not all traditional users can travel to distant sites, unlike commercial roe herring fishers. Therefore, spatial closures may provide a useful tool, but benefits depend on harvest rates, status of individual populations and user access to productive populations.

This study illustrates how considering social benefits can inform trade-off analyses, especially those with spatial dimension. While most management strategy evaluations ignore social metrics in their trade-off analysis, social impacts are associated with most resource management decisions. When such impacts are not explicitly considered, concerns about transparency can mount and inequitable outcomes, such as uneven distribution of rights, control, use and access, become more likely (Bennett, Govan, & Satterfield, 2015). Moreover, trade-offs may not be inherently equal. For example, Canada legally categorizes priority amongst objectives—with conservation first (Department of Fisheries & Oceans, 2006), followed by access for Indigenous food, social, and ceremonial fisheries and finally by commercial fisheries (R. v. Sparrow, 2006). By including social metrics in trade-off analysis, decision-makers can assess which approaches are expected to meet ecosystem-based fisheries management objectives (Halpern et al., 2013; Levin et al., 2018; Poe, Norman, & Levin, 2014). Our study pays particular attention to social equity by disaggregating user groups (commercial and traditional indigenous harvesters) and illustrates the distribution of benefits under different spatial management policies.

We simplified analyses for generality and did not thoroughly examine an important trade-off for the commercial spawn on kelp fishery (which generally only harvests eggs, typically harvests lower biomass and is spatially restricted) and the industrial commercial roe fisheries (which are mobile, generally harvest more biomass and are lethal to adults; Shelton, Samhouri, Stier, & Levin, 2014). We also avoid broader ecosystem trade-offs, given the technical challenges associated with estimating dynamic interactions for pelagic forage fish (Hilborn et al., 2017; Pikitch et al., 2018). Moving forward, research aimed at empirically quantifying spatial dynamics of metapopulations, how they are affected by fishing, climate and interact with other ecosystem components such as predators (Cury et al., 2011) will be critical in weighing the trade-offs imposed by various policy alternatives.

While our specific results arise from models mimicking a spatially complex and ecologically important pelagic fish species, the approach taken here is generalizable. A vast number of resource systems are characterized by properties that may benefit from an approach such as ours. For instance, tropical forest ecosystems, coral reefs and rivers with multiple tributaries are all systems that exhibit structural uncertainty, spatial complexity and the simultaneous utilization by disparate groups who reap benefits ranging from economic, subsistence, social, cultural and/or ecological.

5 | CONCLUSIONS

We demonstrate how integrating spatial fish dynamics and spatial social benefits into management strategy evaluation can quantify trade-offs amongst social–ecological objective. No single policy maximizes all objectives in our hypothetical herring fishery, and some policies are inefficient because they lead to losses without benefiting the objective(s) they were designed to address. However, there is promise for balancing economic, ecological and social objectives by considering spatial dynamics in complex social–ecological systems. For herring fisheries, the extent of trade-offs depends on how well research informs and management addresses the dynamics of fish in space because place-based indigenous fishers, commercial fleets and species that rely on herring all operate with spatial constraints. Thus, we show how considering diverse spatial conditions and objectives can reveal key trade-offs between economic, social and ecological objectives and highlight pathways to improve conservation and management.

ACKNOWLEDGEMENTS

The Packard Foundation, through its Ocean Modelling Forum and The Pew Charitable Trusts (Ocean Science Division, Pew Forage Fish Conservation Initiative) provided funding for DKO, TF, AP and PL. A First Year Assistant Professor Grant from FSU provided funding for DKO. We thank two reviewers as well as LE Peavey Reeves and

S Pau for helpful comments that improved the quality and clarity of the manuscript. AK Salomon and M Hessing-Lewis provided valuable input that shaped the direction of this work.

DATA AVAILABILITY STATEMENT

Source code for the model is available from https://github.com/dkokamoto.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Okamoto DK, Poe MR, Francis TB, et al. Attending to spatial social–ecological sensitivities to improve trade-off analysis in natural resource management. *Fish Fish*. 2019;00:1–12. https://doi.org/10.1111/faf.12409