Received: 3 March 2023 | Revised: 1 September 2023 | Accepted: 28 September 2023

DOI: 10.1111/cobi.14201

Conservation Biology

CONTRIBUTED PAPERS

Selection of planning unit size in dynamic management strategies to reduce human–wildlife conflict

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Article impact statement: Selection of planning unit size in dynamic management strategies must consider environmental variability and data latency.

Funding information
David and Lucille Packard Foundation, Grant/Award Number: 2019-69817; NOAA's OAR Climate Program Office, Grant/Award Number: NA22OAR4310560; NOAA NMFS Office of Protected Resources, Grant/Award Number: NA; NOAA's Integrated Ecosystem Assessment Program, Grant/Award Number: NA

Abstract

Conservation planning traditionally relies upon static reserves; however, there is increasing emphasis on dynamic management (DM) strategies that are flexible in space and time. Due to its novelty, DM lacks best practices to guide design and implementation. We assessed the effect of planning unit size in a DM tool designed to reduce entanglement of protected whales in vertical ropes of surface buoys attached to crab traps in the lucrative U.S. Dungeness crab (*Metacarcinus magister*) fishery. We conducted a retrospective analysis from 2009 to 2019 with modeled distributions of blue (*Balaenoptera musculus*) and humpback (*Megaptera novaeangliae*) whales and observed fisheries effort and revenue to evaluate the effect of 7 planning unit sizes on DM tool performance. We measured performance as avoided whale entanglement risk and protected fisheries revenue. Small planning units avoided up to $47 million of revenue loss and reduced entanglement risk by up to 25% compared to the large planning units currently in use by avoiding the incidental closure of areas with low biodiversity value and high fisheries revenue. However, large planning units were less affected by an unprecedented marine heat wave in 2014–2016 and by delays in information on the distributions of whales and the fishery. Our findings suggest that the choice of planning unit size will require decision-makers to navigate multiple socioecological considerations—rather than a one-size-fits-all approach—to separate wildlife from threats under a changing climate.

KEYWORDS
dynamic management, environmental variability, fisheries, marine heat waves, planning unit, prioritizr, protected species, species distribution models

Selección del tamaño de la unidad de planeación en las estrategias dinámicas de manejo para reducir el conflicto humano-fauna

Resumen: La planeación de la conservación depende por tradición de las reservas estáticas; sin embargo, cada vez hay más énfasis en estrategias de manejo dinámico (MD) que son flexibles con el tiempo y el espacio. Ya que es novedoso, el MD carece de buenas prácticas que guíen el diseño y la implementación. Analizamos el efecto del tamaño de la unidad de planeación en una herramienta de MD diseñada para reducir el número de ballenas que se enredan en las cuerdas verticales de las boyas amarradas a las trampas para cangrejos de la pesquería lucrativa del cangrejo Dungeness (*Metacarcinus magister*) en los Estados Unidos. Realizamos un análisis retrospectivo de 2009 a 2019 con modelos de distribución de la ballena azul (*Balaenoptera musculus*) y la ballena jorobada (*Megaptera novaeangliae)* y observamos los esfuerzos y ganancias de la pesquería para evaluar el efecto del tamaño de siete unidades de planeación sobre el desempeño de una herramienta de MD. Medimos el desempeño como el riesgo de enredamiento evitado y los ingresos protegidos de la pesquería. Las unidades pequeñas de planeación evitaron hasta $47 millones de ingresos perdidos y redujeron el riesgo de enredamiento hasta en 25% en comparación con las unidades grandes que se usan actualmente al evitar el cierre indirecto de áreas con un valor bajo de biodiversidad e ingresos elevados para la pesquería. Sin embargo, las unidades grandes de planeación estuvieron menos afectadas por una ola de calor marino sin precedentes entre 2014 y 2016 y por los retrasos en la información sobre la distribución de las ballenas y la pesquería. Nuestros hallazgos sugieren que la selección del tamaño de la unidad de planeación requerirá que el órgano decisorio navegue múltiples consideraciones socio-ecológicas—en lugar de un enfoque de un-tamaño-para-todos—para separar a la fauna de las amenazas bajo el clima cambiante.

PALABRAS CLAVE

especie protegida, manejo dinámico, modelos de distribución de especie, pesquerías, priorizar, olas de calor marino, unidad de planeación, variabilidad ambiental

【摘要】

传统的保护规划依赖于静态的保护区, 而在空间和时间上具有灵活性的动态管理策略正越来越受到重视。由于该方法的新颖性, 动态管理目前仍缺乏最佳实践来指导其设计和实施。本研究评估了规划单元大小在一项动态管理工具中的作用, 该工具旨在减少美国首长黄道蟹 (*Metacarcinus magister*) 高收益的渔场中受保护鲸鱼被蟹笼浮标的吊绳缠绕的事件。我们对2009–2019年期间蓝鲸 (*Balaenoptera musculus*) 和座头鲸 (*Megaptera novaeangliae*) 的模型分布以及记录的渔场工作和收入进行了回顾性分析, 以评估7种规划单元大小对动态管理工具成效的影响。我们用规避的鲸鱼被缠绕风险和受保护的渔业收入来衡量不同工具的效果。结果表明, 与目前使用的大型规划单元相比, 小型规划单元可以避免附带性关闭生物多样性价值低而渔业收入高的区域, 从而避免了高达4700万美元的经济损失, 并将鲸鱼被缠绕的风险降低了25%。然而, 大型规划单元受到2014–2016年前所未有的海洋热浪以及鲸鱼和渔场分布信息延迟的影响较小。我们的研究结果表明, 在选择规划单元大小时, 决策者需要考虑多种社会生态因素, 而不是采用"一刀切"的方法, 以便在不断变化的气候条件下减少野生动物面临的威胁。**【翻译: 胡怡思; 审校: 聂永刚】**

关键词: 动态管理, 环境变异性, 渔业, 海洋热浪, 规划单元, 优先保护, 受保护物种, 物种分布模型

INTRODUCTION

The single-large-or-several-small (SLOSS) debate over reserve size has persisted in the conservation planning community since the 1970s (Simberloff & Abele, 1976). Proponents of single large reserves argue that large, continuous reserves protect more species and reduce edge effects, whereas proponents of several small reserves posit that the multiple smaller reserves protect wider ranges of biodiversity while providing insurance against disturbance. More recently, the SLOSS debate has deepened to consider planning units (Cheok et al., 2016; Hamel et al., 2013; Richardson et al., 2006; Van Wynsberge et al., 2015)—subdivisions of a planning region that are assessed by cost and biodiversity value and then selected to design a reserve (Pressey et al., 2007). Although multiple trade-offs can influence the choice of planning unit size, smaller units are generally more efficient, exhibit increased flexibility, and require less area to achieve conservation targets compared with larger units (Mills et al., 2010).

Thus far, SLOSS has been investigated with respect to static reserves (i.e., protected tracts of land or ocean that remain fixed in space and time, such as national parks and marine protected areas). However, increasing awareness of environmental variability and availability of real-time data streams on animal and human movements have led to the development of dynamic management (DM). DM is an emergent strategy in which management boundaries and recommendations are updated in near-real time to reflect changing environmental conditions, wildlife–human interactions, socioeconomic factors, and management priorities (Lewison et al., 2015; Maxwell et al., 2015; Welch, Brodie et al., 2019). For example, in the United States, the marine DM tool EcoCast produces daily maps delineating areas that are good and not good for fish (Hazen et al., 2018). On land, the Active Fire Mapping Program produces maps every

6 h of fire activity to delineate evacuation areas (Quayle et al., 2004).

With increasing attention and implementation of DM strategies, the SLOSS debate reemerges in a new context. The effect of planning unit size on DM performance (i.e., ability to achieve desired management outcomes) has not been explored; DM tools typically use the original resolution of environmental data as planning units (Abrahms et al., 2019; Eveson et al., 2015; Hazen et al., 2017). However, this effect requires investigation because the choice of planning unit size in DM may be affected by factors that do not influence static reserve design, including rapidly shifting conservation targets, episodic and extreme environmental events, and information delays. Although static reserves are designed to protect a fixed level of biodiversity (e.g., Aichi target 11 specifies protection of 10% marine and coastal areas), targets for biodiversity protection in DM can change with environmental and socioeconomic conditions (Hazen et al., 2018); for example, policies providing legal protection for threatened species may require decision-makers to increase restrictions following a ship strike event. DM tools therefore need to be flexible enough to accommodate a range of biodiversity targets, and smaller planning units increase the flexibility of static reserves (Mills et al., 2010). DM tools' near-real-time planning unit selection may be affected by episodic and extreme environmental events, such as heat waves, cold waves, storms, and floods, all of which may redistribute biodiversity value and cost across planning units. Finally, the near-real-time data streams frequently used to inform DM tools can be delayed. Socioeconomic and ecological data may take time to compile and process, and real-time planning unit selection may actually be based on spatial information from the previous week or month (Welch, Hazen, Bograd, et al., 2019). Information delay could cause management actions to lag behind if the environment, biodiversity, cost, or all 3 are highly dynamic (Ingeman et al., 2019).

To evaluate the effect of planning unit size on DM tool performance, we used a case study of blue (*Balaenoptera musculus*) and humpback (*Megaptera novaeangliae*) whale entanglement in California's commercial Dungeness crab (*Metacarcinus magister*) fishery. In this fishery, crab are caught in traps attached to surface buoys by vertical ropes, which can result in entanglement, injury, and mortality for large whale species. Dungeness crab is one of California's most lucrative fisheries (Santora et al., 2020), and blue and humpback whales are listed under the U.S. Endangered Species Act and federally protected in U.S. waters under the Marine Mammal Protection Act, which creates steep trade-offs between supporting fisheries revenue and whale conservation.

A prolonged marine heat wave from 2014 to 2016 spatially and temporally redistributed the fishery and whales (Santora et al., 2020), leading to a 10-fold increase in entanglement and a diminished ability for management strategies to navigate these trade-offs (Free et al., 2023; Samhouri et al., 2021). During the heat wave, a domoic acid outbreak resulted in a delayed opening of the Dungeness crab fishery, causing the peak of the fishing season to coincide in space and time with the arrival of foraging whales. In addition, the distribution of prey species was compressed along the coast, resulting in greater density of foraging whales in inshore waters targeted by the crab fishery (Santora et al., 2020). Thus, the heat wave exacerbated management trade-offs between whale entanglement reduction and avoiding losses in fisheries revenue (Samhouri et al., 2021). In response to elevated entanglements during the heat wave, the Risk Assessment And Mitigation Program (RAMP) was established in 2020 to mitigate entanglement risk. A suite of tools was used, including dynamic closures of 1 or more of the 7 large fishery zones.

We used a decade-long retrospective analysis to compare the utility of the 7 RAMP zones and 6 increasingly smaller planning unit sizes at reducing blue and humpback whale entanglements while avoiding losses in fisheries revenue. The effect of planning unit size was evaluated across a suite of conservation targets, during the 2014–2016 marine heat wave, and under multiple lengths of information delay (i.e., delays in information on fishery and whale distributions). We sought to contextualize knowledge and best practices from static reserve design within the context of DM to improve the ability to navigate human–wildlife conflicts under climate variability.

METHODS

Case study background

The RAMP evokes zone closures and additional management actions based on near-real-time information on entanglement reports and whale presence as triggers. Reported entanglements are investigated by the National Marine Fisheries Service to determine the entangling gear type. Whale presence is determined using quantitative whale count thresholds based on a combination of aerial and vessel surveys. Using information on entanglements and whale presences, risk assessments are undertaken every 2 weeks during the fishing season to determine whether management actions, such as zone closures, are needed.

However, there is motivation to explore a DM framework. Many whale entanglements are unreported or reporting is delayed such that the location and timing of the entangling event are unknown. Aerial surveys are costly and patchy in space and time, and observations from whale watching vessels are biased toward inshore areas with high levels of tourism. A predictive DM framework could provide information on the distribution of whales and entanglement risk at fine spatiotemporal resolutions to allow more areas to stay open to fishing while still reducing entanglement risk at whale hotspots. For any management program, including the RAMP, to transition to a DM framework, the effect of planning unit size will need to be explored to ensure management outcomes are achievable. Planning unit size has not been explicitly explored for the RAMP, and the relatively large zones used in practice were selected to safeguard against incomplete information on the distribution of whales and the fishery.

An operational model for blue whales produces new predictions of blue whale distribution each day (https://coastwatch.pfeg.noaa.gov/projects/whalewatch2/about_whalewatch2.html). There is no operational model for humpback whales or an operational data stream for spatially explicit fisheries revenue, but both are possible (Welch, Hazen, Bograd, et al., 2019). As such, our purpose was to investigate how planning unit size affects DM tool performance based on a case study of the RAMP, rather than to provide explicit guidance to the RAMP on planning unit size. We used historical 5-km data on monthly modeled humpback and blue whale distributions and monthly observed fisheries effort produced by Samhouri et al. (2021). We conducted a retrospective analysis with these data to evaluate the ability of DM tools to navigate trade-offs between risk and revenue if the tools had been operational during that time (the RAMP first went into effect in the 2020–2021 fishing season). We explored a decision-making framework in which closures are updated monthly because finer time steps are not possible due to the resolution of the existing humpback whale model output. Time steps of 1 month are likely too coarse to be relevant to RAMP risk assessments, which are conducted every 2 weeks. We tested 5-km planning units because this spatial scale is substantially smaller than one that is practical for on-the-water implementation of Dungeness crab fishery management measures given existing information and technology. Therefore, it provides an idealized scenario for comparison against more realistic scenarios.

Data

Monthly whale and fisheries model output (Appendix S1) from 2009 to 2019 that we used was the same as that generated for Samhouri et al. (2021). Regulations allowing for RAMP zone closures did not come into effect until the 2020–2021 fishing season, so the 2009–2019 time series allowed for the investigation of status quo conditions controlled for the effect of management actions. In brief, model-derived predictions of blue and humpback whale distributions were hindcast for each month over a 5- × 5-km grid in species distribution models (Abrahms et al., 2019; Samhouri et al., 2021). We used the methods of Samhouri et al. (2021) to redistribute fisheries effort following closures. Fishery effort and revenue (U.S. dollar value of landings per grid cell) were calculated for each month over the 5- × 5-km grid based on vessel-monitoring-system data linked to California landings receipts registered to Dungeness crab (Feist et al., 2021). Monthly humpback and blue whale risk in each grid cell was calculated by multiplying fishery effort by blue and humpback whale habitat distribution, respectively.

Prioritizr and zones

For each month in the time series, fisheries closure scenarios (i.e., sets of planning units, see Table 1) were simulated using the RAMP zones (hereafter zones) and the spatial prioritization software Prioritizr (hereafter prioritizr) (Appendix S1).

We used prioritizr to solve the minimum-set problem; that is, what is the minimum set of planning units that must be closed to meet user-defined conservation targets at the cheapest possible cost? In the context of this analysis and setting a conservation target of 10%, prioritizr identified the scenario that avoided at least 10% of each whale's entanglement risk (the target) while protecting as much fisheries revenue as possible (the cost). We tested 17 conservation targets: 1%, 10%, 20%, 30%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95%, and 99%. Prioritizr was run using the data's original resolution as planning units (i.e., the 5- × 5-km grid) and 5 increasingly coarse planning unit sizes (Figure 1a–f).

The 7 zones (Figure 1g) were coarse, with an average latitudinal breadth of 198 km. We tested all possible zone closure combinations for a total of 126 scenarios: 1 zone closure ($n = 7$), 2 zone closures ($n = 21$), 3 zone closures ($n = 35$), 4 zone closures ($n = 35$), 5 zone closures ($n = 21$), and 6 zone closures ($n = 7$). When zones 1–6 were closed, the entire study domain was closed to fishing (Figure 1g). This configuration effectively allowed zones to run like prioritizr—testing all possible scenarios before selecting the optimal scenario.

Effect of planning unit size on performance

The effect of planning unit size on DM tool performance was evaluated using hypervolume and the realized change in avoided whale entanglement risk and protected fisheries revenue under 3 types of objectives. Hypervolume is a measure of the quality of spatial management opportunities (see Table 1) for navigating trade-offs between avoiding bycatch and protecting fisheries revenue (Figure 2). We used both metrics to determine overall performance and the effects of a prominent marine heat wave and data latency on performance.

With hypervolume (Guerreiro et al., 2021), large values indicate better management opportunities and small values indicate worse management opportunities (Appendix S1). In DM, the best single scenario to enact depends on the decision-maker. For example, the best scenario, that is, a combination of planning units to close, may depend on the minimum reduction in whale risk required under protected species policies; may depend on the minimum amount of fisheries revenue decision-makers can protect to sustain fishers' livelihoods; or may be the scenario that simultaneously, maximally optimizes both avoided whale risk and protected fisheries revenue. In lieu of assuming an arbitrary objective, hypervolume is calculated across a full set of possible scenarios to evaluate the overall quality of management opportunities. Hypervolume thereby captures overall performance across all possible objectives and could be applied in diverse trade-off contexts (Lester et al., 2010, 2013; Watson et al., 2009).

The set of scenarios used to calculate hypervolume is termed the Pareto frontier (Figure 2). Pareto frontiers are the set of scenarios that optimize trade-offs between avoided whale risk (y-axis) and protected fisheries revenue (x-axis). The concept of Pareto frontiers originated in the field of production theory, but in recent years, Pareto frontiers have been adopted in conservation science to navigate conflicting trade-offs (Lester et al., 2013; Nelson et al., 2008; White et al., 2012). Hypervolume is affected by 3 features of the Pareto frontier (Cao et al., 2015): trade-off

TABLE 1 Glossary of terms used in methods and results

Dynamic management (DM) tool: *A family of management tools in which spatial boundaries and recommendations are updated in near-real time to reflect changing environmental conditions, wildlife-human interactions, socio-economic factors, and/or management priorities*

RAMP: *The Risk Assessment and Mitigation Program used to support management of the Dungeness crab fishery in California. The RAMP has multiple management tools to mitigate entanglements, e.g. zone closures, depth restrictions, and gear reduction*

Zones: *Seven large fishery zones that can be dynamically closed to fishing by the RAMP to reduce whale entanglement*

Prioritizr: *A software designed to help decision makers solve conservation planning problems*

Planning unit: *An individual area that can be closed to fishing*

Conservation target: *quantitative targets for the minimum amount of whale risk to avoid (e.g. 10%)*

Scenario: *A series of planning units that are closed together*

Pareto frontier: *the set of scenarios that optimize trade-offs between protected fisheries revenue and avoided whale risk*

Hypervolume: *a metric to compare performance across two or more pareto frontiers*

Management opportunities: *the ability of a set of scenarios to navigate trade-offs between avoiding bycatch and protecting fisheries revenue, indicated by hypervolume (larger and smaller hypervolumes indicate better and worse management opportunities, respectively)*

Entanglement risk: *the product of fishery effort and blue or humpback whale habitat distribution*

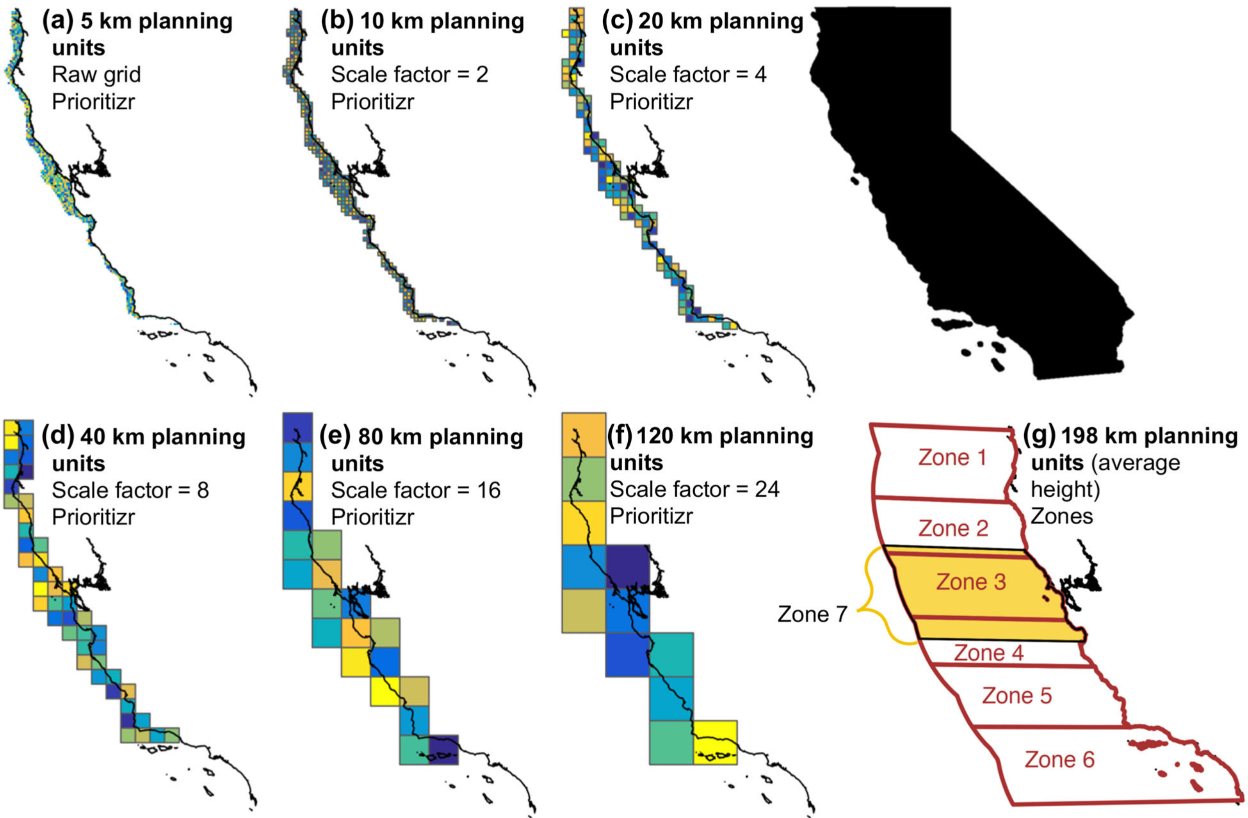

FIGURE 1 Configurations of closures resulting from use of (a–f) the conservation planning software prioritizr and the Risk Assessment and Mitigation Program (RAMP) zones (g) used to evaluate the effect of planning unit size on reductions in whale entanglement risk in fishing gear in California's Dungeness crab fishery. For prioritizr, scale factors indicate how many times larger the latitudinal and longitudinal breath of planning units is than the original resolution (5 × 5 km). For example, a scale factor of 16 indicates planning units that have latitudinal and longitudinal breadths 16 times larger (80 × 80 km) than the original resolution.

optimality (i.e., how close the frontier is to the theoretical optimal scenario of 100% avoided whale risk and 100% protected fisheries revenue); set evenness (i.e., how balanced the spread of scenarios is along the Pareto frontier); and set range (i.e., how big a span the scenarios cover with respect to the objectives [*x*- and *y*-axes]).

For each month and planning unit size, hypervolume was calculated across the full set of scenarios for each planning unit size (Appendix S7). Average monthly hypervolume was compared across the full time series to determine relative management opportunity quality, and a Cox–Stuart test was used to test for a significant trend in hypervolume as planning unit size increased.

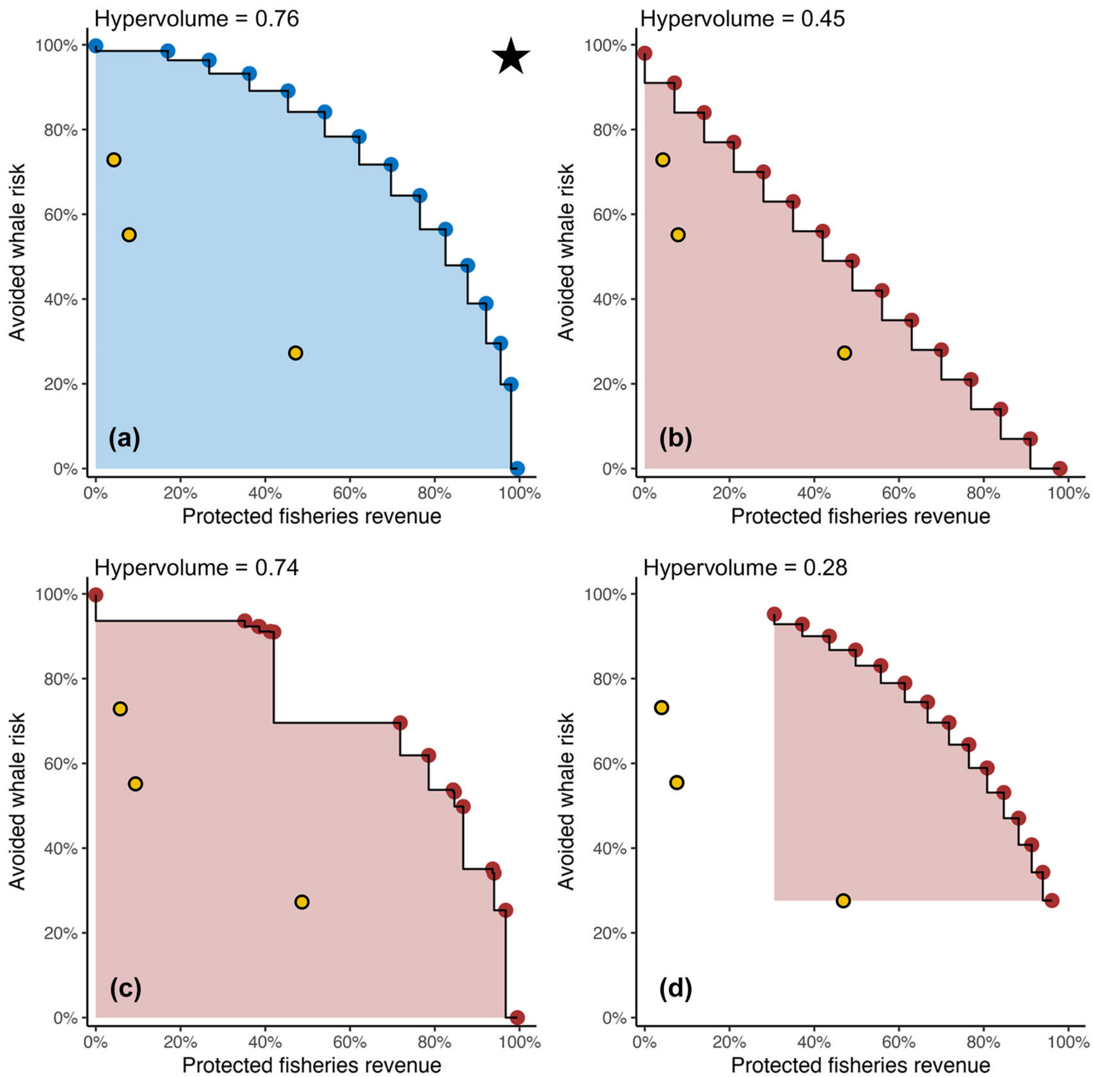

FIGURE 2 Four hypothetical examples of Pareto frontiers consisting of 15 spatial management scenarios (red and blue points) and hypervolumes (red and blue shading): (a) high-performing Pareto frontier with a large hypervolume (0.76) (scenarios optimize trade-offs, are evenly distributed, and cover the full range of possible values) and (b–d) low-performing Pareto frontiers with small hypervolumes due to less optimal trade-offs ([b] hypervolume = 0.45, [c] uneven distribution of scenarios, hypervolume = 0.74, [d] small range of scenarios, hypervolume = 0.28; black star, theoretical optimal scenario, i.e., 100% avoided whale risk and 100% protected fisheries revenue; yellow points, scenarios interior to the frontier dominated by scenarios on the frontier, meaning they have less efficient trade-offs [fewer whales avoided per revenue protected]). Hypervolume is the volume of the decision space between the minimum value of each objective (e.g., 0% avoided whale risk, 0% protected fisheries revenue) and a convex stepwise curve connecting each Pareto frontier scenario (black steps). Hypervolume therefore compares performance across 2 or more Pareto frontiers (the larger the hypervolume, the better the management opportunities).

Although hypervolume is a useful metric to evaluate the quality of management opportunities, it does not capture trade-offs between avoided whale risk and protected fisheries revenue once a closure has been enacted. To evaluate trade-offs between avoided whale risk and protected fisheries revenue, we used 3 hypothetical objective types to select scenarios in each month across the time series (Appendix S1). The first objective (optimal objective [Appendix S8]) was to select the scenario in each month with the closest Euclidean distance to the theoretical optimal scenario (100% avoided whale risk and 100% protected fisheries revenue) (Bre & Fachinotti, 2017; Lin et al., 2016). The theoretical optimal scenario is impossible to achieve because of the conflicting nature of fisheries revenue and entanglement risk. If it were possible to achieve, it would indicate that these features were not conflicting, and an analysis of trade-offs would not be necessary (Bre & Fachinotti, 2017). Using the theoretical optimal scenario to choose scenarios in each month selects for scenarios that simultaneously maximize avoided whale risk and protected fisheries revenue to the greatest possible extent.

The second objective (avoided whale risk objective) was to select the scenario in each month that protects the most fisheries revenue while avoiding at least 40%, 50%, 60%, and 70% of whale risk. This objective prioritizes avoiding whale risk first and protecting fisheries revenue second. The third objective (protected revenue objective) was to select the scenario in each month that avoids the most whale risk while protecting at least 40%, 50%, 60%, and 70% of fisheries revenue.

Although these exact objectives are unlikely to be used in the real world, they allowed us to examine the relative performance of DM tools based on the types of objectives that might be employed.

Monthly hypervolumes were compared during the 2014–2016 marine heat wave versus more normal conditions (2009–2014 and 2016–2019) to examine how the heat wave affected opportunities for navigating trade-offs between avoiding bycatch and protecting fisheries revenue. Kolmogorov–Smirnov tests were used to test for significant differences in hypervolume between marine heat wave and normal conditions.

Data latency is important to consider when working with social–ecological data. Although blue whale distributions are currently predicted at daily time steps, the humpback whale model is not operational. The latency of modeled data is affected by delays in environmental data dissemination (e.g., satellite data streams may be delayed due to technical problems with the sensor) or problems with acquisition of environmental data or dissemination of model outputs (Welch, Brodie et al., 2019). Spatial data on fisheries effort and revenue are also not yet produced operationally, but latency will be affected by how quickly vessel-monitoring-system data and landing receipts can be acquired, checked, merged, and disseminated. Latency is particularly important to consider in the contexts of species' motility. For example, for wide-ranging species, such as large whales, data delays could lead to incorrect inferences on the distributions and risk to bycatch species, whereas this may be less of a problem with more sedentary species.

Using the optimal objective, we tested how the performance of the 7 planning unit sizes decayed as delays in information on the distribution of whales and fisheries effort increased. We tested how the performance of the 7 planning unit sizes decayed as delays in information increased. For each month, information delays were evaluated at 1, 2, and 3 months. For example, February 2010 was managed using the selected closure scenario for January 2010 (1-month lag), December 2009 (2-month lag), and November 2009 (3-month lag). Information was delayed within the season; for example, selected scenarios from the end of 1 season in July were not used to manage the beginning of the next season in November. Instead, the selected scenario for the beginning of a season was used to manage the beginning of the next season; for example, for a 2-month delay, the first 2 months of season 2 (November and December 2010) were managed using the selected scenarios for the first 2 months of season 1 (November and December 2009). Due to the seasonality of the fishery and whale migrations (Appendix S5), when information is unavailable, the best option for managers may be to make inferences based on information from the same period in the previous year (although alternative options may be more useful in practice). Performance decay at each information delay was measured as the Euclidean distance from the selected closure with no information delay (Appendix S9). For each delay length, Kolmogorov–Smirnov tests were used to test for significant differences in decay between the smallest planning unit (5 km) and the largest planning unit (198 km).

RESULTS

Better management opportunities (i.e., larger hypervolumes) were better with small planning units than with large planning units (Figure 3a). Hypervolume decreased significantly as planning unit size increased ($p < 0.05$); the largest planning unit (198 km) had a median hypervolume 35% smaller than the smallest planning unit (5 km). Although all planning unit sizes had similar set ranges, small planning units better optimized trade-offs and had a more even distribution of scenarios with respect to avoided whale risk (Figure 2; Appendices S4 & S5). For small planning unit sizes, selected scenarios were always closer to optimal (Figure 3b), protected more fisheries revenue (Figure 3c), and avoided more whale risk (Figure 3d). On average under the optimal objective (Figure 3b), the smallest planning unit (5 km) protected ~$1 million more revenue and avoided 1.2% more entanglement risk than RAMP zones (198 km). Across the avoided whale risk and protected revenue objectives (Figure 3c,d), the smallest planning unit avoided $31–$47 million of revenue loss and reduced entanglement risk by 22–25% compared with the largest planning unit.

Hypervolume was on average 13–16% lower during the marine heat wave than under normal conditions for each planning unit size (Figure 4). However, this effect was only significant for planning units $\leq 40 \times 40$ km ($p < 0.05$) (Figure 4), whereas the difference at large planning units ($\geq 80 \times 80$ km) was not significant ($p \geq 0.1$). Small planning units had a significant marine heat wave effect due to large differences in hypervolume between the heat wave and normal conditions (on average, 7% greater than differences for larger planning units) and small interquartile ranges (on average, 24% less than larger planning units).

All planning unit sizes were negatively affected by information delay (Figure 5). However, small planning units were most strongly affected; the longer the information delay, the steeper the performance decay (measured as distance from the scenario selected by the optimal objective at no delay). Across all delay lengths, the largest planning unit (RAMP zones) had 28–32% less decay compared with the smallest planning unit (5 km), which was significant for all delay lengths. At the smallest planning unit size, an information delay of 3 months resulted in an average of 20% less whale risk avoided and 5% more fisheries revenue protected than with no information delay. Although small planning units have steeper performance decays under information delays and greater performance loss during the marine heat wave relative to large planning units (Figures 4 & 5), they outperformed larger planning units across time (including normal and marine heat wave periods) at all information delay lengths (e.g., selected scenarios were always closer to optimal) (Figure 3b; Appendix S9).

DISCUSSION

We found no single optimal solution to the choice of planning unit size, which ushers the SLOSS debate into the field of DM.

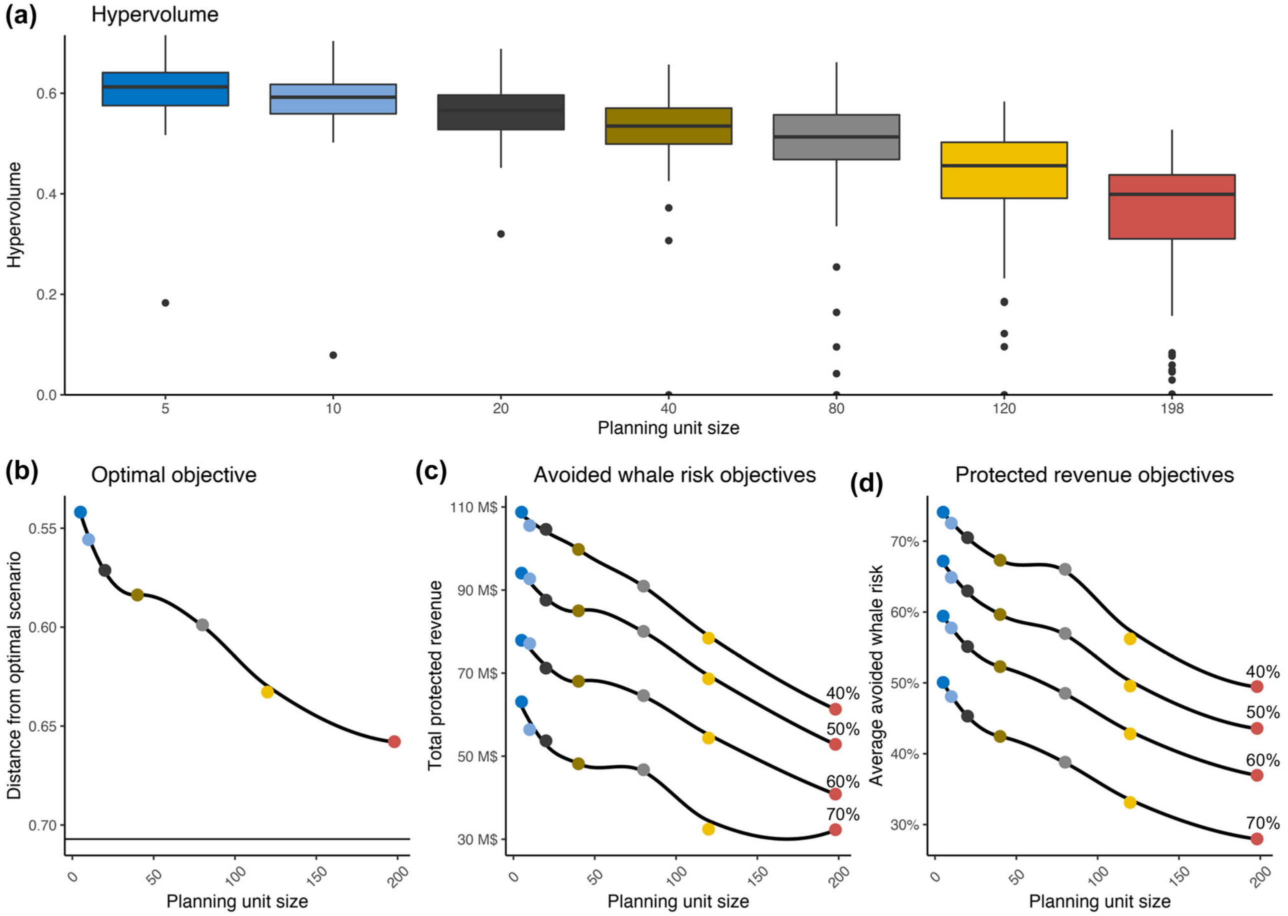

FIGURE 3 (a) Monthly hypervolumes (management opportunities) for the 7 planning unit sizes compared to evaluate the effect of planning unit size on reductions in whale entanglement risk in fishing gear in California's Dungeness crab fishery (bold horizontal lines, median; bar extents, first and third quartiles; whiskers, upper and lower extend to the largest and smallest values no further than 1.5 × the interquartile range [IQR]; points, outliers) and (b–d) hypothetical objective types used to select scenarios in each month across the time series: (b) optimal (horizontal line, Euclidean distance from optimal of a scenario that avoids 50% of whale risk and protects 50% of fisheries revenue), (c) avoid 40%, 50%, 60%, and 70% of whale risk, and (d) protect 40%, 50%, 60%, and 70% of fisheries revenue. The *y*-axis in panel (b) is inverted so that panels (b–d) have consistent directionality in performance (i.e., all panels range from lowest performance at the axis origin to highest performance at the axis extreme).

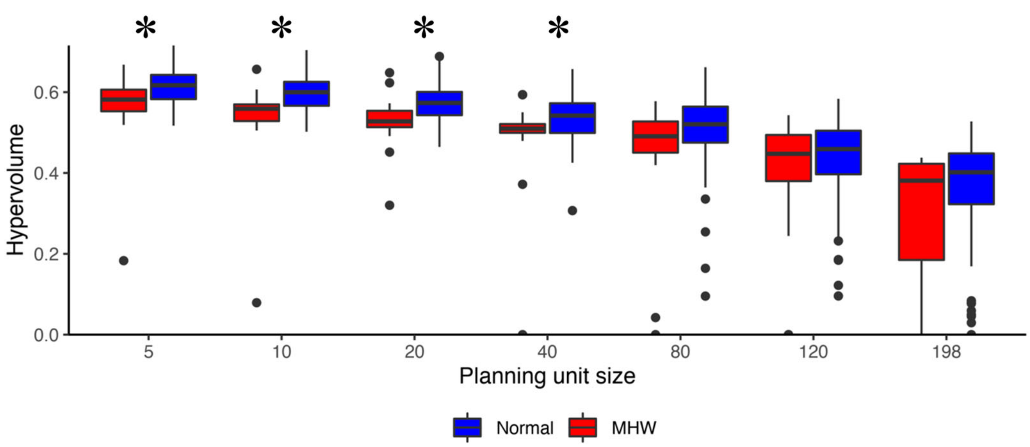

FIGURE 4 Monthly hypervolumes (management opportunities) for the 6 prioritizr configurations of different planning unit sizes and the Risk Assessment and Mitigation Program (RAMP) zones during marine heat waves (MHW) versus normal conditions (asterisks, statistically significant differences between MHW and normal conditions via Kolmogorov–Smirnov tests; bold horizontal lines, median; bar extents, first and third quartiles; whiskers, upper and lower extend to the largest and smallest values no further than 1.5 × the interquartile range [IQR]; points, outliers).

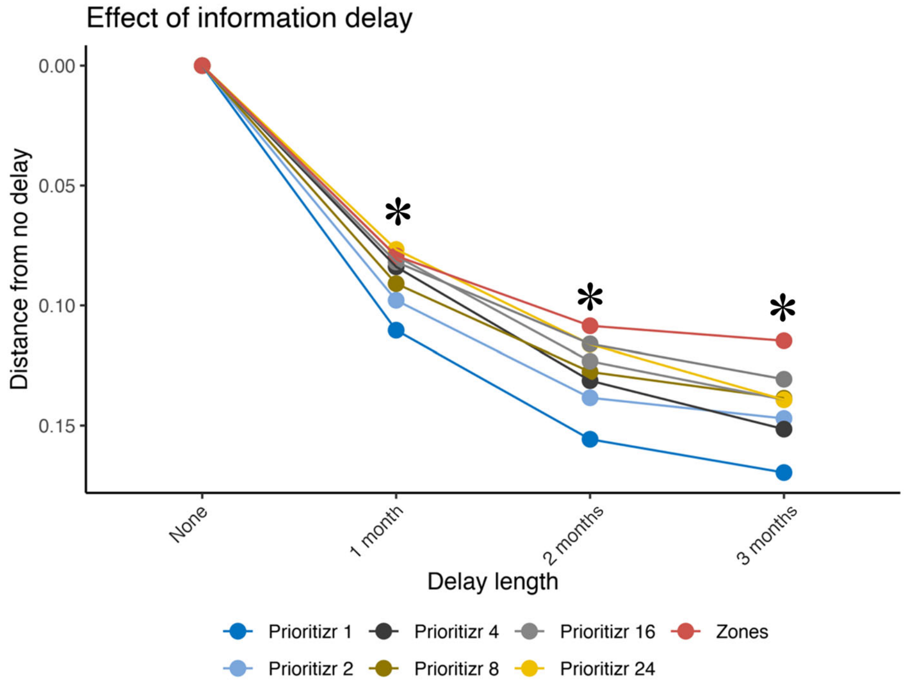

FIGURE 5 Average monthly effect of delays in information on crab fishery and whale distributions for the 7 planning unit sizes (*y*-axis, Euclidean distance from the closure selected by the optimal objective at no information delay; asterisks, statistically significant differences in distributions between the smallest and largest planning units via Kolmogorov–Smirnov tests).

Ultimately, the choice of planning unit size will require decision-makers and fishers to navigate trade-offs between multiple social–ecological and logistical considerations (Figure 6). We found that small planning units had the highest performance, providing better spatial management opportunities relative to larger planning units (Figure 3a) and avoiding more whale risk and protecting more fisheries revenue regardless of objective type or conservativeness (Figure 3b–d). This result emerged because small planning units can align with distributions of biodiversity and cost with more spatial precision, avoiding the incidental closure of low-biodiversity, high-cost waters (i.e., lose–lose areas) that occurs with large planning units. Critically, small planning units avoided up to $39 million of revenue loss and reduced entanglement risk by up to 23% compared with the large zones that are currently in use.

However, spatial precision can be disadvantageous during extreme and episodic environmental events, information delay, or distribution uncertainty (Figure 6). Even if closures had been part of the management toolbox during the 2014–2016 marine heat wave, spatial management opportunities to navigate the trade-offs between avoiding bycatch and protecting fishery revenue were worse during the heat wave relative to historical conditions, regardless of planning unit size. However, this difference was more severe for small planning units (Figure 4). Spatial overlap between the fishery and whales increased during the heat wave due to a compression of prey and a delayed fishery opening (Santora et al., 2020), which reduced the prevalence of areas with high whale entanglement risk and low fisheries revenue (Samhouri et al., 2021). Large planning units were less affected by this increase in overlap because they have inherently less precision to find and close areas where whale

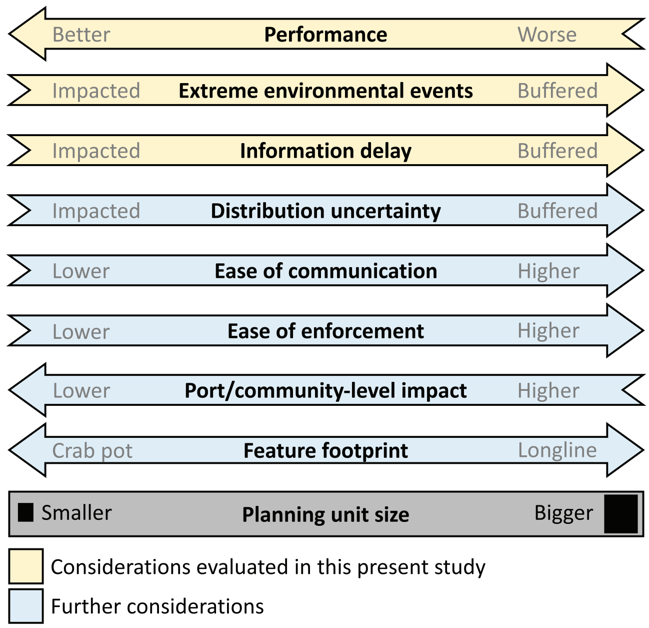

FIGURE 6 Overall performance of management of dynamic management scenarios relative to planning unit (PU) size and social–ecological and logistical factors associated with PU size that affect management decisions (arrow direction for factors, positive management outcomes). Performance is the quality of management opportunities, indexed by hypervolume and the ability to navigate trade-offs between avoiding whale entanglement risk and protecting fisheries revenue under different types of management objectives. The extreme environmental events is a marine heat wave, and information delay is delay in information on the distribution of whales and the crab fishery. Feature footprint captures the spatiotemporal distribution (e.g., size, mobility) of the features being managed (e.g., whales, the fishery).

entanglement is high and fisheries revenue loss is low. This consideration is very important from a management perspective, and a substantial part of the rationale for creating relatively large zones (CDFW, personal communication 2023). Similarly, large planning units were less affected by performance decay as information delay increased compared with small planning units (Figure 5) because their less-precise alignment with whale and fishery distributions at any given period provides an incidental safeguard against changing distributions across time. We explored the effect of information delays (lags in distributional information on whales and the fishery); however, delays due to the time it takes to make and communicate decisions and implement them are also possible. We hypothesize that large planning units will be less affected by performance decay across all types of delay, but this is as an avenue for future research. Finally, the precision of small planning units is beneficial if the exact and complete distribution of whales and the fishery is known. Social–ecological data will always have gaps and uncertainties (Pressey, 2004), particularly model-derived distributions (Beale & Lennon, 2012), and the lower precision of larger planning units provides risk-averse accommodation of uncertainty.

The choice of planning unit size will also be influenced by the authority given to and the ability of fishery managers to communicate and effectively enforce closures (Figure 6). DM scenarios are more challenging to manage than static reserves because of their temporal complexity (i.e., spatial orientation of closures changes over time). The greater spatial complexity of closures designed using smaller planning units (i.e., patchier closures and more complex boundaries [Appendix S8]) will exacerbate this challenge. However, large planning units may disproportionately affect specific communities of resource users, for example, scenarios that close all waters to fishing near a specific port or region (Seary et al., 2022). The patchiness of small planning units is likely to distribute impacts more equitably across communities.

Finally, planning unit size will depend on the spatial and temporal footprint of the features being managed. Although crab pot gear is small enough to be contained in a 5- × 5-km planning unit, a 45-km-long drifting longline is not. Planning unit size will also depend on fleet mobility. High-powered vessels may be able to move outside large planning units following a closure, whereas small vessels may not. Over the temporal frequency (Welch, Hazen, Bograd, et al., 2019) of the DM tool (1 month in our case study), lower mobility species, such as crab, may remain in the same 5- × 5-km planning unit; however, highly mobile species, such as whales, are less likely to do so. Low temporal durability of distributional information could reduce the protective benefit of closures during their phase of operation. In practice, information delay and distribution uncertainty likely interact with species' and fleet mobility such that each has more of an effect on highly mobile species and fleets than on sedentary species and fleets. In our case study, which involved a highly mobile bycatch species and a relatively sedentary target species, it is likely that information delay and distribution uncertainty have more negative impacts on whale conservation than on fisheries revenue. In a converse scenario involving a relatively sedentary bycatch species and a mobile target species (e.g., bycatch of relatively sedentary groundfish while targeting relatively mobile Pacific whiting [*Merluccius productus*]), fisheries revenue is more likely to be negatively affected by information delay and distribution uncertainty.

We explored how a major environmental perturbation—the 2014–2016 northeast Pacific marine heat wave—reshuffled opportunities for bycatch protection and fisheries revenue. In this case, the heat wave created a perfect storm of whale entanglements, but DM regulations were not yet accessible to fisheries managers until the 2020–2021 fishing season. Moreover, heat waves that occurred in the region during 2019 and 2020 (Weber et al., 2021) did not result in the marked increase in entanglements of the 2014–2016 event. There is wide variation in the drivers, evolution, and characteristics of marine heat waves and other climate shocks (Holbrook et al., 2019; Schlegel et al., 2017), which likely leads to wide variation in species and industry response (e.g., Cavole et al., 2016; Li et al., 2019). Although the heat wave we considered increased overlap between target and bycatch species and reduced the prevalence of effective closures, the converse outcome is also possible. Similar investigations into the effect of planning unit size in other regions should explore how past environmental perturbations redistribute risk and revenue, ideally across multiple perturbation events to capture how physical differences between events may lead to differences in ecological and economic impact. Evidence from diverse social–ecological systems indicates that climate change and associated environmental perturbations are amplifying human–wildlife conflict globally (Abrahms et al., 2023), increasing the demand for climate-ready management solutions to navigate trade-offs (Meyer-Gutbrod et al., 2021; Welch, Hazen, Briscoe, et al., 2019).

The practice of spatial management is under constant evolution, at each advancement translating lessons learned from past iterations to meet new objectives. Following historical forest conservation practices in India and Africa and, later, the establishment of Yellowstone National Park, reserves moved into the coastal seas (Ramp et al., 2006) and eventually pelagic oceans, requiring novel ideas about how to accommodate ocean dynamics into conservation planning (Carr et al., 2003; Hyrenbach et al., 2000). Planning unit selection evolved from the theoretical SLOSS debate, to simple algebra (Kirkpatrick, 1983), to advanced optimization algorithms (Ball et al., 2009; Brito-Morales et al., 2022; Hanson et al., 2020) guided by a systematic approach to designing reserves (Margules & Pressey, 2000). The volume of data available for decision-making from satellite Earth observation, animals as environmental sensors, and human mobility data has changed a social–ecological problem into one of data analytics, where the solution space is outside the historically available tools. As the field of DM matures, inferences from static reserve design will need to be reexamined, revised, and reimplemented to ensure robust strategies that can accommodate an increasingly dynamic world.

ACKNOWLEDGMENTS

This work was supported in part by the NOAA NMFS Office of Protected Resources and NOAA's Integrated Ecosystem Assessment Program. H.W. received funding from NOAA's

OAR Climate Program Office (award NA22OAR4310560). O.L. was supported in part by the David and Lucille Packard Foundation grant 2019–69817. We thank K. Forney (NOAA) for providing the humpback species distribution model, B. Feist (NOAA) for the development of the 5- × 5-km grid, and D. Lawson (NOAA) for important insights. Outputs from the blue whale habitat model are available at https://coastwatch.pfeg.noaa.gov/projects/whalewatch2/whalewatch2_map.html. Confidential vessel-level landings, registration, and vessel monitoring system data may be acquired from the California Department of Fish and Wildlife and the U.S. National Marine Fisheries Service Office of Law Enforcement, subject to a nondisclosure agreement.

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SUPPORTING INFORMATION

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

How to cite this article: Welch, H., Liu, O. R., Riekkola, L., Abrahms, B., Hazen, E. L., & Samhouri, J. F. (2024). Selection of planning unit size in dynamic management strategies to reduce human–wildlife conflict. *Conservation Biology*, *38*, e14201. https://doi.org/10.1111/cobi.14201