social and cultural

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9   **Title:** Attending to spatial social-ecological sensitivities to improve trade-off analysis in natural

10   resource management

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45   **Running Title:** Spatial social-ecological trade-offs

Abstract:

47   Balancing trade-offs among social-ecological objectives is a central aim of natural resource

48   management.   However, objectives and resources often have spatial dimensions, which are

49   usually ignored in trade-off analyses. We examine how simultaneously integrating social-

50   ecological benefits and their spatial complexities can improve trade-off analysis. We use Pacific

51   herring (*Clupea pallasii,* Clupeidae) —an ecologically important forage fish with social, cultural

52   and economic value to communities and commercial fisheries—as a case study. By combining

53   spatial management strategy evaluation with social benefits analysis, we illustrate when policies

54   aimed at aggregate stocks versus spatially segregated substocks of fish fail to balance trade-offs

55   among social-ecological objectives. Spatial measures (e.g., area-based closures) may achieve

56 some objectives but produce alternative trade-offs that are sensitive to assumptions about fish
57 population dynamics and social complexities. Our analyses identify policies that are inefficient
58 (e.g., yielding economic costs without producing social or ecological gains), highlight
59 management strategies that generate trade-offs and indicate when costs are distributed unequally
60 for different user groups. We also point to strategies with outcomes that are robust to spatial
61 uncertainties and reveal research priorities by identifying which performance metrics exhibit
62 sensitivity to spatial ecological assumptions. Collectively, our analyses demonstrate how
63 incorporating social objectives and spatial dynamics into management strategy evaluation can
64 reveal trade-offs and the implications of management decisions.

65 **Keywords**: fisheries, management strategy evaluation, metapopulations, social-ecological
66 systems, spatial planning, trade-offs

67 **Table of contents**

Introduction

86

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

98   Trade-offs occur when gains in one objective lead to losses for another objective. Strategies
99   are inefficient when an alternative strategy can make improvements in one or more objectives
100   without commensurate costs to other objectives, and inequalities occur when benefits or costs are
101   not equally distributed among individuals or sectors.   Numerous approaches for trade-off
102   analysis have been developed and applied for optimization in conservation and management (e.g.
103   Hoekstra, 2012; Mangel & Dowling, 2016; Nelson et al., 2009; Watts et al., 2009); however,
104   quantifying trade-offs, inefficiencies, and inequities among multiple objectives in social-
105   ecological systems can be difficult because dynamics that control outcomes are often non-
106   commensurate (Daw et al., 2015; but see Mangel & Dowling, 2016), poorly understood, or
107   spatially heterogeneous (Ban et al., 2013; Brown et al., 2001; Epstein et al., 2018; Halpern et al.,
108   2011; Pomeroy & Douvere, 2008).

109   Many fish populations exhibit spatial structure, as do the food webs and fishing communities
110   that rely on them (Martin & Hall-Arber, 2008; Sanchirico & Wilen, 2005). Thus, benefits of fish
111   to ecosystems (including humans) are often spatially structured and asymmetric among user
112   groups. While spatial dynamics likely affect management outcomes (Dowling et al., 2004;
113   Pomeroy & Douvere, 2008; Wright et al., 2019), many trade-off analyses ignore space because
114   of logistical and knowledge constraints (Koehn et al., 2013). For example, quantifying and
115   forecasting fish movement is notoriously difficult (Payne et al., 2010; Waples, 1998). Trade-off

116   analyses also often omit social or cultural (e.g., community cohesion) dimensions owing to their

117   complexity and limited information (Chan et al., 2012; Pascoe et al., 2014; Plagányi et al., 2013).

118   Recent work in fisheries has begun integrating space or social-ecological benefits into trade-off

119   analysis (Daw et al., 2015; Dowling et al., 2004; Halpern et al., 2011; Lester et al., 2013; Mangel

120   & Dowling, 2016; Pascoe et al., 2019; Plagányi et al., 2015; Plagányi et al., 2013; Punt et al.,

121   2016b). Far fewer studies directly address the intersection of how management strategies affect

122   resources in space and time and how those outcomes affect diverse, spatially explicit social-

123   ecological benefits.

124   Pacific herring (*Clupea pallasii,* Clupeidae) present a case study of how spatial dynamics

125   can underlie conflict in the form of disputes over management practices (Levin et al., 2016). In

126   British Columbia (BC) and Alaska, herring are valued by commercial fleets (Cleary et al., 2018),

127   indigenous peoples (Brown & Brown, 2009; Jones et al., 2017; McKechnie et al., 2014;

128   Thornton & Kitka, 2015) and predators (Surma et al., 2018a; Surma et al., 2018b). Indigenous

129   harvest of herring and herring roe provides cultural, spiritual, nutritional, and local economic

130   benefits (Jones et al., 2017; Thornton & Kitka, 2015) and traces back thousands of years

131   (McKechnie et al., 2014). Non-indigenous commercial fishing in BC began largely in the 1930s,

132   collapsed from intense overfishing and weak year-classes in the 1960s (Hourston, 1980), and

133   recovered sufficiently to re-open at more conservative harvest levels (Cleary et al., 2018). Recent

134   events catalyzed efforts to rethink herring management (Brown & Brown, 2009; Cleary et al.,

135   2010; Jones et al., 2017; Kronlund et al., 2018; von der Porten et al., 2016); namely, periods of

136   low productivity and biomass in the 2000s for three of the major BC stocks (Cleary et al. 2018),

137   followed by partial recoveries and reopening of fisheries in one of these stocks.

138   Discordant perceptions about stock dynamics and management approaches have arisen in

139   part from collapse of important spawning areas at sub-stock scales, and differential spatial access

140   to the resource for indigenous versus industrial commercial fishers (Brown & Brown, 2009;

141   Cleary et al., 2010; Levin et al., 2016; von der Porten et al., 2016). Indigenous fishers are often

142   constrained to fishing in traditional areas and have called for finer scale spatial management and

143   spatial closures (Alaska Admin. Code, 2019; Thornton & Kitka, 2015). In contrast, mobile

144   commercial fishers may care more about regional-scale abundance for maintaining stable

145   livelihoods. As a result, evaluation of alternative management options requires an understanding

146 of how benefits to indigenous communities, commercial fishers and ecosystems arise from
147 interactions between management strategies and spatial dynamics of herring and people.

148   We illustrate how trade-off analysis can improve conservation policy by considering spatially
149 explicit resource dynamics and social-ecological benefits informed by a diverse group of fishery
150 participants. Specifically, we explore how variation in Pacific herring (1) commercial harvest
151 rates, (2) fishery closure thresholds, and (3) spatial closures affect trade-offs among ecological,
152 social-cultural and economic objectives. For simplicity, we focus on integrating spatial and
153 social-cultural considerations, but acknowledge that a diversity of other factors are important
154 (i.e. predators, market dynamics, etc.). We explore the value of integrating spatial dynamics and
155 social-cultural information, rather than provide explicit management advice. Our approach is
156 flexible and generalizable to other resource contexts.

157 **Methods**

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

168 *MSE framework*

169   Our MSE framework includes: 1) a simulated management strategy to regulate the
170 commercial fishing fleet, 2) an operating model describing herring population dynamics, the
171 commercial fishing fleet and simulated scientific data on the fish populations, and 3) a non-
172 spatial statistical catch-at-age stock assessment model. Using these three elements in a feedback
173 loop, we simulate alternatives under various biological assumptions. The appendix and tables S1-
174 S3 provide a full description of the model equations and parameter values.

175   The herring operating model is age-structured, with six spatially-segregated spawning
176   locations, emulates life history of herring and incorporates uncertainties about spatial dynamics
177   of the fish and fleet (Figure 1, see Appendix for more details).   For generality, the model is
178   simplified compared to empirical fisheries in a variety of ways.   Simplifications include an
179   assessment model with information not normally available (e.g. known mortality) and ignoring
180   potentially important biological nonlinearities (e.g. predator-prey interactions, Allee effects,
181   etc.).   We use a baseline 20% stochastic migration rate (for results with 1%, and 70% migration
182   or density dependent migratory behavior of MacCall et al.   (2018), see Appendix). The non-
183   spatial aspects of the fish population dynamics model (growth, mortality, productivity) are tuned
184   to estimated properties (Department of Fisheries and Oceans, 2015b).   We make simple
185   assumptions about migration rates, migratory behavior and productivity, and conduct sensitivity
186   analyses by varying fish migratory dynamics and spatial productivity among scenarios.

187   *Triple-bottom-line objectives and performance metrics*

188   Simulation outputs are evaluated using nine performance metrics (Table 1) to represent
189   standard fisheries metrics, ecological considerations, and human well-being associated with
190   harvest (Appendix, Table S3). Fisheries metrics include average herring roe yield from the
191   commercial fishery, proportion of years the fishery is open and catch stability.   We estimate
192   catch stability as the inverse of the average annual variation in catch, which is the mean of the
193   absolute value of first differences in catch divided by the mean catch. Ecological metrics include
194   the proportion of total spawning biomass comprised of older (age 4+) fish, biomass depletion,
195   and the probability of falling below 20% of unfished biomass. We present outcomes for three
196   important human well-being metrics out of nine that were created through social benefits surveys
197   (see below). We selected these three for simplicity and in part because of outcome redundancy.
198   Metrics are scaled from 0 to 1 for the sake of comparison, with higher values representing a more
199   positive outcome for that metric. Scaling factors are either a) the theoretical maximum when one
200   exists (e.g. yield is scaled to Maximum Sustainable Yield, MSY) or b) scaled to the observed
201   maximum across all scenarios.

202   *Social benefits surveys*

203   The impacts of Pacific herring management on the social objectives are explored by linking
204   model outputs to social benefits potentially accrued by herring user groups. We explore benefits

205   to: (a) indigenous harvesters who practice a culturally-important traditional harvest for food,

206   social and ceremonial use of herring roe on kelp or tree branches (known as *k'aaw*, in Haida);

207   and (b) mobile commercial seine or gillnet fishers who target pre-spawning aggregations of adult

208   herring in major stock areas. Evaluating the distribution of social benefits across these two

209   groups enables analysis of social differentiation and equity.

210   The social benefits used in the present analysis were identified through extensive traditional

211   knowledge studies in Haida Gwaii (Haida Marine Traditional Knowledge Participants et al.,

212   2011; MP unpublished data; Jones, 2005), producing a more comprehensive typology of herring-

213   associated social and cultural benefits. We identified a subset of these benefits for use in our case

214   study: (a) ability for the commercial fleet to practice harvest, (b) ability for the indigenous Haida

215   to practice harvest, and (c) indigenous Haida community and social relationships (Appendix,

216   Table S3). This subset of social benefits was selected through a consensus process by an expert

217   cross-disciplinary working group (the Ocean Modeling Forum Pacific Herring working group,

218   oceanmodelingforum.org/working-groups/pacific-herring/). Criteria used in selecting these social

219   benefits include: universal applicability to each sector/group, relevance to management

220   objectives (Council of the Haida Nation & Her Majesty the Queen in Right of Canada, 2018;

221   Marine Planning Partnership Initiative, 2015), and bundled and derivative co-benefits such that

222   accrual of one benefit includes additional services (e.g., ability to practice the harvest is

223   interconnected with transmission of fishing knowledge and maintaining cultural identity, etc. -

224   Klain et al., 2014). For details, equations and parameter values see the appendix.

225   *Management Strategies*

226   *I. Harvest Rates*

227   Target harvest rates used in the simulations include 10%, 20%, 25% and 37.5%

228   (corresponding to 20%, 40%, 50%, and 75% of the theoretical equilibrium F_{MSY} - fishing rate

229   that produces maximum sustainable yield - given the operating model). The latter two rates are

230   recommended for forage fish when there is relatively high knowledge about population

231   dynamics, status and trends, and dependent predators (Pikitch et al., 2012), and the former two

232   are implemented for BC herring stocks (DFO 2015a).   Harvest rates are applied to biomass

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

234   quota).

235   *II. Thresholds*

236   The three lower limit thresholds for fishery closure used in the simulations (all based on

237   estimated "unfished biomass", $\hat{B}_0$) are 25% $\hat{B}_0$ (DFO 2015a), 30% $\hat{B}_0$ (Pikitch et al., 2012) and

238   40% $\hat{B}_0$ (recommended by Pikitch et al., 2012). In line with current practices for herring, these

239   strategies close the fishery when biomass is forecasted to be below a proportion of $\hat{B}_0$. Thus, the

240   decision to open the fishery requires an estimate for $\hat{B}_0$ in each year and a forecast given the

241   results of a statistical catch-at-age stock assessment model. Specific mathematical details are

242   given in the appendix.

243   *III. Spatial closures*

244   We simulated a commercial harvest closure on a single spawning location of high value for

245   cultural and traditional use by indigenous groups (hereafter, "critical location"). In these closure

246   simulations, the total fishery quota is either 1) the same quota as without spatial closures but only

247   extracted from the open locations, or 2) reduced by the proportion of pre-harvest biomass

248   observed in the critical location in the prior year.

249

250   **Results**

251   *I. Target Harvest Rates*

252   Varying harvest rates generally led to a trade-off between commercial yield and all other

253   metrics. While yields increased with harvest rate, these came at the cost of other economic,

254   social and ecological benefits (Figure 2). The most conservative harvest rate (10%) resulted in

255   high scores for all metrics except commercial yield, which was reduced by 37%, 44%, and 54%

256   compared to harvest rates of 20%, 25% and 37.5%, respectively (Figure 2). Migration rates and

257   closure thresholds did not change the rank order of results. Importantly, the status quo harvest

258   rate (20%) is well below the theoretical equilibrium F_{MSY} value from the operating model but

259   still has noteworthy impacts on traditional practice (~10 unit decline from the 10% harvest rule)

260   and commercial catch stability (~12 unit decline from the 10% harvest rule).   The trade-off

261   between yield and traditional practice was consistent regardless of the closure threshold (Figure

262   3a).

263   *II. Thresholds*

264   Elevating thresholds for fishery closures reduced commercial sector benefits without

265   providing substantial increases in indigenous social benefits. For a given harvest rate, elevating

266   fishery closure thresholds above the status quo created inefficient management strategies.

267   Specifically, higher thresholds (for a given harvest rate) increased the frequency of closures

268   (Figure 3b, c) and slightly reduced average commercial yield (Figure 3b, d), but did not increase

269   traditional practice benefits (Figure 3).   For example, with a harvest rate of 20%, elevating

270   closure thresholds from 25% to 40% of B_0 increased closure frequency more than 5-fold without

271   meaningful benefits to ecological or traditional user group performance metrics (Figure 3b).

272   Moreover, setting both target harvest rates and closure thresholds at high levels (target harvest

273   >20% and threshold ≥25% B_0) exacerbated these inefficiencies by creating more frequent

274   closures, lower stability of the commercial harvest, and reductions in traditional fishing benefits

275   (Figure 3b, d).

276   Increases in ecological and social metrics under scenarios of higher closure thresholds were

277   not discernable except with higher harvest rates (i.e., 37.5% – Figure 3b, c, d).   Even in these

278   cases, improvements in social benefits such as traditional user groups' ability to practice the

279   fishery, while measureable, were small and still left these metrics well below values attained

280   with other strategies (Figure 3b); moreover, those marginal improvements came at the expense of

281   reduced catch stability and yields (Figure 3c, d). In contrast, elevating closure thresholds at lower

282   harvest levels didn't guarantee persistent access to spawn in places that matter for indigenous

283   fishers. At a 20% harvest rate for example, all closure thresholds yielded >10% risk of collapse

284   (Figure 3b).   Assumptions about adult migration altered the magnitude of effects of higher

285   closure thresholds. Increased migration rates with higher closure thresholds produced greater

286   ecological and social benefits but still resulted in reduced catch stability and yield (Appendix –

287   Figure S2).

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

295   The nature and magnitude of these trade-offs were dictated in part by 1) whether the closed
296   area was a source or sink of fish productivity (Figure 4 b-d) and 2) and whether recruits were
297   attracted to spawning areas with higher biomass of older fish (Appendix Figure S3). Closing an
298   unproductive critical location (a sink population) to commercial fishing without adjusting quotas
299   (Figure 4 b-d, blue versus red lines) increased the risk of collapse at fished sites without
300   providing substantial social benefit, and imposed costs to commercial yield. This occurred
301   because increased fishing on source populations reduced overall productivity. However,
302   adjusting the quota (Figure 4 b-d, black versus blue lines) reduced yield while also reducing risk
303   of collapse and increasing social benefits. As the critical location became more productive, the
304   tripartite trade-off between ecological risk, commercial yield, and traditional practice was
305   exacerbated.

Discussion:

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

313   In many natural resource settings, non-spatial management policies are used with the hope
314   that they will achieve a particular spatial objective (Halpern et al., 2011). When we considered
315   non-spatial management alternatives (target harvest rates and biomass thresholds), they were
316   generally inefficient or produced direct trade-offs. For example, only the lowest rate of
317   commercial harvest used here maximized traditional practice and community social benefits and

318 minimized risk of stock collapse at local scales. Yet this harvest rate dramatically reduced
319 commercial yield.

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

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

338   This study illustrates how considering social benefits can inform trade-off analyses,
339 especially those with spatial dimension. While most management strategy evaluations ignore
340 social metrics in their trade-off analysis, social impacts are associated with most resource
341 management decisions. When such impacts are not explicitly considered, concerns about can
342 transparency mount, and inequitable outcomes, such as uneven distribution of rights, control, use
343 and access, become more likely (Bennett et al., 2015). Moreover, trade-offs may not be
344 inherently equal. For example, Canada legally categorizes priority amongst objectives – with
345 conservation first (Department of Fisheries and Oceans, 2006), followed by access for
346 Indigenous food, social, and ceremonial fisheries and finally by commercial fisheries (R. v.
347 Sparrow, 2006). By including social metrics in trade-off analysis, decision-makers can assess

348 which approaches are expected to meet ecosystem-based fisheries management objectives
349 (Halpern et al., 2013; Levin et al., 2018; Poe et al., 2014). Our study pays particular attention to
350 social equity by disaggregating user groups (commercial and traditional indigenous harvesters)
351 and illustrates the distribution of benefits under different spatial management policies.

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

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

Conclusions

370 We demonstrate how integrating spatial fish dynamics and spatial social benefits into
371 management strategy evaluation can quantify trade-offs among social-ecological objective. No
372 single policy maximizes all objectives in our hypothetical herring fishery, and some policies are
373 inefficient because they lead to losses without benefiting the objective(s) they were designed to
374 address. However, there is promise for balancing economic, ecological and social objectives by
375 considering spatial dynamics in complex social-ecological systems. For herring fisheries, the
376 extent of trade-offs depends on how well research informs and management addresses the
377 dynamics of fish in space because place-based indigenous fishers, commercial fleets and species

378 that rely on herring all operate with spatial constraints. Thus, we show how considering diverse
379 spatial conditions and objectives can reveal key trade-offs between economic, social and
380 ecological objectives and highlight pathways to improve conservation and management.

381 **Acknowledgements**

388

389 **Data availability statement**

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

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626

627 Table 1: Performance metrics in the MSE. Normalization factors are the maxima used to scale
628 values to a maximum of 1 (see Appendix for definitions).

Metric	Type	Description	Normalization Factor

Yield	Economic	Average herring roe catch in tonnes per year	MSY ~ 5.5 (x1,000 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

629

630 **List of Figures:**

631 **Figure 1**: A) Hypothetical herring fisheries and example simulations. Heuristic layout of
632 subpopulations, migration among subpopulations, extraction from available subpopulations by
633 mobile fisheries and extraction from a subset of three subpopulations by localized (indigenous)
634 fisheries, including a critical traditional use spawning location (CL). Example simulations with
635 20% adult and juvenile migration under 20% target harvest rate and a $25\%B_0$ threshold at the
636 stock-scale (B & C - sum of biomass across all spawning subpopulations) or at the subpopulation
637 scale (D & E - biomass from individual spawning subpopulations). B & D) Dark blue line the
638 sum of post-harvest spawning biomass across all spawning subpopulations; Thin black lines -

639   individual stock assessment estimates for post-harvest spawning biomass for each year; Red
640   points - forecast spawning biomass prior to harvest; Grey bars - catch summed across all
641   spawning subpopulations; Horizontal pink line - true 25%B_0 closure threshold (B_0 is estimated in
642   each year, but annual estimates are not shown for simplicity).   C & E) Thick black line -
643   biomass at the spawning subpopulations designated as the CL which is either closed (C) or open
644   to non-traditional use commercial harvest (E); individual colored lines - biomass at other
645   spawning subpopulations. Example simulation runs are shown for illustrative purposes. For
646   comparison in performance among management strategies see Figs. 2, 3, 4 and Appendices.
647   Results shown are for a base case of 20% adult and juvenile diffusive migration.

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

664   **Figure 3:** Comparison of performance metrics for the three lower closure thresholds. Axes show
665   standardized forms of performance metrics (scored 0-1 – where 1 is the theoretical or observed
666   maximum benefit) with polygons connecting individual management scenarios. (a) Effect of
667   thresholds (different colors & lines) and harvest rate (different shapes) on the trade-off between
668   yield (for the commercial roe fishery) and traditional practice. (b) Outcomes for the suite of
669   performance metrics for the three closure thresholds at a 20% harvest rate.   (c) Effect of

670   thresholds (different colors & lines) and harvest rate (different shapes) on the trade-off between

671   (b) yield (for the commercial roe fishery) and catch stability (years the fishery is open). (d)

672   Effect of thresholds and harvest rate on the bivariate outcome of catch stability and traditional

673   practice. For each bivariate comparison, the inefficient outcomes are those with a reduction in

674   one axis without change in the other [i.e. thresholds are inefficient for circles and squares in (c)

675   because they create a cost to fishery openings without a benefit to traditional practice or yield].

676   Full results, including for different migration scenarios and target harvest rates are shown in the

677   Appendix. Note the axis in (a) ranges from 0.4 to 1 to illustrate the range of observed responses

678   and responses are either naturally scaled 0-1 or scaled by their maximum across all simulations.

679   Results shown are for a base case of 20% adult and juvenile diffusive migration.

680   **Figure 4**: Comparison of performance metrics for the spatial management scenarios at a 20%

681   (~40%F_{MSY}) target harvest for (a) all performance metrics with no spatial asymmetry in fish

682   productivity, and (b-c) sensitivity of select performance metrics to assumptions about critical

683   location productivity [source (high) to sink (low)]. Black dotted lines - all sites are open; red

684   dashed lines - the critical site is closed but the harvest quota is not adjusted; blue solid lines - the

685   critical site is closed and the harvest quota is adjusted for the spawning biomass in the closed

686   area in the prior year, crossed with different spatial productivity and recruitment behavior. Note

687   the axis in (a) ranges from 0.5 to 1 to illustrate the range of observed responses and responses are

688   either naturally scaled 0-1 or scaled by their maximum across all simulations. In contrast, the

689   axis in (c) is relative to MSY. OL and CL risk avoidance in (a) represent 1 minus the risk of

690   collapse at the open locations or the critical location. Results shown are for a base case of 20%

691   adult and juvenile diffusive migration. See Appendix Figure S2 for results with different

692   migration rates and Figure S3 for results with nonlinear recruitment behavior.

Figure 1

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Figure 2

Figure 3

Figure 4