## Title
Striking a balance between biodiversity conservation and socioeconomic viability in the design of marine protected areas.



## Journal
Conservation biology : the journal of the Society for Conservation Biology, 22(3)

## ISSN
0888-8892

## Authors
Klein, CJ
Chan, A
Kircher, L
et al.

## Publication Date
2008-06-01

## DOI
10.1111/j.1523-1739.2008.00896.x

Peer reviewed

*Contributed Paper*

# Striking a Balance between Biodiversity Conservation and Socioeconomic Viability in the Design of Marine Protected Areas

C. J. KLEIN,*†‡‡ A. CHAN,† L. KIRCHER,*† A. J. CUNDIFF,‡† N. GARDNER,**† Y. HROVAT,† A. SCHOLZ,§ B. E. KENDALL,† AND S. AIRAMÉ§§

*Centre for Applied Environmental Decision and Analysis, The University of Queensland, St Lucia, Qld 4072, Australia
‡USDA Forest Service Cooperative Forestry, Mail Stop 1123, 1400 Independence Avenue SW, Washington, D.C. 20250-1123, U.S.A.
§Ecotrust, 721 NW Ninth Avenue, Suite 200, Portland, OR 97209, U.S.A.
†Donald Bren School of Environmental Science and Management, University of California Santa Barbara, Santa Barbara, CA 93106-5131, U.S.A.
§§Marine Science Institute, University of California Santa Barbara, Santa Barbara, CA 93106-6150, U.S.A.
**Columbia Land Trust 750 Commercial Street #208, Astoria, OR 97103, U.S.A.

**Abstract:** *The establishment of marine protected areas is often viewed as a conflict between conservation and fishing. We considered consumptive and nonconsumptive interests of multiple stakeholders (i.e., fishers, scuba divers, conservationists, managers, scientists) in the systematic design of a network of marine protected areas along California's central coast in the context of the Marine Life Protection Act Initiative. With advice from managers, administrators, and scientists, a representative group of stakeholders defined biodiversity conservation and socioeconomic goals that accommodated social needs and conserved marine ecosystems, consistent with legal requirements. To satisfy biodiversity goals, we targeted 11 marine habitats across 5 depth zones, areas of high species diversity, and areas containing species of special status. We minimized adverse socioeconomic impacts by minimizing negative effects on fishers. We included fine-scale fishing data from the recreational and commercial fishing sectors across 24 fisheries. Protected areas designed with consideration of commercial and recreational fisheries reduced potential impact to the fisheries approximately 21% more than protected areas designed without consideration of fishing effort and resulted in a small increase in the total area protected (approximately 3.4%). We incorporated confidential fishing data without revealing the identity of specific fisheries or individual fishing grounds. We sited a portion of the protected areas near land parks, marine laboratories, and scientific monitoring sites to address nonconsumptive socioeconomic goals. Our results show that a stakeholder-driven design process can use systematic conservation-planning methods to successfully produce options for network design that satisfy multiple conservation and socioeconomic objectives. Marine protected areas that incorporate multiple stakeholder interests without compromising biodiversity conservation goals are more likely to protect marine ecosystems.*

**Keywords:** conservation costs, conservation planning, fishing effort, fishing exclusion zones, marine biodiversity, marine reserves, Marxan, protected areas

Estableciendo un Balance entre la Conservación de la Biodiversidad y la Viabilidad Económica en el Diseño de Áreas Marinas Protegidas

**Resumen:** *El establecimiento de áreas marinas protegidas a menudo es visto como un conflicto entre la conservación y la pesca. Consideramos intereses de consumo y no consumo de múltiples grupos (i.e., pescadores, buceadores, conservacionistas, manejadores, científicos) para el diseño sistemático de una red de áreas*

‡‡*email c.klein@uq.edu.au*
*Paper submitted March 30, 2007; revised manuscript accepted October 22, 2007.*



DOI: 10.1111/j.1523-1739.2008.00896.x

*marinas protegidas a lo largo de la costa central de California en el contexto del Acta de Iniciativa de la Protección de Vida Marina. Con la asesoría de manejadores, administradores y científicos, un grupo representativo de los interesados definió las metas socioeconómicas y de conservación de la biodiversidad que respondieran a las necesidades sociales y conservaran ecosistemas marinos, en el marco de los requerimientos legales. Para satisfacer las metas de conservación, analizamos 11 hábitats marinos en 5 zonas de profundidad, áreas de lata diversidad de especies y áreas con especies de estatus especial. Minimizamos los impactos socioeconómicos adversos mediante la minimización de los efectos negativos de los pescadores. Incluimos datos de pesca de escala fina aportados por sectores de pescadores comerciales y recreativos en 2 pesquerías. Las áreas protegidas diseñadas considerando pesquerías comerciales y recreativas redujo los impactos potenciales de las pesquerías ~21% más que en áreas protegidas diseñadas sin considerar el esfuerzo de pesca y resultaron en un pequeño incremento en el área total protegida (~3.4%). Incorporamos datos confidenciales de pesca sin revelar la identidad de las pesquerías específicas o de los sitios de pesca. Situamos a una porción de las áreas protegidas cercanas a parques terrestres, laboratorios marinos y estaciones de monitoreo científico para abordar las metas socioeconómicas no consumptivas. Nuestros resultados muestran que un proceso de diseño conducido por sectores interesados puede utilizar métodos sistemáticos de planificación de la conservación para producir opciones exitosas de diseño de redes para satisfacer múltiples objetivos de conservación y socioeconómicos. Las áreas marinas protegidas que incorporan intereses de múltiples sectores sin comprometer las metas de conservación de la biodiversidad tienen mayor probabilidad de proteger los ecosistemas marinos.*

**Palabras Clave:** áreas protegidas, biodiversidad marina, costos de conservación, esfuerzo de pesca, Marxan, planificación de la conservación, reservas marinas, zonas de exclusión de pesca

## Introduction

To conserve marine biodiversity, marine protected areas must have a solid foundation in biology and include representative and unique marine habitats (Roberts et al. 2003*a*). In addition, the success of marine protected areas at protecting biodiversity depends on user compliance (Sumaila & Charles 2002; Moore et al. 2004), which highlights the importance of explicitly addressing the needs of stakeholders in the planning process (Richardson et al. 2006). Yet, protected areas designed to accommodate social needs may result in outcomes that do not adequately conserve marine ecosystems (Agardy 1994; Roberts et al. 2003*a*). The need to strike a balance between biodiversity conservation and socioeconomic viability in protected-area design is evident. Designing a network of marine protected areas that considers both socioeconomic and biodiversity factors has moved to the forefront of systematic conservation planning (Sala et al. 2002; Stewart & Possingham 2005; Richardson et al. 2006).

Typically, socioeconomic factors are considered secondary to biological factors in the design of marine protected areas (Scholz et al. 2004) and tend to be analyzed post hoc for areas selected based only on biophysical data (Stewart & Possingham 2005). Where they are included in a design of marine protected areas, socioeconomic factors can result in outcomes that compromise biodiversity conservation goals (Sala et al. 2002). There are few examples that consider socioeconomic factors in the selection of areas for protection and do not compromise biodiversity conservation goals. Stewart & Possingham (2005) demonstrated that the inclusion of data on the commercial rock lobster fishery reduces the impact of a reserve on that fishery by more than one-third and only slightly increases the size of the reserves compared with reserves designed without consideration of the lobster fishery. Richardson (2006) showed that the incorporation of fine-resolution commercial fishing information in marine-reserve design substantially reduces the economic losses incurred by fishers, compared with reserves designed without consideration of fishery losses and those derived from coarse-resolution data. Although these studies make significant strides toward the inclusion of socioeconomic data in marine-reserve design, they do not address nonconsumptive user interests (i.e., scuba divers, managers, conservationists). In addition, these studies only represent a small sample of consumptive user interests because they include the socioeconomic cost of only one fishery (e.g., rock lobster) or one fishing sector (e.g., commercial fishing) and ignore the impact of marine protected areas on other fisheries and industries.

We explicitly considered consumptive and nonconsumptive interests of multiple stakeholders (i.e., fishers, scuba divers, conservationists, managers, scientists) in the design of a network of marine protected areas along California's central coast in the context of California's Marine Life Protection Act Initiative, a public-private effort to implement the Marine Life Protection Act (CDFG 2005*b*). In addition to using biophysical data to achieve conservation objectives, we incorporated consumptive user interests by including fishing data from the recreational and commercial fishing sectors across 24 fisheries and established siting criteria that ensured nonconsumptive

user objectives were met. Our approach effectively incorporated confidential data on commercial fishing grounds without revealing the identity of specific fisheries or individual fishing sites and simultaneously addressed conservation and other nonconsumptive stakeholder interests.

## Methods

### Policy Context and Planning Region

California's Marine Life Protection Act mandates the design and management of a network of marine protected areas to protect marine life, habitats, ecosystems, and natural heritage and to improve recreational, educational, and study opportunities provided by marine ecosystems (State of California 1999). As part of the initiative to implement the Marine Life Protection Act, California's central coast was the first of 5 regions to undergo a stakeholder-driven process to design a network of marine protected areas. Here, we defined stakeholder interests on the basis of the *Regional Goals and Objectives*, including conservation and socioeconomic goals (CDFG 2005*a*), developed by a representative group of stakeholders from California's central coast and informed by managers, administrators, and a scientific advisory team as part of the initiative process (Table 1).

The planning region was defined by the 5556-m (3-nautical-mile) legal limits to California's state waters from Pigeon Point (lat 37.185°, long −122.39°) to Point Conception (lat 34.449°, long −120.471°). To be consistent with the scale of fishing data, we used the California Department of Fish and Game's standard marine planning unit ($n = 1381$) as the planning units for this project. The planning units were typically 1 nautical mile square, but their size varied at the land and federal water borders.

**Table 1. Summary of biophysical and socioeconomic goals and objectives developed by stakeholders (CDFG 2005*a*) and applied to the design of a network of marine protected areas.**

| Goal | Objective |
|---|---|
| Biodiversity conservation | protect representative and unique marine habitats across various depth zones |
| | protect areas of high species diversity and populations of special status |
| Socioeconomic viability | consumptive users: minimize negative socioeconomic impacts |
| | nonconsumptive users: improve recreational, educational, and study opportunities provided by marine ecosystems by siting protected areas close to population centers, research institutions, and current monitoring sites |
| | site protected areas adjacent to terrestrial parks and marine laboratories to facilitate management, enforcement, and monitoring |

### Biodiversity Considerations

The Scientific Advisory Team of the initiative recommended the inclusion of specific habitats across 5 depth zones (intertidal, intertidal to 30 m, 30–100 m, 100–200 m, and >200 m; CDFG 2005*b*). The stakeholder group adopted the scientific recommendations and added specific areas of biodiversity significance and species of special status as additional biodiversity features to include in the protected areas (CDFG 2005*c*). From these lists, we identified 47 conservation features using data from the California Department of Fish and Game's Marine Geodatabase (McClintock et al. 2006), that could be mapped with consistent quality and coverage across the planning region (Table 2). Server based tools and geodatabase to support marine-protected-area planning. Presentation at the 20th annual meeting. Society for Conservation Biology, Arlington, Virgina), that could be mapped with consistent quality and coverage across the planning region (Table 2). We stratified each of the habitats identified by the Science Advisory Team into the recommended depth zones (where the habitat occurs) and treated them as separate conservation features. We used ArcGIS (ESRI, Redlands, California) to calculate the amount of each conservation feature in each planning unit.

The stakeholder group and Science Advisory Team did not indicate how much of each feature would be adequate to ensure its protection. To be consistent with international recommendations for protected areas (IUCN 2003), we targeted a minimum of 30% of each conservation feature in networks of marine protected areas.

**Table 2. Biophysical conservation features identified by the Marine Life Protection Act Initiative's scientists and stakeholders that can be mapped on the basis of peer-reviewed spatial data.**

| *Features identified by scientists** | *Additional features identified by stakeholders* |
|---|---|
| Rocky reef (granite), 5 dz | areas of high bathymetric complexity |
| Rocky reef (sandstone and shale), 5 dz | shelf-slope break (100–200 m) |
| Rocky reef (Franciscan complex), 5 dz | shallow and deep pinnacles |
| Sandy or soft ocean bottoms, 5 dz | persistant kelp beds |
| Underwater pinnacles, 4 dz | estuaries with presence of coho or steelhead populations |
| Submarine canyons, 4 dz | |
| Kelp forest (*Macrocystis pyrifera*), 2 dz | areas of high fish diversity and/or density |
| Kelp forest (*Nereocystis lutkeana*), 2 dz | marine mammal rookeries and haulouts |
| Eelgrass beds, 1 dz | sea otter habitat |
| Surfgrass beds, 2 dz | seabird colonies |
| Estuaries, 1 dz | areas of high seabird diversity and/or density |

**We indicate the number of depth zones (dz) in which each of the features occurs. Each feature in each depth zone was targeted separately.*

## Socioeconomic Considerations

### CONSUMPTIVE USER INTERESTS

To satisfy consumptive socioeconomic goals of the stakeholders (Table 1), we calculated the recreational and commercial fishing effort in each planning unit. This served as a proxy for the "negative socioeconomic impact" associated with closing that unit to fishing. We used effort rather than revenues because the data on commercial landings of fish collected by the California Department of Fish and Game have poor spatial resolution. In addition, spatial maps of fishing effort were derived from qualitative assessments (see later) and did not include revenue information.

Recreational fishing was defined as fishing done from charter boats, private vessels, or rental boats. We used 2 data sets that reported recreational fishing effort from private and rental boats and charter boats, respectively. The data set on private and rental boats was derived from 5514 in-person interviews conducted at ports in 2004, which represents about 15% of the estimated number of private- and rental-boat fishing trips made in the study region during that year (Scholz et al. 2006). The charter-boat data were collected by on-board observers from 1987 to 1998. Both data sets were compiled by the California Department of Fish and Game and contain the number of recreational fishing trips made to each planning unit for each of the following species: California halibut (*Paralichthys californicus)*, Chinook salmon (*Oncorhynchus tshawytscha*), Pacific sanddab (*Citharichthys sordidus*), and rockfish (various species in the *Sebastes* genus). We used the number of fishing trips made to each planning unit as a surrogate for recreational fishing effort.

To determine the relative fishing effort in each planning unit for each recreational fishery (i.e., how important each planning unit is to each individual fishery), we divided the number of trips in each planning unit by the total number of trips made by the entire fishery. We summed the relative fishing effort for each of the 4 recreational fisheries for each planning unit, which resulted in an index of relative recreational fishing effort across all 4 fisheries for a given planning unit ($R_i$):

$$R_i = \sum_{k=1}^{M} \frac{a_{ik}}{\sum_{j=1}^{N} a_{jk}}, \tag{1}$$

where $M$ is the number of recreational fisheries, $N$ is the number of planning units, and $a_{ik}$ is the number of fishing trips made to planning unit $i$ in fishery $k$. The value of $R_i$ showed the relative importance of each planning unit across all 4 recreational fisheries. By adding the relative fishing effort across fisheries, rather than the total fishing effort, each fishery was given equal consideration.

Commercial fishing data were derived from 109 in-person interviews with commercial fishers in 2005 (Scholz et al. 2006). The interviews were conducted by trained field staff equipped with a geographical information system with electronic nautical maps so that fishers could map their fishing grounds and indicate their relative importance. For each fishery the surveys aimed to capture fishing information from at least 50% of the landings in 2003–2004 or at least 5 fishers from each fishery. These data include the relative importance of a given planning unit to individual fishers across 19 commercial fisheries: anchovy (*Engraulis morda*), cabezon (*Scorpaenichthys marmoratus*), dungeness crab (*Cancer magister*), California halibut (*P. californicus)*, kelp greenling (*Hexagrammos decagrammus*), lingcod (*Ophiodon elongatus*), Pacific mackerel (*Scomber japonicus)*, deep nearshore rockfish (various species in the genus *Sebastes*), nearshore rockfish (various species in the genus *Sebastes*), shelf rockfish (various species in the genus *Sebastes*), slope rockfish (various species in the genus *Sebastes*), rock crab (*C. antennarius*), Chinook salmon (*O. tshawytscha*), sardine (*Sardinops sagax*), sablefish (*Anoplopoma fimbria*), white seabass (*Atractoscion nobilis*), surfperch (various species in the genus *Hyperprosopon*), spot prawn (*Pandalus platyceros*), and market squid (*Loligo opalescens*).

We summed the relative importance of each planning unit across all fishers in a fishery and used this as a surrogate for commercial fishing effort in this analysis. In addition, we considered kelp harvesting a commercial fishery, as does the California Department of Fish and Game. We used information on harvestable kelp beds as a surrogate for effort for the kelp harvesting industry. If a particular planning unit contained a harvestable kelp bed, including it in a protected area would be considered a loss of harvesting effort.

To determine the relative fishing effort for each planning unit for each fishery (i.e., how important each planning unit is to each individual fishery), we divided the surrogate for effort in each planning unit by the total effort for the entire fishery. We summed the relative fishing effort for each of the 20 fisheries for each planning unit, resulting in an index of relative commercial fishing effort across all fisheries for a given planning unit ($C_i$):

$$C_i = \sum_{k=1}^{P} \frac{b_{ik}}{\sum_{j=1}^{N} b_{jk}}, \tag{2}$$

where $P$ is the number of commercial fisheries, $N$ is the number of planning units, and $b_{ik}$ is the surrogate for fishing effort in planning unit $i$ in fishery $k$. The value of $C_i$ showed the relative importance of each planning unit across all 20 commercial fisheries. By adding the relative

fishing effort across fisheries, rather than the total fishing effort, each fishery was given equal consideration.

This method of calculating $R$ and $C$ assigned greater weight to planning units that were proportionally more important to fishers in a particular fishery, regardless of total effort in the fishery. Thus, $R$ and $C$ were not proportional to the total extractive economic value of each planning unit. Nevertheless, this approach increased the likelihood that each fishery would be affected in equal proportion by areas closed to fishing—a socially and politically favored approach. If total fishing effort was used to calculate $R$ and $C$, and $R$ and $C$ were minimized in the design algorithm, the resulting protected areas might disproportionably affect smaller fisheries.

We estimated the combined effort for each planning unit across the recreational and commercial industries ($E_i$):

$$E_i = \frac{C_i}{P}(\alpha) + \frac{R_i}{M}(1 - \alpha), \tag{3}$$

where $\alpha$ is a weighting parameter that is included to allow the planner to assign a relative value to the commercial and recreational fishing industries. Information on the social and economic value of each industry could be used to assign $\alpha$ values. To our knowledge quantitative information on social values did not exist for the study region and information regarding economic values of each industry was unreliable. Therefore, we assumed that the recreational and commercial industries had equal values and assigned $\alpha = 0.5$. This weighting decision also was supported by several fishers participating in the study as a scientifically sound approach in the face of inaccurate value estimates and changes in economic value of specific fisheries over time.

#### NONCONSUMPTIVE USER INTERESTS

To satisfy nonconsumptive socioeconomic goals of the stakeholders (Table 1), we identified planning units that were adjacent to scientific monitoring sites, research institutions, educational institutions, population centers, and terrestrial parks. There were 132 monitoring sites in our study region, maintained by 6 organizations. Each organization provided us with their monitoring site locations, and we counted the number of monitoring sites per planning unit.

There were 34 marine educational institutions and laboratories near the study region. We incorporated this information by identifying the planning units adjacent to institutions. We identified coastal cities and coastal access points of major roads from inland cities with data from the U.S. Geological Survey (USGS 2000). We assumed that residents of inland cities were most likely to spend time on the coast at the nearest coastal access points. We incorporated this information by identifying the planning units adjacent to these points. We identified 155 planning units near local, state, and national parks adjacent to the ocean on the basis of information on park landmarks from the U.S. Tele Atlas North America (Tele Atlas North America 2005).

### Selecting Protected Areas

There are typically 2 strategies used to solve a reserve-design problem: minimum set or maximal coverage. The objective of the minimum-set strategy is to minimize the resources expended (i.e., area, money) while meeting the conservation objectives. The objective of maximal coverage is to maximize the level of feature representation given a fixed amount of resources (Possingham et al. 2006). The primary objective of this protected-area design was to minimize the "cost" of the protected areas to the fishing industry while ensuring that the conservation and nonconsumptive socioeconomic goals were achieved. Therefore, we used the minimum-set strategy in this reserve-design problem. We used Marxan software (Ball & Possingham 2000; Possingham et al. 2000) to design networks of marine protected areas that incorporated goals and constraints described by the stakeholder group. We chose Marxan over other iterative and optimizing algorithms because of its unique ability to provide multiple solutions to meet objectives and its capacity to handle large data matrices (Leslie et al. 2003). Marxan uses a simulated annealing algorithm to configure protected areas that minimize a linear combination of planning-unit costs and reserve-system boundary length while ensuring that biodiversity targets are met (Possingham et al. 2000). The boundary-length modifier is a variable that controls the importance of minimizing the total perimeter of the network relative to the planning unit cost. As the modifier is increased, greater emphasis is placed on minimizing the boundary length relative to the cost of the planning unit. We applied Marxan with and without a boundary-length modifier.

We implemented Marxan for 3 different planning scenarios. Using the simulated annealing and iterative improvement features of Marxan, we generated 1000 different solutions that satisfied the objectives of each scenario. This algorithm is distinct from other iterative improvement algorithms in that the occasional acceptance of a bad choice allows the system to move out of local optima, thereby increasing the efficiency of the search (Stewart & Possingham 2005). As a result, many good solutions with different spatial configurations could be generated, providing options for design that satisfied all biophysical and socioeconomic goals. Marxan generates a summed solution that corresponds to the number of times an individual planning unit is selected out of 1000 solutions. We displayed summed-solution results to highlight how often the planning unit contributed to efficient and systematic protected-area design that satisfied biophysical and socioeconomic criteria. We compared differences in

**Table 3. Area, boundary length, and lost fishing effort of the best marine-protected-area solutions 1, 2c, 3.**[a]

| *Scenario* | *Area ($km^2$)* | *Boundary length (km)* | *Portion of fishing effort lost (%)*[b] |
|---|---|---|---|
| 1 | 877 | 1952 | 31.7 |
| 2c | 907 | 1362 | 10.6 |
| 3 | 894 | 1343 | 10.6 |

[a] *Trade-offs between area, boundary length, and lost effort are made to accomplish the different biodiversity and socioeconomic objectives of protected-area scenarios 1, 2c, and 3.*
[b] *Portion of total fishing effort lost if the areas identified in the solution of the protected-area scenario are closed to fishing, assuming displaced effort is lost and not applied in other areas.*

selection frequencies between scenarios by subtracting the selection frequencies obtained under one scenario by those obtained under another. To compare the efficiency of each solution at minimizing potential loss of fishing effort, we used the single best solution in each scenario (that which met targets at the least cost).

### The Planning Scenarios

The objectives of planning scenario 1 were to satisfy biodiversity conservation goals (Table 1); thus, we designed a network of protected areas that included 30% of each conservation feature with the cost of a planning unit equal to the area of the planning unit. For scenarios 2a–2c, the objective was to satisfy biodiversity conservation and consumptive user socioeconomic goals. Thus, we designed protected areas that included 30% of each conservation feature and minimized potential losses to recreational fishing (*R*, scenario 2a) and commercial fishing (*C*, scenario 2b) and losses to both industries (*E*, scenario 2c). The objective of scenario 3 was to satisfy goals for biodiversity conservation and consumptive and nonconsumptive users. Thus, we designed protected areas that included 30% of each conservation feature; included some monitoring sites; were adjacent to educational institutions, population centers, and terrestrial parks; and minimized potential loss of fishing effort to the recreational and commercial fishing industries combined (*E*).

## Results

We assessed protected areas designed with (scenario 2c) and without (scenario 1) consideration of fishing effort in terms of area, boundary length, and potential loss of the recreational and commercial fisheries (Table 3). Solutions for scenario 1 and 2c satisfied all biophysical conservation goals. Protected areas designed with consideration of commercial and recreational fisheries (scenario 2c) reduced the potential impact to the fishing industries approximately 21% more than protected areas designed without consideration of fishing effort (scenario 1) and resulted in a small increase in the total area protected (approximately 3.4%). The boundary length of the scenario 2c solution was approximately 31% smaller than for scenario 1, producing a more spatially compact outcome. Scenario 2c was superior to scenario 1 for implementation because it had less potential economic impact to the fishing industry and its spatial compactness was more realistic for implementation (Roberts et al. 2003*b*).

Protected areas designed to consider the recreational industry (scenario 2a), commercial industry (scenario 2b), and recreational and commercial industries combined (scenario 2c) were assessed in terms of lost effort, assuming the protected areas were closed to fishing, and displaced effort was lost and not applied in other areas (Fig. 1). The solutions to scenarios 2a, 2b, and 2c satisfied all biodiversity conservation goals. Losses of recreational,

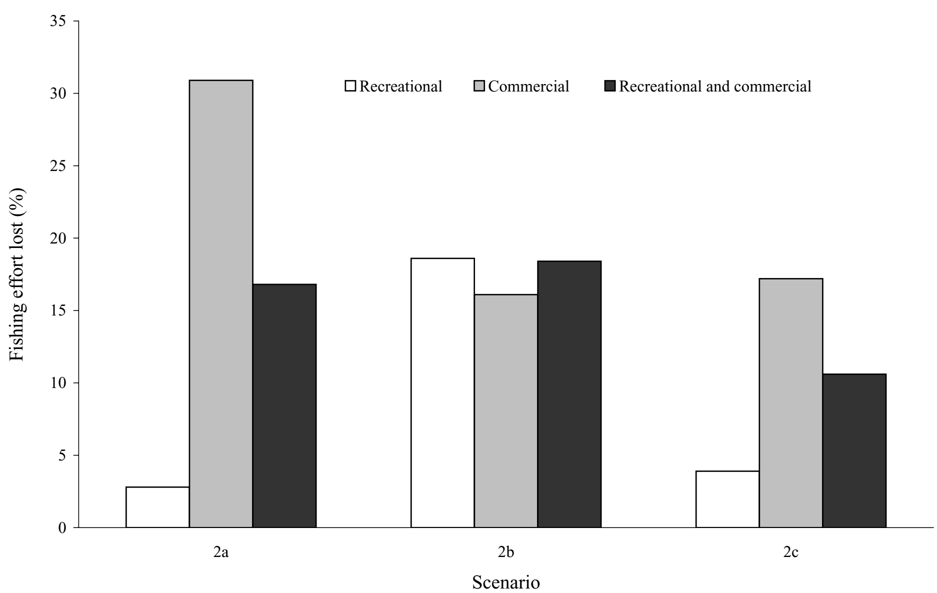


*Figure 1. Percentage of recreational, commercial, and combined fishing effort displaced by marine protected areas identified in the best solutions generated by scenarios 2a, 2b, and 2c. Lost effort is expressed as the sum of effort (recreational, commercial, or combined) for each planning unit selected for the best solution divided by the total effort for that industry or the industries combined.*

commercial, and combined effort were best minimized in scenarios 2a, 2b, and 2c, respectively, showing strong correlation between the objectives and the results. For example, the objective of scenario 2a was to minimize a linear combination of planning unit costs, *R*, and scenario 2a performed best at minimizing potential loss of recreational fishing effort for scenarios 2a–2c.

In scenario 2c the objective was to minimize a linear combination of planning unit costs, *E*. If the best solution of scenario 2c was closed to fishing, 10.6% of the combined commercial and recreational fishing effort could be lost. When separated by industry, 3.9% and 17.2% of the recreational and commercial fishing effort, respectively, could be lost. Although the potential losses to commercial fisheries were disproportionately large, this solution (scenario 2c) performed only slightly worse than the solution that aimed to minimize the potential loss of effort to commercial fishing alone (scenario 2b). The best solution for scenario 2c displaced only 1.1% more recreational fishing effort than scenario 2a and 1.1% more commercial fishing effort than scenario 2b. Scenario 2a was substantially less efficient at minimizing loss to commercial fishing than scenario 2b (14.8% difference) because costs to commercial fisheries were not considered explicitly; likewise, scenario 2b was substantially less efficient at minimizing potential loss of recreational effort than scenario 2a because costs to recreational fisheries were not considered explicitly. Scenario 2c was the most efficient at minimizing loss of effort to both fishing industries because this scenario considered costs to both commercial and recreational fisheries.

The best solution of the protected areas designed to consider all socioeconomic factors (scenario 3) were smaller (approximately 1.4%) in area and perimeter than protected areas designed with consideration of consumptive socioeconomic factors alone (scenario 2c; Table 3). The best solutions from scenarios 2c and 3 affected fishing effort equally. Solutions satisfying nonconsumptive socioeconomic goals in addition to biophysical and consumptive goals suffered no losses in efficiency.

We illustrated priority areas for scenarios 1, 2c, and 3 using the summed-solution method (Fig. 2). The summed-solution method shows the number of times each planning unit was selected by Marxan over 1000 runs of the software. Because the differences between scenarios 2c and 3 were subtle, we highlighted the differences in the selection frequencies (Fig. 3).

Finally, for scenario 3 we applied Marxan with a boundary-length modifier to highlight the trade-offs between spatial compactness and foregone fishing effort. We identified a boundary-length modifier with an acceptable trade-off between boundary length and lost effort (Fig. 2d) with a method developed by Stewart and Possingham (2005). The potential loss of fishing effort predicted by the best solution produced with a boundary-length modifier was 5% greater than the solution produced without a modifier. The boundary length of the best solution produced with a boundary-length modifier was 67% smaller than without a modifier.

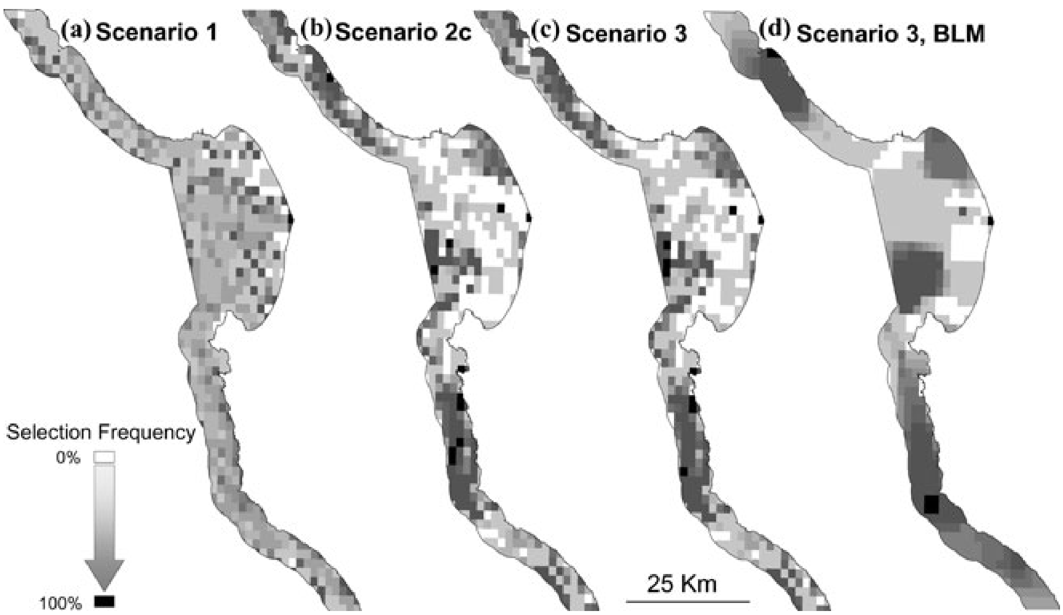


*Figure 2. Selection frequency of each planning unit in protected-area design scenario (a) 1, (b) 2c, and (c & d) 3 with and without a boundary length modifier (BLM), measured as the number of times each planning unit was selected in 1000 solutions. Only the northern portion of the study region is featured to highlight solution details. For each of 1000 solutions, 5 million iterations of the algorithm were applied to find an efficient solution.*

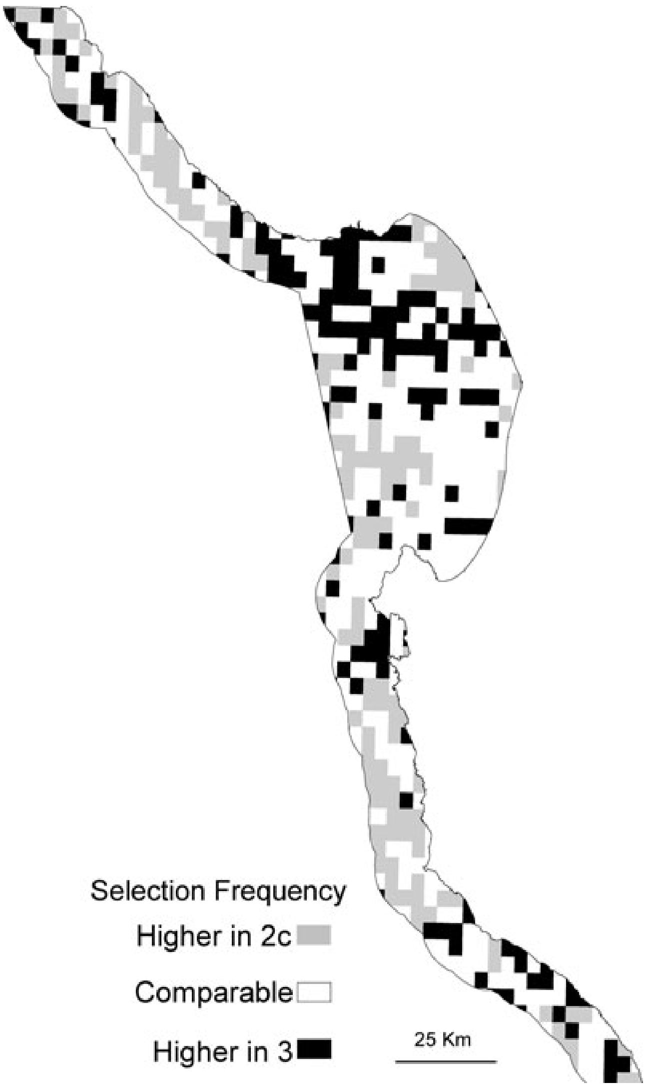


*Figure 3. The difference in the spatial distribution of selection frequencies between protected-area design scenarios 2c and 3. Only the northern portion of the study region is featured to highlight solution details.*

## Discussion

Networks of marine protected areas from all planning scenarios in this study met all biodiversity goals of the stakeholder and scientific advisory groups and could be considered for implementation to conserve marine ecosystems (Roberts et al. 2003*a*). Yet, the success of protected areas depends on user compliance (Sumaila et al. 2000; Moore et al. 2004), and solutions that do not incorporate consumptive socioeconomic interests (scenario 1) are likely to fail because of lack of community support. We demonstrated that marine protected areas can be designed efficiently to meet the goals and objectives of multiple stakeholders. Networks designed specifically to incorporate socioeconomic goals (scenarios 2c and 3) in an a priori manner produced solutions that were notably more efficient at minimizing impact to 24 commercial and recreational fisheries than networks produced when socioeconomic goals were not incorporated.

A conservationist might argue that protecting areas less important to fishers is no better for conservation than the status quo of not protecting anything. Nevertheless, our method did not avoid important fishing grounds at all cost because a key constraint of the approach was that all conservation targets must be achieved in the solution. For example, if a narrowly distributed habitat was always associated with high fishing effort (i.e., underwater pinnacles), then a portion of this habitat was included in the final solution, regardless of its impact to fishing. We avoided important fishing grounds when there were other areas containing the same conservation features in less-important fishing grounds. Every planning unit in the study region is fished, so it was not feasible to select an area that is not fished for protection.

Our methods minimized socioeconomic impact of marine protected areas without compromising biodiversity conservation targets. It is possible, however, that our method prioritizes areas of low-quality habitat because there may be a positive correlation between habitat quality and fishing effort. For example, areas of high-quality habitat may be associated with dense populations of fish and, therefore, may be more heavily fished. To account for this, one could incorporate data on habitat quality by ensuring that a portion of all conservation features is protected in areas with good habitat quality. To our knowledge, data on habitat quality across the study region are not currently available. On the other hand, areas containing low-quality habitat may have been historically important fishing grounds; concentrated fishing in these areas over a time period could have degraded habitat quality. Protecting these areas could aid in restoring these habitats and the populations they sustain. Quality of habitat is not the only factor that may influence the importance of fishing grounds. For example, important fishing grounds can also be found near ports and in the wind shadow of land masses.

Networks of marine protected areas designed to address socioeconomic goals were influenced by the spatial distribution and concentration of fishing effort. When added to the problem, these factors produced more spatially compact results in comparison with scenario 1 and are likely to be more feasible for implementation (Roberts et al. 2003*b*) because it is easier to maintain compliance with fewer large areas than numerous smaller areas. Our results also showed that additional spatial compactness can be achieved with a boundary-length modifier. Nevertheless, an increase in spatial compactness resulted in a greater loss of fishing effort. Although the trade-offs between ease of enforcement and impact to consumptive users were not our primary focus, this is an intriguing area of further research. Rather than being considered as

secondary design criteria, they could be factored into the design of marine protected areas as explicit objectives, essentially adding a further constraint on the optimization.

The integration of our approach with the Marine Life Protection Act Initiative, which foresees the design of potential marine protected areas along the northern and southern coasts of California by 2011, would be an effective way to satisfy multiple stakeholder goals. One of the major potential improvements resulting from the use of our approach concerns the ability to use sensitive information about the location of fishing effort in an effective manner. In the first iteration of the initiative, a stakeholder group was asked to propose networks of marine protected areas for California's central coast that satisfied the *Regional Goals and Objectives* (Table 1). Although they had access to spatially explicit biophysical data and recreational fishing data, the stakeholders did not have access to existing commercial fishing data at sufficient granularity. As part of the initiative process, the state commissioned a private nonprofit organization to collect spatially explicit, fine-scale commercial fishing data for 24 fishing industries (used in this study). Nevertheless, these data were not released to the stakeholder group because they contained confidential information about individual fishing grounds. Instead, the stakeholders submitted proposals for evaluation and then received general recommendations from the Science Advisory Team describing how they could reconfigure their proposals to minimize impact to the fishing industries. The stakeholders then reconfigured their proposals to incorporate these recommendations while ensuring other biodiversity and socioeconomic conservation goals were met. This method of designing protected areas that meet multiple biodiversity and socioeconomic objectives was imprecise, inefficient, time-consuming, and costly.

Our method incorporated confidential socioeconomic data into a design process and resulted in solutions that did not compromise the confidentiality of specific fisheries or individual fishing grounds. This expands on previous attempts to incorporate fishing data into protected-area design because it considers multiple fisheries and multiple fishing industries (i.e., commercial and recreational). In addition, we demonstrated a way to combine multiple biodiversity and socioeconomic factors and efficiently produce solutions that met the desired goals and objectives. Explicitly incorporating nonconsumptive socioeconomic considerations into the design process offers a unique and innovative approach to systematically designing marine protected areas with multiple objectives. Use of areas close to population centers, research institutions, and current monitoring sites as proxies for nonconsumptive activities serves as a proxy for locations where there are opportunities for education, research, and recreation. Ideally, we would use spatially explicit information about a range of market and non-market, nonconsumptive activities at resolutions comparable to biophysical, and consumptive use data. Although this approach is desirable, the necessary data are rarely collected in advance of the design of marine protected areas. The California Marine Life Protection Act Initiative recently commissioned surveys of nonconsumptive and recreational fishing uses in the next region of implementation, affording an interesting opportunity to improve our approach with better data.

This approach is intended to support, not replace, a stakeholder-driven design process. The expert knowledge of stakeholders is necessary throughout the design process, and indeed it was an important source of data in our analysis (i.e., commercial fishing grounds). Stakeholders serve important roles by articulating their priorities and contributing to goals and objectives for marine protected areas. Using our method, the stakeholders can visualize how their goals can be used to locate potential sites for marine protected areas and how changing the goals can influence the possible solutions (Leslie et al. 2003). The solutions from our approach depend on the spatial data used to represent biodiversity and socioeconomic factors. Because it is unlikely that the data are free from error, the expert advice of stakeholders is necessary in cross-checking the results. Our method shows how various efficient solutions can be generated and provided to the stakeholders for further analysis and consideration in their design process.

By assuming that lost fishing effort is not redistributed to surrounding areas and all protected areas would be fishing exclusion zones (as opposed to areas that allow fishing on a restricted basis), we overestimated the impact of the protected-area solutions to the fishing industries for 2 reasons. First, in practice, protected areas are implemented with varying levels of protection with different fishing restrictions. Ideally, a systematic approach similar to ours would be used to consider multiple ocean zones, each with multiple objectives, and produce solutions delineating the spatial location of each zone. Second, not all fishing effort would be lost due to reservation because some effort may be redistributed to unreserved areas.

Modeling the impact of marine protected areas to fishers, considering redistribution of effort, could play an important role in protected-area planning. This is an important area of further research. A dynamic model of this sort could be created with information about fish densities across the planning region, catchability of each species, the costs of fishing (e.g., related to travel time and sea conditions), and an understanding of the economic and social factors that govern entry and exit to the fishery. A less data-intensive (although not necessarily less accurate) model could map fish habitat and estimate how much of it is underutilized (on the basis of information on fishing effort). This model would determine how much of the effort displaced from the protected areas could

be reallocated across the region. Nevertheless, fishery yield is not the only relevant economic variable; profit is arguably more important to the individual fisher and, depending on the nature of fishing costs, may not scale linearly with yield. It is likely that fishers already are fishing in the most profitable locations, so that even if it is possible to maintain yields, the effort that is displaced from the marine protected areas could be less profitable (although spillover may compensate for that [e.g., White & Kendall 2007]).

In general, marine protected areas that incorporate multiple stakeholder interests without compromising biodiversity conservation goals are more likely to protect marine ecosystems. To the extent that our approach is adopted in by the Marine Life Protection Act Initiative, successive stages of the California experience may illustrate the robustness of marine protected areas designed by considering a priori socioeconomic and ecological objectives.

## Acknowledgments

We thank The Donald Bren School of Environmental Science and Management at the University of California Santa Barbara (UCSB), the Partnership for Interdisciplinary Studies of Coasts and Oceans (PISCO), Ecotrust, the Marine Life Protection Act Initiative staff, and The University of Queensland for supporting this project. This is PISCO contribution number 274. We thank the following people for providing perspectives, insight, and valuable feedback throughout this project: S. Gaines, M. Gleason, S. Hastings, H. Lenihan, M. McGinnis, G. Osherenko, D. Stoms, and W. McClintock. Financial support was provided by The Donald Bren School of Environmental Science and Management at UCSB, PISCO, and Ecotrust. PISCO is funded primarily by the Gordon and Betty Moore Foundation and David and Lucile Packard Foundation.

### Literature Cited

Agardy, M. T. 1994. Advances in marine conservation: the role of marine protected areas. Trends in Ecology & Evolution **9:**267–270.

Ball, I. R., and H. P. Possingham. 2000. Marxan (V1.8.2): Marine reserve design using spatially explicit annealing, a manual. University of Queensland, Brisbane, Australia.

CDFG (California Department of Fish and Game). 2005*a*. Adopted regional goals and objectives package. CDFG, Sacramento, California.

CDFG (California Department of Fish and Game). 2005*b*. California Marine Life Protection Act initiative draft master plan framework: a recommendation to the California Fish and Game Commission. CDFG, Sacramento, California.

CDFG (California Department of Fish and Game). 2005*c*. California Marine Life Protection Act Initiative regional profile of the central coast study region. CDFG, Sacramento, California.

IUCN (World Conservation Union). 2003. Recommendations of the 5th IUCN World Parks Congress. IUCN, Gland, Switzerland.

Leslie, H., M. Ruckelshaus, I. R. Ball, S. Andelman, and H. P. Possingham. 2003. Using siting algorithms in the design of marine reserve networks. Ecological Applications **13:**S185–S198.

McClintock, W., M. Gleason, P. Serpa, B. Sherwood, and B. Pfefferle. 2006. Server based tools and geodatabase to support marine protected area planning in California. Conservation without borders abstracts: contributed poster presentations at the 20$^{th}$ annual meeting. Society for Conservation Biology, Arlington, Virginia.

Moore, J., A. Balmford, T. Allnutt, and N. Burgess. 2004. Integrating costs into conservation planning across Africa. Biological Conservation **117:**343–350.

Possingham, H. P., I. R. Ball, and S. Andelman. 2000. Mathematical methods for identifying representative reserve networks. Pages 291–305 in S. Ferson and M. Burgman, editors. Quantitative methods for conservation biology. Springer-Verlag, New York.

Possingham, H. P., K. A. Wilson, S. J. Andelman, and C. H. Vynne, editors. 2006. Protected areas: goals, limitations, and design. Sinauer Associates, Sunderland, Massachusetts.

Richardson, E. A., M. J. Kaiser, G. Edwards-Jones, and H. P. Possingham. 2006. Sensitivity of marine-reserve design to the spatial resolution of socioeconomic data. Conservation Biology **20:**1191–1202.

Roberts, C. M., et al. 2003*a*. Ecological criteria for evaluating candidate sites for marine reserves. Ecological Applications **13:**S199–S214.

Roberts, C. M., et al. 2003*b*. Application of ecological criteria in selecting marine reserves and developing reserve networks. Ecological Applications **13:**S215–S228.

Sala, E., O. Aburto-Oropeza, G. Paredes, I. Parra, J. C. Barrera, and P. K. Dayton. 2002. A general model for designing networks of marine reserves. Science **298:**1991–1993.

Scholz, A., K. Bonzon, R. Fujita, N. Benjamin, N. Woodling, P. Black, and C. Steinback. 2004. Participatory socioeconomic analysis: drawing on fishermen's knowledge for marine protected area planning in California. Marine Policy **28:**335–349.

Scholz, A., C. Steinback, and M. Mertens. 2006. Commercial fishing grounds and their relative importance off the central coast of California. Ecotrust, Portland, Oregon.

State of California. 1999. California Marine Life Protection Act (MLPA). Fish and Game Code 2850–2863. State of California, Sacramento. Available from http://www.dfg.ca.gov/mlpa/mlpa_language.pdf (accessed October 2007).

Stewart, R. R., and H. P. Possingham. 2005. Efficiency, costs and tradeoffs in marine reserve system design. Environmental Modeling & Assessment **10:**203–213.

Sumaila, U. R., and A. T. Charles. 2002. Economic models of marine protected area: an introduction. Natural Resource Modeling **15:**261–272.

Sumaila, U., S. Guenette, J. Alser, and R. Chuenpagdee. 2000. Addressing ecosystem effects of fishing using marine protected areas. ICES Journal of Marine Science **57:**752–760.

Tele Atlas North America. 2005. Parks. Environmental Systems Research Institute, Redlands, California.

USGS (US Geological Survey). 2000. Census 2000 urban and rural classification. Bureau of Census. Environmental Systems Research Institute, Redlands, California.

White, C., and B. Kendall. 2007. A reassessment of equivalence in yield from marine reserves and traditional fisheries management. Oikos 116: 2039–2043.