Spatial marine zoning for fisheries and conservation

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Protected areas are an effective tool for reducing biodiversity loss. Current legislation distinguishes various types of marine protected areas, each allowing different levels of resource extraction. However, almost all of the theory for spatial conservation planning is focused on identifying no-take reserves. The current approaches to zoning for multiple types of protected areas could result in suboptimal plans in terms of protecting biodiversity and minimizing negative socioeconomic impacts. We overcame these limitations in the first application of the multizone planning tool, Marxan with Zones, to design a network of four types of protected areas in the context of California's Marine Life Protection Act. We have produced a zoning configuration that entails mean value losses of less than 9% for every fishery, without compromising conservation goals. We also found that a spatial numerical optimization tool that allows for multiple zones outperforms a tool that can identify one zone (ie marine reserves) in two ways: first, the overall impact on the fishing industry is reduced, and second, a more equitable impact on different fishing sectors is achieved. Finally, we examined the tradeoffs between representing biodiversity features and impacting fisheries. Our approach is applicable to both marine and terrestrial conservation planning, and delivers an ecosystem-based management outcome that balances conservation and industry objectives.

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Worldwide, protected areas are a cornerstone of most conservation strategies (Soulé 1991), because they are one of the most effective actions for curbing biodiversity loss (Bruner *et al.* 2001; Possingham *et al.* 2006). As a result, there are several international mandates for the establishment of protected areas (eg the Convention on Biological Diversity). In response, national and local governments have developed initiatives for implementing marine protected areas (MPAs), including Australia's Environmental Protection and Biodiversity Conservation Act, Massachusetts' Ocean Act, New Zealand's Biodiversity Strategy, and Great Britain's Marine Bill.

Most marine conservation programs involve some form of zoning. However, the theory behind spatial conservation planning focuses on selecting one type of protected area – no-take reserves. There are many different types of MPAs, with different levels of protection, ranging from areas that allow selective extraction of resources to those that are strictly no-take (see www.unep-wcmc.org/protected_areas/categories/ and www.mpa.gov/). One long-standing approach in designing reserves is to use numerical optimization tools (eg Marxan, Zonation) to identify areas that cost-effectively achieve ecological objectives, namely comprehensively and adequately representing biodiversity (Kirkpatrick 1983; Possingham *et al.* 2006). However, use of these tools is limited in settings where planners face the more complex problems of prioritizing for multiple types of MPAs and resource uses. To compensate for the lack of an appropriate zoning tool, planners can use an optimization tool to design reserves and then build other types of protected areas around them, on the basis of ecological, socioeconomic, and political criteria, as is done in the Great Barrier Reef Marine Park and California's Channel Islands Sanctuary (Airame 2005; Fernandes *et al.* 2005). Other spatial zoning approaches based on multi-criteria analysis exist (Villa *et al.* 2002; Bruce and Eliot 2006; Portman 2007), but they ignore important principles of protected-area design (Margules and Pressey 2000; Possingham *et al.* 2006). The resulting zoning plans do not ensure that biodiversity features (ie species and habitats) are represented cost effectively and are therefore unlikely to be economically viable or to protect biodiversity.

The current approaches used to design MPAs could result in plans that do not equitably minimize negative impacts to stakeholders. For example, Klein *et al.* (2008a) used Marxan to identify MPAs that minimize impacts to two fishing sectors – commercial and recreational fisheries – while achieving biodiversity targets. In Marxan, only one variable can be minimized, which in this case was the sum of commercial and recreational fishing effort. Although the overall impact was minimized, the commercial and recreational fishing sectors were impacted disproportionately, with 17% and 4% of their grounds lost, respectively – a socially and politically unfavorable outcome where commercial and recreational fishing interests frequently conflict. We hypothesized that a more equitable outcome could be achieved with a multizone optimization tool that allows for the definition of more specific constraints, including setting targets for fisheries in areas where fishing is allowed.

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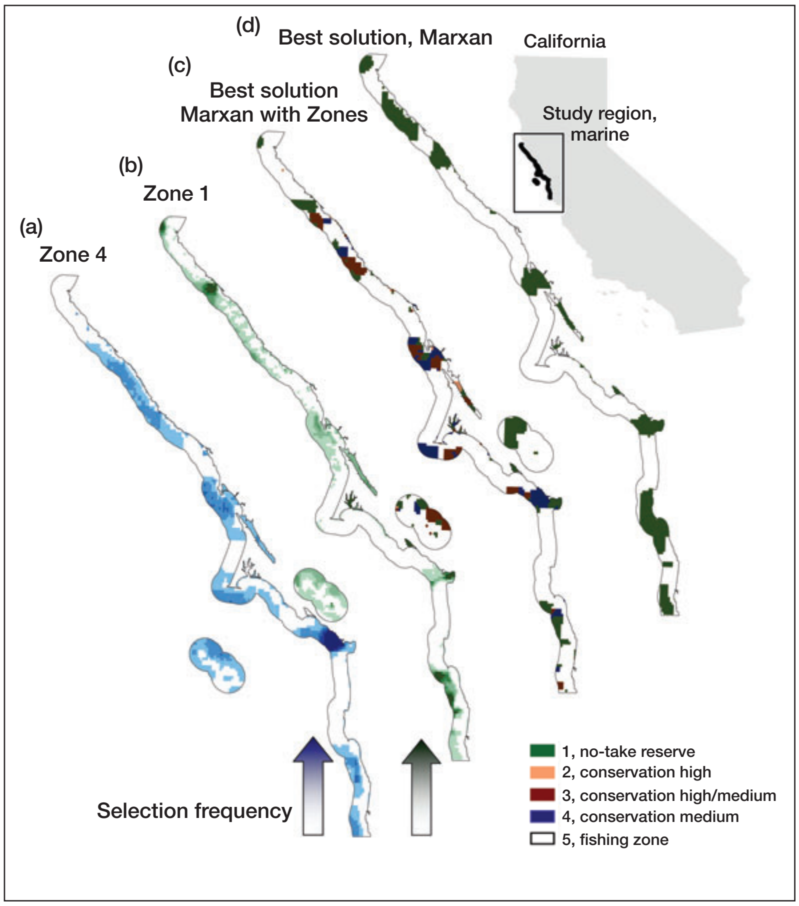

Figure 1. *The zoning solutions are displayed as the frequency with which sites are selected for an indicated zone (selection frequency) across 100 individual solutions and as the best solution (ie achieves targets for the least cost). (a) Zone 4 selection frequency via Marxan with Zones (Scenario 2); (b) Zone 1 selection frequency via Marxan with Zones (Scenario 2); (c) best solution via Marxan with Zones (Scenario 2); and (d) best solution via Marxan (without zoning). The study region is located off the northern part of California's central coast.*

Here, we present the first application of such a multi-zone numerical optimization tool to design a network of MPAs, using the objectives and zones defined by California's Marine Life Protection Act Initiative (hereafter, "Initiative"). We identify multiple zoning configurations for four different types of MPAs with different fishing restrictions and biodiversity conservation targets. Our aim is to determine what, if any, socioeconomic advantages can be delivered by a tool that allows for multiple zones versus a tool that can identify only one type of MPA. We also examine the tradeoffs between representing biodiversity features and impacting fisheries.

Methods

Policy context and planning region

California's Marine Life Protection Act mandates the design of a network of MPAs. The planning team divided the state waters into five regions, in which planning takes place in successive stages, from 2004 to 2011. Two regions have undergone a stakeholder-driven design process informed by managers, administrators, and scientists. Our analysis was conducted on the region defined by the 5556-m legal limits to California's state waters from Pigeon Point (37.185°N latitude, 122.39°W longitude) to Alder Creek (39.005°N, 123.696°W) and around the Farallon Islands (37.733°N, 123.033°W) – exclusive of San Francisco Bay – a total area of 1977.5 km^2 (Figure 1). We divided the region into 3610 planning units, each of which could be allocated to a zone. We addressed two of the Initiative's core objectives in designing a network of MPAs: (1) protect representative and unique habitats, and (2) minimize negative socioeconomic impacts (Klein *et al.* 2008b).

Data

We used the same spatial data representing habitats, depth zones, and commercial fishing value as used in the Initiative. Habitats included coastal marshes, eelgrass, estuaries, hard bottom, kelp forests, soft bottom, surfgrass, and tidal flats (CDFG 2007). We subdivided these features into three biogeographic regions (North, South, and the Farallon Islands) and three depth zones (intertidal, intertidal–30 m, and 30–100 m). Thirty-two separate biodiversity features were targeted for inclusion in a MPA.

Spatial fishing data were derived from 174 interviews with fishermen, conducted in 2007 (Scholz *et al.* 2008). The surveys attempted to capture information from at least 50% of the landings and/or ex-vessel revenue from 2000–2006, and at least five fishermen per fishery. These data include the value in 2006 US dollars of a given planning unit to individual fishermen across eight commercial fisheries: California halibut (CH), chinook salmon (CS), coastal pelagic finfish (CPF), dungeness crab (DC), deep nearshore rockfish (DNR), market squid (MS), nearshore rockfish (NR), and sea urchin (SU). Recreational fishing data were not included in our analysis, because high-quality, spatially explicit data for recreational fishing were unavailable.

Zoning

Marxan (Ball and Possingham 2000; Possingham *et al.* 2000), the most commonly used protected-area design tool, was modified so that it can identify solutions with multiple zones. We used the resulting Marxan with Zones (Watts *et al.* 2009) to design a network of MPAs. We planned for five zones, each restricted to different fisheries (in parentheses below), as defined in the Initiative:

(1) no-take marine reserve (all fisheries restricted); (2) conservation area, high (CH, DC, DNR, NR, MS, SU, CS <50 m); (3) conservation area, high/medium (CH, DNR, NR, SU); (4) conservation area, medium (DNR, NR, SU); and (5) commercial fishing zone (no fishing restrictions). Marxan with Zones aims to identify a zoning configuration that achieves a set of targets for a minimum "cost". To satisfy the Initiative's objective of minimizing negative socioeconomic impact, we define cost as commercial fishing value. The cost of placing a particular planning unit ($i = 1,\ldots,M$) into a particular zone ($j = 1,\ldots,N$) is represented by c_{ij}, which is the sum of value for all fisheries ($k = 1,\ldots,P$) not allowed to fish in that zone:

$$c_{ij} = \sum_{k=1}^{P} a_{ik} b_{kj} ,$$

where a_{ik} is the value of the i^{th} planning unit to the k^{th} fishery, and b_{kj} indicates if the k^{th} fishery is not allowed to fish in the j^{th} zone. If the k^{th} fishery is not allowed to fish in the j^{th} zone, $b_{kj} = 1$; otherwise, b_{kj} is equal to 0.

Marxan with Zones minimizes the total cost of the zoning plan (C):

$$\mathrm{C} = \sum_{i=1}^{M} \sum_{j=1}^{N} c_{ij} x_{ij} ,$$

where $x_{ij} = 1$ if the i^{th} planning unit is included in the j^{th} zone, subject to the constraint that a set of zone-specific targets and a planning unit can only be placed in one zone, such that:

$$\sum_{j=1}^{N} x_{ij} = 1 .$$

We implemented Marxan with Zones for two different scenarios, each with different zone-specific targets (Watts *et al.* 2009). In Scenario 1, we represented 10% of the distribution of each biodiversity feature in a no-take reserve (Zone 1) and an additional 20% in any of the four protected-area zones (Zones 1–4). We evaluated the results of Scenario 1 to determine the proportion of lost value overall as well as for each of the fisheries. In Scenario 2, in an attempt to more equitably affect the fisheries, we also targeted a percentage of each fishery's total value, where the fishing targets could only be achieved in zones where the given fishery was not restricted. We targeted the same proportion for each fishery and incrementally increased the target by 1% until 100% of the fishing grounds were placed in a zone without spatial fishing regulations. We evaluated the results of Scenario 2 to determine the tradeoffs between representing biodiversity features and impacting fisheries. In addition, we compared the results of our scenarios to those produced using Marxan (without zoning), where we targeted 30% of each biodiversity feature for inclusion in a no-take reserve. Given that Marxan can select areas important for only one type of protected area, we assume that selected areas are a cost to all fisheries. We did not compare the results with those derived from other systematic conservation planning tools (eg Zonation, C-Plan), because they solve different mathematical problems.

Marxan with Zones uses a simulated annealing algorithm to identify near-optimal zoning configurations that minimize the sum of planning unit and zone boundary costs (Watts *et al.* 2009). To control for the level of fragmentation of solutions, the user can indicate the relative importance of minimizing the boundary of the selected areas within a zone, relative to their planning unit cost, by adjusting a parameter called the "zone boundary cost" (Watts *et al.* 2009). We chose a zone boundary cost for each zone that produced solutions that represented an acceptable tradeoff between boundary length and cost, using a method based on that developed by Stewart and Possingham (2005). We generated 100 different, near-optimal solutions with different spatial configurations for each scenario.

Results

We compare the solutions to each scenario in terms of impact on individual fisheries and the commercial fishery as a whole (Figure 2). Fishing targets of up to 91% for each fishery could be achieved, while still meeting the biodiversity targets. This entails value losses of less than 9% for every fishery. However, in the scenario without fishing targets (Scenario 1), three of the fisheries lost

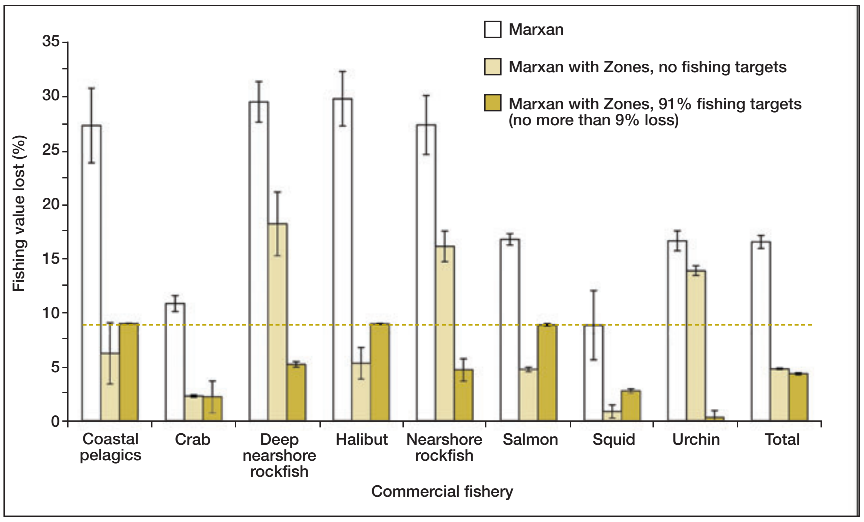

Figure 2. *Proportion of fishing value lost to each individual fishery, and the commercial fishery as a whole, in protected-area networks designed via Marxan and Marxan with Zones (with and without fishing targets). The average (± standard deviation) value lost across 10 solutions that achieved the planning objectives for the least cost is displayed.*

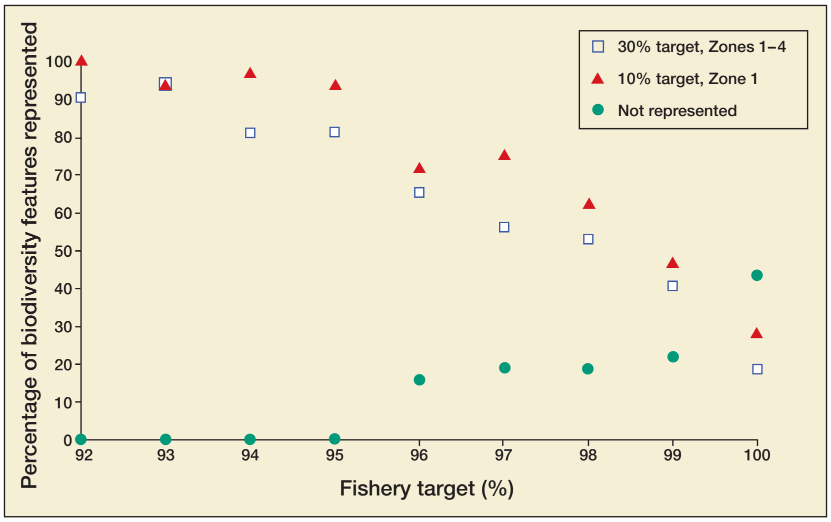

Figure 3. *Tradeoffs made between achieving the zone-specific biodiversity targets and fishing targets for the best solution (ie the solution that achieves targets for the least cost) to each scenario with different fishing targets. When the fishing target is < 92%, the targets for all biodiversity features are achieved.*

> 9% of their value, with one losing 18% of its value. Although the overall impact across the fisheries between scenarios is similar (Figure 2), the addition of fishing targets in Scenario 2 ensured a more equitable impact on individual fisheries. As predicted, solutions produced with Marxan have greater negative impact on fisheries than those produced using zoning software (Figure 2).

When the fishing target for each fishery is greater than 91%, not all of the biodiversity targets can be achieved. We examined the tradeoffs between achieving the zone-specific biodiversity targets and fishing targets for scenarios with different fishing targets (Figure 3). As the fishing target is increased, the number of biodiversity features that achieve both zone-specific targets declines. If we target 93% and 95% of the value for each fishery, the resulting solution achieves its targets for 90% and 80% of the biodiversity features, respectively. If the fishing targets are > 96%, 16–44% of the biodiversity features are not represented in a MPA.

MPA Zones 1 and 4 are frequently selected to achieve the planning objectives (Figure 1). Zones 2 and 3 are not often selected for two reasons. First, they have more fishing restrictions than does Zone 4, thereby making them more costly to implement; second, we did not constrain biodiversity targets to these zones, as was done in Zone 1. In some planning units, the cost of allocating to more than one zone is equivalent. For example, the cost of allocating a planning unit to Zones 3 and 4 is equivalent where halibut fishing does not occur. This is because the only difference between the zones is that halibut fishing is allowed in Zone 4. In such cases, planning units have an equal chance of being allocated to zones with equivalent costs. On the other hand, the selection frequency of Zone 4 is high in areas valuable to the halibut fishery, because it is the only MPA zone that allows halibut fishing. Figure 1 shows the selection frequency of Zones 1 and 4, as well as the "best" solution (ie achieves targets for the least cost) to Scenario 2.

Discussion

Zoning of the ocean has captured the interest of many, as a means to protect biodiversity, manage fisheries, implement ecosystem-based management, and plan for climate change (Douvere 2008). A major limitation of existing spatial planning approaches is their inability to simultaneously consider different types of zones with different possible uses. We demonstrate the first application of the multi-zone planning tool, Marxan with Zones (Watts *et al.* 2009), to design a network of four types of MPAs.

We found that a spatial numerical optimization tool that allows for multiple zones outperforms a tool that can identify marine reserves, in two ways. First, the overall impact on the fishing industry is reduced. Second, there is a more equitable impact on different fishing sectors. These results confirm that, for any optimization problem, expanding the control variables results in greater flexibility and better outcomes (Tuck and Possingham 2000; Grantham *et al.* 2008). In Marxan with Zones, the addition of zones and the ability to specify certain costs and targets for each zone are the control variables that offer improved results over Marxan.

Marxan with Zones can accommodate more specific constraints that can be applied to consider both biodiversity and socioeconomic considerations. We demonstrate this functionality by setting two types of zone-specific constraints: (1) biodiversity targets for MPAs and (2) fishery targets in zones where fishing is allowed for a particular fishery. We applied the software both with and without fishing targets and found that the addition of fishing targets produces solutions that affect the individual fishing sectors more equitably. Although a socially and politically favored outcome in this context (Klein *et al.* 2008a), this may not be desirable in other planning processes. Other options for setting fishing targets are to apply a different fishing target for each fishery where, for example, the target is proportional to the overall value of the commercial fishing industry. Alternatively, targets could reflect the minimum value needed for the fishery to remain profitable, derived from population modeling that considers a fishery's sustainability. In addition, more specific fishing targets could be set for each fishery at each port, to better control for the impacts to different fishing communities.

Our estimation of impact assumes that each MPA eliminates fishing opportunities in areas closed to specific fisheries and that fishermen are unable to mitigate the impacts in other ways. This assumption is most likely an overestimation, making our estimation of impact a "worstcase scenario", because some fishing effort would shift to unprotected areas (Scholz *et al.* 2008). Our cost (fishing value) does not represent the true cost to fishermen and could be improved by considering the spatial variation of fishing costs, other fishing industries (eg recreational), benefits of spillover (ie export of fish from inside to outside of a protected area), and redistribution of effort after reservation (ie change in fishing location and intensity after protected areas are implemented). This is an important area of further research, albeit one that requires substantial amounts of information on fleet behavior, fish populations, and other dynamic parameters (Pelletier and Mahevas 2005; Branch *et al.* 2006).

Designing protected areas that consider both socioeconomic and biodiversity factors has moved to the forefront of conservation planning (Stewart and Possingham 2005; Klein *et al.* 2008a). We demonstrate a method for evaluating zoning plans that shows the tradeoffs between achieving biodiversity and fishing targets. In any planning process, tradeoffs between conservation and socioeconomic interests will be made; if these tradeoffs are not transparent in a planning process, the result may not adequately conserve marine ecosystems. We show results for one set of zone-specific conservation targets, although there may be utility in analyzing tradeoffs with other targets. Our biodiversity targets do not reflect what is adequate to ensure their protection, and the result of their application is not meant for implementation, but rather to demonstrate novel approaches to planning for conservation.

We suggest that the use of planning tools complements, rather than replaces, a stakeholder-driven zoning process (Klein *et al.* 2008b). California will design MPAs along the entire coast by 2011 to satisfy the state's Marine Life Protection Act. Adapting ideas from this article into the process can help stakeholders and decision makers to implement MPAs that balance competing socioeconomic and biodiversity interests. Moreover, our approach is applicable to both marine and terrestrial conservation planning. It delivers an ecosystem-based management outcome that balances conservation and industry objectives.

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