LETTER

Effectiveness of marine reserve networks in representing biodiversity and minimizing impact to fishermen: a comparison of two approaches used in California

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Abstract

We compared the effectiveness of marine reserve networks designed using a numerical optimization tool with networks designed by stakeholders during the course of California's Marine Life Protection Act Initiative at representing biodiversity and minimizing estimated negative impacts to fishermen. We used the same spatial data representing biodiversity and recreational fishing effort that were used by the stakeholders to design marine reserves. In addition, we used commercial fishing data not explicitly available to the stakeholders. Networks of marine reserves designed with numerical optimization tools represented the same amount of each habitat, or more, and had less of an estimated impact on commercial and recreational fisheries than networks designed by the stakeholders. The networks designed by the stakeholders could have represented 2.0–9.5% more of each habitat with no additional impact on the fisheries. Of four different marine reserve proposals considered in the initiative, the proposal designed by fishermen was more efficient than the proposals designed by other stakeholder groups at representing biodiversity and minimizing impact to the fishing industry. These results highlight the necessity of using comprehensive information on fishing effort to design a reserve network that efficiently minimizes negative socioeconomic impacts. We recommend that numerical optimization tools support, not replace, the stakeholder-driven reserve design process along California's northern and southern coasts to help accomplish two of the initiative's core objectives: (1) Protect representative and unique marine habitats, and (2) Minimize negative socioeconomic impacts. The involvement of stakeholders is necessary as additional factors important to reserve design can not be considered using a numerical optimization tool.

Introduction

Reservation of the ocean has captured the interest of regional, national, and international agencies as a means to protect biodiversity and manage fisheries. As a result, many initiatives have been established to promote the design and implementation of marine reserves around the globe (e.g., World Commission on Protected Areas, Australia's Environmental Protection and Biodiversity Conservation Act, California's Marine Life Protection Act). Various marine reserve design approaches have been explored in the academic literature and in practice. One long-standing approach is to use numerical optimization tools to design marine reserve networks that meet biodiversity targets efficiently (Kirkpatrick 1983; Leslie *et al.* 2003). Despite the prevalence of this approach in academic literature, there are few practical applications that have used numerical optimization tools to design marine reserves.

The use of numerical optimization tools to design marine reserves is not widely accepted for various reasons. A primary reason for rejection is that most applications do not use socioeconomic data to inform the location of reserves. Successful marine reserve design processes involve stakeholders and consider socioeconomic information to select reserves (Kelleher 1999; Salm *et al.* 2000; NRC 2001; Richardson *et al.* 2006). Recently, researchers have demonstrated how socioeconomic information can be used to determine the location of reserves with numerical optimization tools, without compromising biodiversity conservation objectives. Stewart & Possingham (2005), Richardson *et al.* (2006), and Klein *et al.* (2008) found that incorporating fine-resolution commercial fishing information in marine reserve design substantially reduces the economic losses incurred by fishermen (Although seemingly anachronistic, fishermen of both genders tend to refer to themselves as fisher*men*. We follow this usage, not least since the more scholarly "fisher" or "fisherperson" is considered offensive), compared with reserves designed without consideration of fishery losses. The primary socioeconomic focus of these studies was the interests of fishing groups, as marine reserves are often considered a conflict between fishing and conservation interests.

In this article, we compare the effectiveness of marine reserve networks designed using a numerical optimization tool with networks designed by groups of stakeholders in California's Marine Life Protection Act Initiative at representing biodiversity and minimizing estimated negative impacts to fishermen. As part of the initiative, three stakeholder groups each developed a proposal for marine protected areas along the central coast of California, the first of five regions in the state to undergo a stakeholder-driven protected area design process. Two core objectives of the initiative were to protect representative and unique marine habitats and minimize negative socioeconomic impacts (CDFG 2005a). We used a numerical optimization tool, Marxan (Ball & Possingham 2000; Possingham *et al.* 2000), to design reserve networks that are consistent with these objectives. We compare the efficiency of resulting solutions at representing marine habitats and minimizing impact to fisheries with that achieved by networks designed in the initiative.

The involvement of stakeholders in marine reserve design is necessary as not all factors important to reserve design can be considered using a numerical optimization tool. As the initiative expands to California's northern and southern marine regions, it will continue to be driven by stakeholders. The exact design approach is flexible, however, and this study can be used to inform the marine reserve design processes in the other regions of California and around the world. In this article, we suggest ways that numerical optimization tools can support stakeholder-driven marine reserve design processes to help accomplish two common design objectives: (1) Protect representative and unique marine habitats, and (2) Minimize negative socioeconomic impacts.

Methods

Policy context and planning region

There are six goals in California's Marine Life Protection Act that mandate the design of a network of marine protected areas that protect marine life and habitats, ecosystems, natural heritage and improve recreational, educational, and study opportunities provided by marine ecosystems (State of California 1999). As part of the initiative to implement the Act, *Regional Goals and Objectives* (CDFG 2005a) were developed by stakeholders in consultation with administrators, managers, and scientists to help the stakeholder groups design networks of protected areas consistent with the Act's goals. The scientific advisory team provided guidelines (Table 1) that quantified the science-related *Regional Goals and Objectives* (CDFG 2005b). The scientists consolidated the guidelines into evaluation criteria that were used to measure how well the proposed networks achieved the Act's goals. The initiative's scientific guidelines address a majority of the initiative's *Regional Goals and Objectives* and were used as the basis for our analysis. We did not aim to design networks that achieved all of the scientific guidelines for two reasons: (1) Our analysis was only concerned with no-take marine reserves and the scientific guidelines

Table 1 Summary of the initiative's scientific guidelines

1. The diversity of species, habitats, and human uses prevents a single optimum network design.
2. Every "key" marine habitat (Table 1) should be represented in the network.
3. Protected areas should extend from the intertidal zone to deep waters.
4. Protected areas should have an alongshore span of 5–20 km.
5. Protected areas should be placed within 50–100 km of each other.
6. Each "key" habitat should be replicated at least 3–5 times.
7. Placement should take into account local resource use and stakeholder activities.
8. Placement should take into account the adjacent terrestrial environment and associated human activities.
9. Network design should account for the need to evaluate and monitor biological changes within the protected areas.

The scientific guidelines address a majority of the initiative's *Regional Goals and Objectives* (CDFG 2005b).

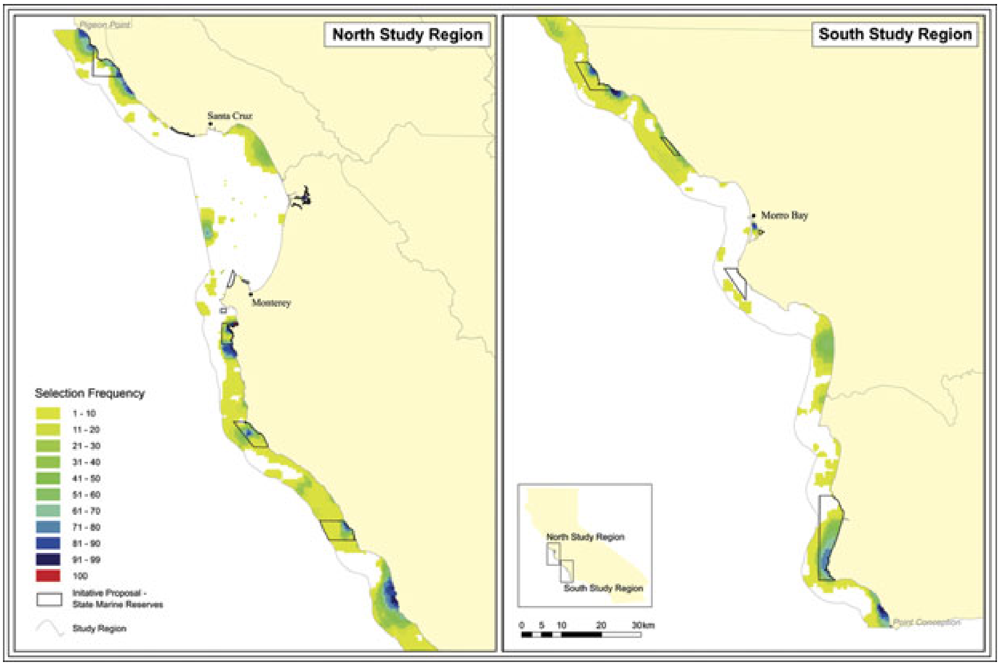

Figure 1 Comparison of the spatial configuration of marine reserves designed in the California Marine Life Protection Act Initiative (network 4) and marine reserves designed using Marxan software (with all fishing data). The Marxan solutions are displayed as the frequency with which sites are selected (selection frequency) across 100 individual solutions that achieve the biodiversity conservation and socioeconomic objectives reasonably efficiently.

applied to all three types of protected areas considered in the initiative; and (2) None of the initiatives networks met all of the guidelines (Scientific Advisory Team 2006). We addressed guideline 1 by producing multiple networks that accomplish the objectives; guideline 2 by representing the same amount of each habitat represented in the initiative's reserves; guideline 3 by targeting each feature in five different depth zones; guidelines 4, 5, and 6 by ensuring the size, spacing, and replication of the best solution were comparable to the initiative's reserves; and guideline 7 by minimizing negative impact on commercial and recreational fisheries. Scientific guidelines 8 and 9 were not addressed in our analysis because they were not considered in the scientific evaluation of the initiative's networks.

The central California coast planning region (Figure 1) was defined by the state water boundaries from Pigeon Point (37° 11′ 6.7554′ Lat., –122° 23′ 29.3994′ Long.) to Point Conception (34° 26′ 56.3994′ Lat., –120° 28′ 14.5194′ Long.). The area of the planning region is 2,978 km^2, extending from the shore out to 3 nautical-miles (5.6 km) in most areas.

Data

We used the same spatial data representing biodiversity attributes (i.e., habitats and depth zones) and recreational fishing effort used in the initiative. We also used fine-scale spatial commercial fishing effort data that were not available to the initiative's stakeholders to design marine reserves (Scholz *et al.* 2006). Because of the poor spatial resolution of California landings data, we did not use revenue data.

Biodiversity data represented three types of rocky reef, soft bottom, two types of kelp forests, submarine canyons, eelgrass, surfgrass, and estuaries (Table 2). In the initiative and in this article, many of the biodiversity features were subdivided along five depth zones—intertidal, intertidal–30 m, 30–100 m, 100–200 m, >200 m.

Recreational fishing is defined as fishing from charter, private, or rental boats. Surveys conducted by the California Department of Fish and Game depict the number of fishing trips made to each planning unit (site that could be selected for reservation) for seven fisheries (Scholz *et al.* 2006). We used the number of fishing trips made to each planning unit as a surrogate for recreational fishing effort.

Commercial fishing data were derived from 109 in-person interviews with commercial fishermen in 2005 (Scholz *et al.* 2006). Trained field staff equipped with a geographical information system and electronic nautical maps asked fishermen to map their fishing grounds and indicate their relative importance. For each fishery, the surveys aimed to capture fishing information from at least

Table 2 Amount of each habitat across various depth zones in four networks of marine reserves considered in the initiative

Key habitats	Depth zones	1	2	3	4
Estuary (km^2)		2.90	4.01	4.06	3.22
Sand beach (km)		51.7	84.1	79.4	75.4
Shallow sand (km^2)		67.0	85.4	82.3	93.6
Deep sand (km^2)	30–100 m	34.4	159.8	90.9	70.6
	100–200 m	1.22	13.5	2.87	2.33
	> 200 m	16.0	31.1	33.2	18.2
Rocky intertidal (km)		74.7	119	106	88.7
Shallow rock (km^2)		22.5	53.3	53.0	42.4
Deep rock (km^2)	30–100 m	3.3	20.3	12.3	12.1
	100–200 m	0.0981	4.37	0.180	0.0430
	> 200 m	0.412	3.99	0.127	0.0763
Kelp, presence ’89, ’99, ’02, ’03 (km^2)		9.61	22.9	21.7	19.3
Kelp, persistent 3/4 years (km^2)		2.20	2.44	2.10	1.52
Shallow canyon (km^2)		0.135	0.0310	0.139	0.170
Deep canyon (km^2)	30–100 m	0.393	0.465	0.432	0.668
	100–200 m	0.700	0.603	0.452	0.743
	> 200 m	5.49	12.9	11.2	8.20
Additional habitats					
Coastal marsh (km)		21.4	28.3	19.9	18.3
Eelgrass (km^2)		0.0845	0.108	0.0856	0.0674
Surfgrass (km)		64.9	97.1	91.7	76.1
Tidal flats (km)		21.5	22.7	17.6	15.9

Note: These amounts were used as targets to design networks of marine reserves using the Marxan software. “Key” habitats are defined in the Marine Life Protection Act. The additional habitats and depth zones were added as important features by the scientific advisory team.

50% of the landings in 2003–2004, or at least five fishermen per fishery. These data include the relative importance of a given planning unit to individual fishermen across 19 commercial fisheries. We used the relative importance of each planning unit to a fishery as a surrogate for commercial fishing effort.

An index of relative fishing effort across all commercial and recreational fisheries was calculated in Klein *et al.* (2008) and was used to determine the estimated impact to fisheries in this study. The method used to calculate the index assigned greater weight to planning units that were proportionally more important to fishermen in a particular fishery, regardless of the total effort of the fishing industry. Thus, the index is not proportional to the total extractive economic value of each planning unit. This approach increased the likelihood that each fishery would be affected in equal proportion by areas closed to fishing.

Reserve design—initiative’s approach

A different network of marine protected areas was proposed by three different subgroups and evaluated by the initiative’s scientific advisors. Network 1 was developed by commercial and recreational fishermen, network 2 was developed by conservationists, and network 3 was developed by a mixed interest group. The stakeholders in these three groups comprise a larger stakeholder group of 29 core members and 27 alternates that were chosen to represent fishing, conservation, tourism, and recreational interests of the region. Using the information from the three proposed networks, the Fish and Game Commission developed network 4 for implementation. (This network was accepted for implementation as of August 15, 2006; after this date minor changes were made to this network and it was implemented on September 21, 2007).

Each network was evaluated by the scientific advisory team on the basis of the scientific guidelines (Table 1). Scientists computed the size of and spacing between protected areas, the estimated impact of each network on commercial and recreational fisheries, and the amount of habitat represented across various depth zones (Table 2). With this information, each stakeholder group had the opportunity to revise their proposal to better address the guidelines pertaining to the initiative’s science related goals and objectives (CDFG 2005b). The networks and individual protected areas within the networks were not required to achieve the scientific guidelines (CDFG 2005b). During the design process, stakeholders had access to a web-based geographic information system to view biodiversity and recreational fishing data. They did not have access to the commercial fishing data and relied, in an indirect way, upon evaluation information from the scientific advisors to determine the impact of their network on fishing.

Reserve design—numerical optimization approach

The primary objective was to identify places that include a portion of each biodiversity feature while minimizing the estimated impact on the fishing industry. For each biodiversity feature, we targeted the amount contained in each of the initiative’s networks (Table 2). We identify near-optimal solutions that achieve this objective using reserve design software called Marxan (Ball & Possingham 2000; Possingham *et al.* 2000). Marxan uses a simulated annealing algorithm to select areas that minimize the sum of planning unit and boundary costs while ensuring that conservation targets are met (Possingham *et al.* 2000). By adjusting a parameter called the boundary length modifier, the user can indicate the relative importance of minimizing the boundary of the selected areas relative to their cost to control for the level of fragmentation of the solutions. We used a boundary length modifier of 0.001, which allowed Marxan to select clustered groups of planning units (i.e., candidate reserves) that were comparable in size and spacing to the reserves proposed by the initiative's proposals. The planning units ($n = 13{,}328$) were typically 500 meters square, but their size varied at the region's borders. Using the same biodiversity data, we applied Marxan with two different planning unit costs: (1) Limited fishing data—we used the same fishing data (i.e., recreational) available to the stakeholders in the initiative; (2) All fishing data—In addition to the recreational data, we used commercial fishing data not explicitly available to the stakeholders in the initiative. The planning unit cost was defined as the relative fishing effort of seven recreational fisheries (with limited fishing data) and of 26 commercial and recreational fisheries (with all fishing data) (Klein *et al.* 2008). Each planning unit cost reflected what portion of the fishing effort would be lost if designated a reserve.

Solutions to four scenarios were generated that represent, at minimum, the same amount of each biodiversity feature as each of the initiative's network of marine reserves. There are many good solutions with different spatial configurations that satisfy the planning objectives. We produced 100 good solutions using Marxan.

Comparison

Although three types of protected areas were designed in the initiative, we restricted our analysis to no-take marine reserves because our approach cannot simultaneously identify multiple zones with different protection levels. We compared the efficiency of each approach at minimizing impact to fisheries, reported as lost effort due to reservation. We used this information to determine if more of each habitat could be represented in a reserve network with no additional fishing effort lost. To do this, we increased the target amount of each habitat by an equal percentage until solutions with the desired impact were produced. Finally, we compared the areas frequently selected (>90%) in our analysis with the areas selected in the initiative's networks.

Results

Estimated fishing impact

When equivalent biodiversity and fishing data were used in Marxan, the networks had less of an impact on fisheries than networks designed in the initiative for scenarios 2, 3, and 4 and a greater impact than the network designed by fishermen (Figure 2). When additional

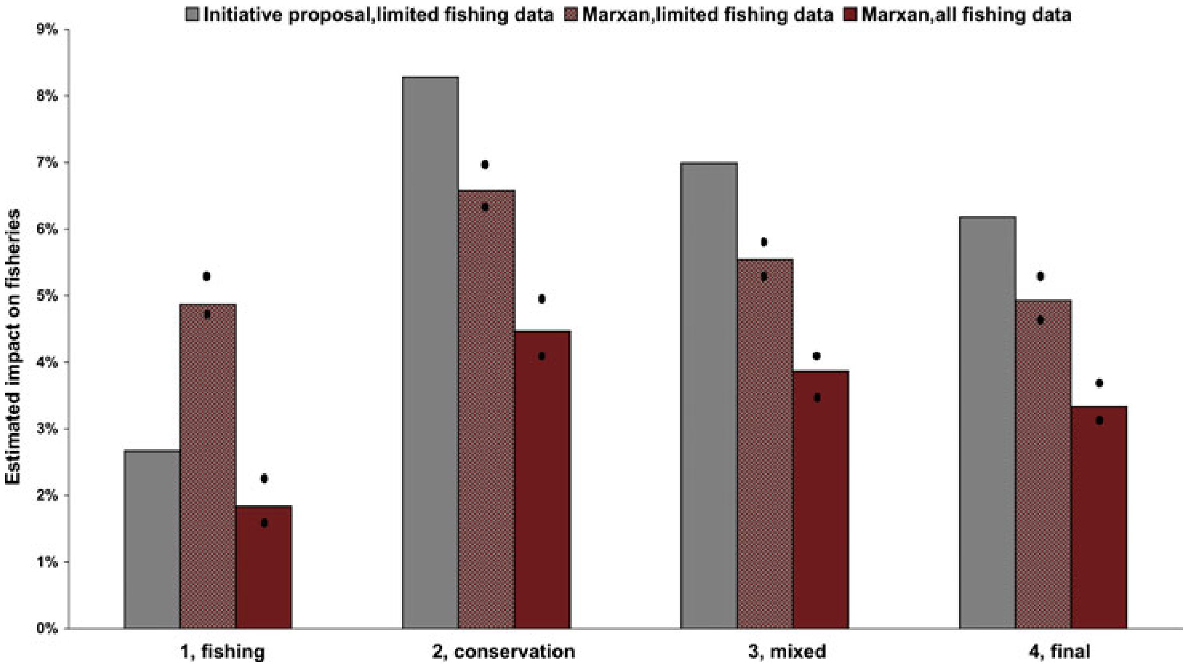

Figure 2 Comparison of the impact of marine reserve networks designed in the initiative and with Marxan on commercial and recreational fisheries. The fishing impact from the best, minimum and maximum cost solution of 100 Marxan solutions that achieved the planning objectives is displayed. The minimum and maximum cost solutions are indicated with a black dot. Network 1 was developed by commercial and recreational fishers, network 2 by conservationists, network 3 by a mixed interest group, and network 4 was the solution selected for implementation by The California Fish and Game Commission on August 15, 2006.

Table 3 Percentage of study region reserved in networks designed in the initiative and using Marxan (all fishing data)

	1	2	3	4
Initiative	5.13%	12.81%	9.52%	8.32%
Marxan	5.15%	12.68%	9.58%	8.39%

fishing data were used in Marxan, the networks had less of an impact on fisheries than all four networks designed in the initiative (Figure 2). The networks designed by fishermen (network 1) had the lowest impact on fisheries and were most efficient at meeting biodiversity targets for a minimum cost. The percentage of the study region reserved by networks designed using different approaches was comparable (Table 3). Interestingly, the networks designed with Marxan (with all fishing data) were slightly larger than the initiative's networks 1, 3, and 4 and had less of an impact on fisheries. Because of the size differences between the networks designed in the initiative and with Marxan, we calculated the impact per area of each network. Per unit area, the initiative's networks 1 to 4 impacted fisheries 1.5, 1.8, 1.8, and 1.9 times more than the average network designed in Marxan (with all fishing data), respectively. The amount of each habitat represented in the initiative's reserves was the minimum amount represented in the reserves designed by Marxan.

Habitat representation

Marine reserves with the same impact as the initiative's proposals could protect more of each habitat. At least 2%, 9.5%, 8.5%, and 6% more of each habitat could be protected in proposals 1 to 4, respectively, without having a greater impact on the total fishing industry.

Selection frequency

Some planning units are always selected, and thus necessary to meet the stated planning objectives (Figure 1). The initiative's networks 1-4 contained 100%, 72%, 100%, and 100%, respectively, of the planning units always selected in 100 Marxan solutions (all fishing data). Other planning units are frequently selected (> 90%), and thus important to meet the planning objectives (Figure 1). The initiative's networks 1–4 contained 78%, 53%, 52%, and 33%, respectively, of the planning units frequently selected in 100 Marxan solutions (all fishing data).

Discussion

Of the four marine reserve networks considered in California's Marine Life Protection Act Initiative, the proposal design by the fishermen was most efficient at representing biodiversity and minimizing estimated impacts to the fishing industry. The fishermen had experiential knowledge of the spatial distribution of fishing effort and used this information to design networks that had minimal negative impact on their industry (CDFG 2005a). The other stakeholders had less knowledge of fishing effort and did not have access to fine-scale commercial fishing data due to confidentiality considerations. If the other stakeholder groups were provided with this information, they could have been more efficient at representing biodiversity and minimizing impact to the fishing industry. As demonstrated in this article, using a numerical optimization tool, Marxan, makes it possible to incorporate confidential fishing data into marine reserve design without revealing the identity of specific fisheries or individual fishing grounds.

Using the Marxan software, we designed networks of marine reserves that represented at least the same amount of each habitat and had less of an impact on commercial and recreational fisheries than networks designed by the stakeholder groups in the initiative. When using Marxan and the same data used by the stakeholder groups, networks 2–4 had less of an impact on commercial and recreational fisheries whereas network 1 had more of an impact than the networks designed in the initiative. Given equivalent biodiversity and fishing information, the use of Marxan can produce networks that have a lower negative impact on fisheries than networks designed without using an optimization tool. The additional experiential knowledge held by the fishermen allowed them to design a network of marine reserves that had less negative impact on the fisheries than networks designed with limited fishing data (recreational only) in Marxan. This indicates that, regardless of design method, knowledge of fishing effort is an important factor in designing networks that represent habitat and minimize negative impact on fisheries. However, achieving the objective of designing networks that aim to minimize impact on fishermen while achieving habitat representation goals can be designed most efficiently when both Marxan and comprehensive fishing data are used in their design. In addition, we show how Marxan can be used to design networks of marine reserves that represented more of each habitat with an equivalent impact on the fisheries as the networks designed by the stakeholders.

The results depicting the estimated impact of marine reserves on fishermen are dependent on the data collection methods of the fishing effort and the index that we used to measure effort. The data were collected from a representative sample of fishermen from each fishery across the entire study region. As a result, use of these data to design reserves could cause spatially separated fishing communities to incur a different amount of impact. To mitigate for this effect, fishing data should be collected from a representative sample of fishermen from each community. In addition, there is a substantial amount of discussion about how marine reserves impact fisheries and what factors determine these impacts (Nowlis & Roberts 1999; Roberts *et al.* 2001; Gell & Roberts 2003). Factors not considered in the index used (e.g., redistribution of effort after reservation and the benefits of spillover on fisheries) may be important for determining the impact of reserves on fishermen (Klein *et al.* 2008; White & Kendall 2007). This is an important area of further research, albeit one that requires substantial amounts of information on fleet behavior and other dynamic parameters. This type of data was not available for this analysis and, in fact, the fishing data that we used to determine the fishing effort index contained more detail and are of a higher quality than typically available in marine planning.

The initiative's scientific guidelines address a majority of the initiative's *Regional Goals and Objectives* and were used as the basis for our analysis. We designed networks that minimized estimated negative impact on fishermen and were comparable to the reserve networks designed in the initiative in terms of habitat representation, size, and spacing. In reality, however, the stakeholders considered additional factors not included in the scientific guidelines (e.g., enforcement, other zones) in designing networks of protected areas that we were unable to consider due to data availability and computational constraints. These additional considerations may have influenced the location, and thus impact to fisheries, of the reserves. If we could consider these additional factors in Marxan, the impact of the resulting networks on fishermen may be different from the results presented. An ideal comparison of two approaches would have identical design criteria.

Given these caveats, we suggest that the use of Marxan complement, not replace, a stakeholder-driven reserve design process, given reliable data across the planning region. Stakeholders play the central role in defining the conservation and socioeconomic objectives used to design protected areas (Richardson & Funk 1999). The quantitative objectives (e.g., conservation targets, protected area size) could be applied using Marxan to produce potential sites for reservation, providing a starting point for discussion between stakeholders. The stakeholders could then alter the exact boundaries of the protected areas taking into account other considerations important to a reserve design process (e.g., enforcement). In addition, if stakeholders reach consensus about important areas to include and exclude from a reserve system, this information can be used in Marxan to design reserves that accommodate these preferences. Using Marxan, stakeholders could identify areas that are always or frequently selected to achieve the biodiversity conservation and socioeconomic objectives. Unless there are substantial mitigating factors, stakeholders should include areas frequently selected in Marxan, that is, those required to efficiently achieve the biodiversity conservation and socioeconomic objectives (Pressey 1998; Ferrier *et al.* 2000), in their network proposals (Carwardine *et al.* 2005). Network 4, chosen on August 15, 2006 by the California Fish and Game Commission for implementation, does not include reserves in six areas that were selected frequently in Marxan (Figure 1). Instead, there are six reserves in network 4 that were never selected in Marxan. The inclusion of the areas selected frequently instead of the areas never selected may have resulted in solutions that more efficiently achieve the planning objectives.

California will undergo marine reserve design processes along the state's northern and southern coasts by 2011 to satisfy California's Marine Life Protection Act Initiative. Adopting ideas from this article into the remaining marine reserve design processes will help stakeholders design marine reserves that accomplish two of the initiative's core objectives: (1) Protect representative and unique marine habitats, and (2) Minimize negative socioeconomic impacts (CDFG 2005a). In addition, the methods used in this article can be adapted to marine and terrestrial conservation planning processes anywhere in the world.

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