Applying ecological criteria to marine reserve design: A case study from the California Channel Islands

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APPLYING ECOLOGICAL CRITERIA TO MARINE RESERVE DESIGN: A CASE STUDY FROM THE CALIFORNIA CHANNEL ISLANDS

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Abstract. Using ecological criteria as a theoretical framework, we describe the steps involved in designing a network of marine reserves for conservation and fisheries management. Although we describe the case study of the Channel Islands, the approach to marine reserve design may be effective in other regions where traditional management alone does not sustain marine resources. A group of agencies, organizations, and individuals established clear goals for marine reserves in the Channel Islands, including conservation of ecosystem biodiversity, sustainable fisheries, economic viability, natural and cultural heritage, and education. Given the constraints of risk management, experimental design, monitoring, and enforcement, scientists recommended at least one, but no more than four, reserves in each biogeographic region. In general, the percentage of an area to be included in a reserve network depends on the goals. In the Channel Islands, after consideration of both conservation goals and the risk from human threats and natural catastrophes, scientists recommended reserving an area of 30–50% of all representative habitats in each biogeographic region. For most species of concern, except pinnipeds and seabirds, information about distributions, dispersal, and population growth was limited. As an alternative to species distribution information, suitable habitats for species of concern were used to locate potential reserve sites. We used a simulated annealing algorithm to identify potential reserve network scenarios that would represent all habitats within the smallest area possible. The analysis produced an array of potential reserve network scenarios that all met the established goals.

Key words: biogeography; Channel Islands; connectivity; ecological linkages; fisheries management; habitat; marine reserves; MPA; reserve size; simulated annealing.

INTRODUCTION

Federal and local policies and agencies have recognized and attempted to conserve scenic, ecological, and scientific values of the marine environment in many parts of the world. However, regulations have not been effective for numerous marine species because established targets (e.g., maximum sustainable yields and minimum threshold levels) do not sustain all species (e.g., Mace and Sissenwine 1993, Agardy 1997) and actual catch may exceed established targets (e.g., Roughgarden and Smith 1996). Additionally, single species management has contributed to failure of regulations to sustain fisheries because the scope of regulations generally does not include the critical ecological linkages among species and between species and the environment (e.g., Dugan and Davis 1993). In the California Channel Islands, a steady deterioration of marine resources (e.g., Dugan and Davis 1993, California Department of Fish and Game 1999, Parrish et al. 2000, Pacific Fishery Management Council 2000) has led many to question the ability of current fisheries management approaches to provide long-term ecological and economic viability.

Fully protected marine reserves can be used to supplement traditional fisheries management. Marine reserves not only provide a means of establishing sustainable fisheries and long term economic viability, but also contribute to the conservation of habitats and unexploited species, while providing opportunities for marine research and education (Roberts and Hawkins 2000). Design of reserve networks should aim to maximize ecological, economic, and cultural benefits, as well as to enhance educational and research opportunities. To maximize both ecological and economic benefits, reserve network configurations must minimize short-term economic impacts and maximize long-term economic viability of fisheries. Thus, both ecology and

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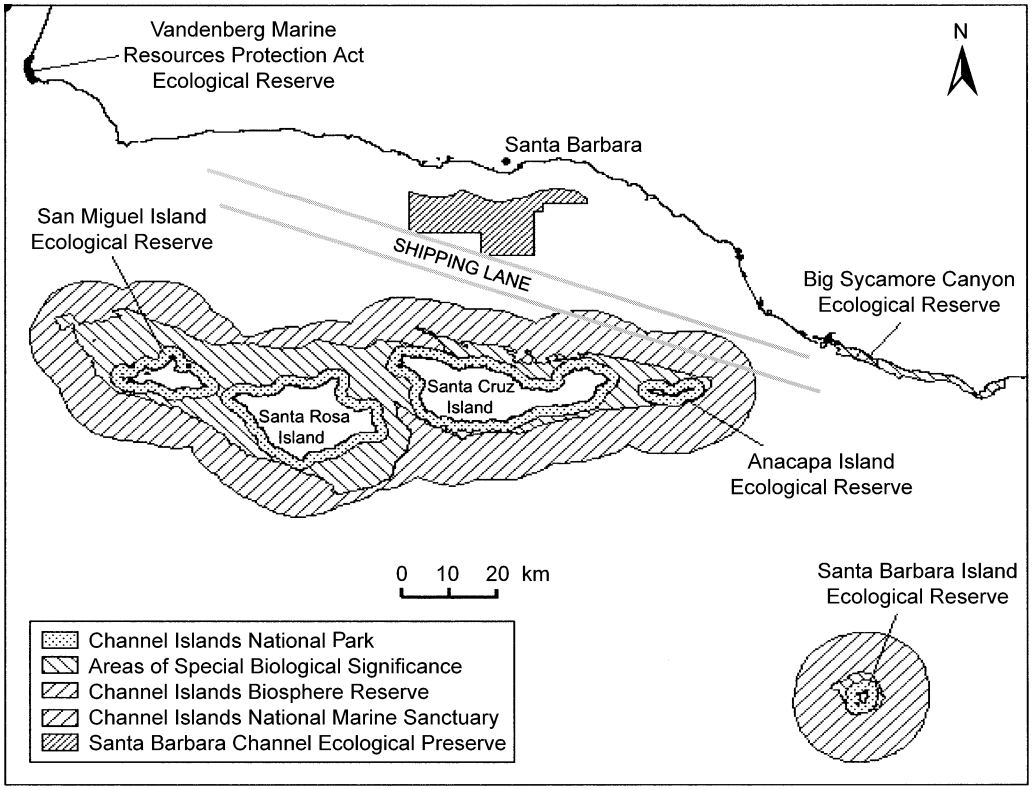

FIG. 1. The California Channel Islands region and existing marine protected areas.

economics should contribute to, but neither should compromise, marine reserve design (M. Cahn, *unpublished manuscript*).

In 1999, a process to develop a network of marine reserves in the California Channel Islands was initiated by a group of federal and state agencies, commercial and recreational fishermen, environmentalists, and other members of the Santa Barbara community, hereafter called the Marine Reserves Working Group (MRWG). Two advisory panels were formed to assist the MRWG, a 15-member Science Advisory Panel (SAP) that evaluated ecological and physical data, and a five-member socioeconomic panel that evaluated economic data from commercial and recreational industries in the Channel Islands.

Ideally a network of marine reserves for a particular area should be planned within the context of other reserves and fisheries management regulations in adjacent areas (Roberts et al. 2001). In 1999, the California Assembly established the Marine Life Protection Act (Assembly Bill 993) to develop a comprehensive marine protected area (MPA) program in California's marine waters. The outcome of the Channel Islands process is likely to influence fisheries regulations and the distribution of future reserves in the State.

The regional context is an important consideration for marine reserve network design because changing the scale of the planning region will affect the relative importance of areas within that region. For example, if the California Channel Islands are placed within the context of the Southern California Bight (~275 000 km^2), the entire Channel Islands National Marine Sanctuary (4294 km^2) potentially could be set aside as a reserve to meet the conservation goals of the larger region. Because of the limited jurisdiction of the lead agencies, the MRWG focused its efforts on the area within the Channel Islands National Marine Sanctuary (Fig. 1).

Eleven federal, state, and local agencies have some jurisdiction in the planning region (Fig. 1). The Sanctuary and Channel Islands National Park overlap around the northern Channel Islands and Santa Barbara Island, however neither agency regulates commercial or recreational fishing. The National Park has responsibilities under the Organic Act to conserve scenery, natural and historic objects, and wildlife unimpaired for future generations. Sanctuary regulations prohibit oil and gas exploration and several other activities. The California Department of Fish and Game manages fisheries in state waters, within 5.6 km of shore. Only one small (12 ha) marine reserve (Landing Cove, Anacapa Island) prohibits all take of marine organisms yearround (Fig. 1). The California Fish and Game Commission (an appointed board) has the authority to es-

TABLE 1. Goals for marine reserves in the Channel Islands National Marine Sanctuary established by the Marine Reserves Working Group.

Goal categories	Goals for marine reserves
Ecosystem biodiversity	To protect representative and unique marine habitats, ecological processes, and populations of interest in the Channel Islands National Marine Sanctuary
Sustainable fisheries	To achieve sustainable fisheries by integrating marine reserves into fisheries management
Economic variability	To maintain long-term socioeconomic viability while minimizing short-term socioeconomic losses to all users and dependent parties
Natural and cultural heritage	To maintain areas of visitor, spiritual, and recreational opportunities which include cultural and ecological features and their associated values
Education	To foster stewardship of the marine environment by providing educational opportunities to increase awareness and encourage responsible use of resources

tablish additional marine reserves within State waters. The U.S. Fish and Wildlife Service, National Marine Fisheries Service, U.S. Coast Guard, State Lands Commission, and Santa Barbara and Ventura Counties also have some jurisdiction within the Channel Islands region.

Goals for marine reserves

The MRWG developed several goals for marine reserves in the Channel Islands (Table 1): conserving ecosystem biodiversity; achieving sustainable fisheries; restoring sustaining natural areas for recreational and spiritual opportunities; and increasing awareness and encouraging responsible use and enjoyment of marine resources by providing sites for educational opportunities.

In this paper, we describe the selection and application of ecological criteria to a marine reserve siting process in the California Channel Islands and the use of a simulated annealing algorithm to identify suites of potential reserves that meet minimum criteria for size, habitat representation and connectivity. Although our example focuses on a single region, this approach to reserve network siting is applicable to other regions where marine reserve networks may be used as tools to help achieve conservation goals.

ECOLOGICAL CRITERIA

Percentage to set aside in reserves

One of the most important questions in conservation is how much area should be in reserves. To address this question, the SAP evaluated the status of fishery resources in the planning region and the goals for conservation and fisheries management. For conservation goals, the benefit of a reserve increases with size (e.g., Margules et al. 1988, Dayton et al. 2000, Roberts and Hawkins 2000). Larger reserves protect more habitats and populations, providing buffers against losses from environmental fluctuations or other natural factors that may increase mortality rates or reduce population growth rates. For fisheries management goals, the benefit of a reserve does not increase directly with the area it occupies (e.g., Carr and Reed 1998). The maximum benefit of fully protected reserves for fisheries, in terms of sustainability and yield, occurs when the reserve is large enough to export sufficient larvae and adults, and small enough to minimize the initial economic impact to fisheries (Carr and Reed 1998). After consideration of the goals (Table 1) and review of the literature, the SAP recommended that 30–50% of the Channel Islands National Marine Sanctuary should be reserved to achieve both conservation and fisheries goals of the MRWG (Airamé et al. 2001).

Biogeographic representation

Roberts et al. (2003) proposed that there should be an autonomous marine reserve network for each distinct biogeographic region contained within a planning region. The complex geography of the California Channel Islands influences ocean circulation (Brown 1994) and, consequently, the distributions of habitats and species (Dailey et al. 1993). Three main biogeographic regions emerged when the area was subdivided according to physical and biological differences using existing information (e.g., Valentine 1966, Horn and Allen 1978, Ebling et al. 1980, Kanter 1980, Littler 1980, Murray et al. 1980, Seapy and Littler 1980, Apt et al. 1988, Engle 1993, Dugan et al. 1995, 2000). Bathed by the California Current, San Miguel and northern Santa Rosa Island lie in the Oregonian Province, supporting biotic assemblages characteristic of central and northern California, Oregon, and Washington (Murray et al. 1980, Seapy and Littler 1980). Anacapa and the eastern tip of Santa Cruz Island are surrounded most of the year by temperate waters characteristic of the Californian Province (Murray et al. 1980, Seapy and Littler 1980). Sea surface temperature maps (Institute for Computational Earth Sciences Systems [ICESS] 2001) suggest that Santa Barbara Island and southern Santa Rosa and Santa Cruz Islands represent a transition between cooler and warmer temperate waters.

It is important to consider the dynamic nature of this transition between two major biogeographic provinces.

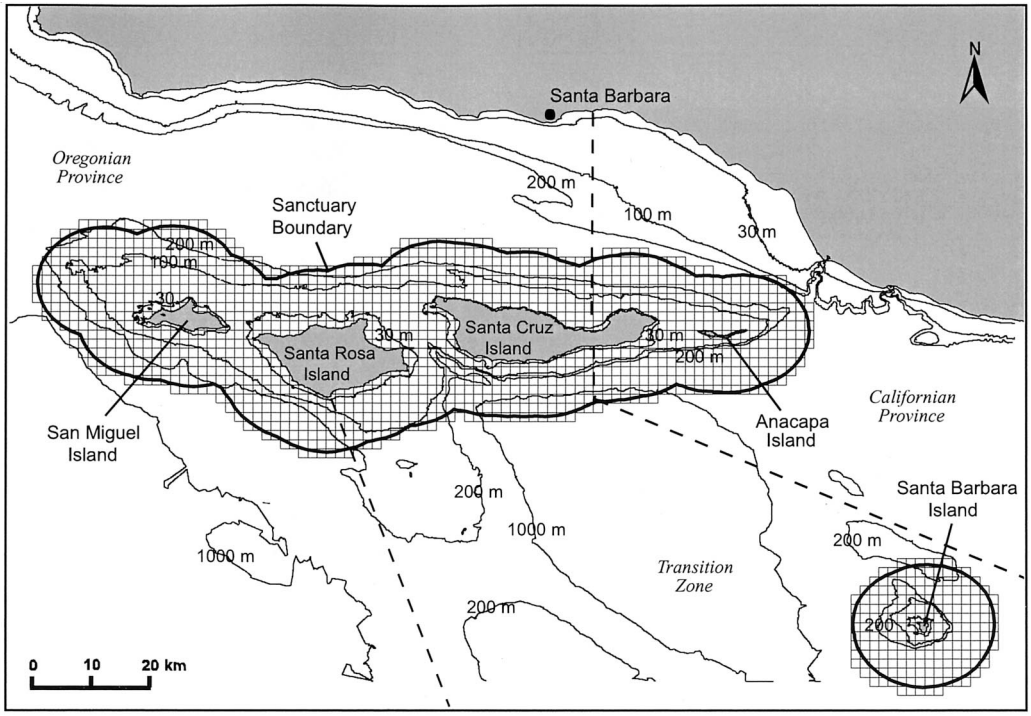

FIG. 2. Biogeography and bathymetry of the Channel Islands National Marine Sanctuary. The planning region was divided into three main bioregions (dashed line): the Oregonian Province, the Californian Province, and the Transition Zone. Each bioregion was subdivided into 1 × 1 minute (~1 × 1 nautical mile) ''planning units'' (grid cells) following longitudinal and latitudinal lines. Each planning unit was assigned to a depth interval: photic zone (0–30 m), shallow continental shelf (30–100 m), deep continental shelf (100–200 m), and continental slope (>200 m).

Persistent thermoclines may shift tens of miles, or more, during environmental fluctuations such as El Niño-Southern Oscillation (McGowan et al. 1998). For the planning process, however, explicit biogeographic boundaries were required. The SAP used available information on sea surface temperature (ICESS 2001) for rough guidance and, in the areas of sharpest transition, drew biogeographic boundaries that followed the deepest bathymetric contour (under the assumption that these might provide a significant boundary to movement of some species, especially nearshore species that rarely enter pelagic waters; Fig. 2). Following recommendations in Roberts et al. (2003), the SAP recommended one to four reserves be designated within each of the three biogeographic regions, comprising 30–50% of the area in the Channel Islands National Marine Sanctuary.

Habitat representation and heterogeneity

The goal of conserving ecosystem biodiversity requires protection of representative and unique marine habitats within each biogeographic region (Roberts et al. 2003). To address the goals for habitat conservation in the design process, it is necessary to define the representative and unique marine habitats in the planning region. The SAP recommended a simple, multidimensional habitat classification, using depth, exposure, substrate type, dominant plant assemblages, and a variety of additional features (Table 2). An important ecological criterion for reserve design was the protection of a suitable amount of each habitat type within each biogeographic region (e.g., 30–50%).

The availability and distribution of data for the planning region limited the level of detail in the habitat classification. Although swath mapping and sidescan sonar data provide a promising means of quantifying the distribution of deepwater habitats, the available data only cover a small percentage of the Channel Islands planning region. Combining widespread sidescan sonar with ground truthing from submersibles and remotely operated vehicles may be an effective method of mapping habitats at the scale needed for marine habitat designations in large planning regions, but these data were not available for the Channel Islands.

As an alternative to these types of data, the SAP used existing maps and sediment samples taken throughout the planning region. These included a Shoreline Inventory Database (Minerals Management Service [MMS] 2000) that describes a variety of coastal features in Santa Barbara County, a series of maps of >5000 sediment grabs around the Channel

TABLE 2. Ecological criteria for marine reserve design in the Channel Islands and the approximate abundance of each criterion in each biogeographical province in the Channel Islands National Marine Sanctuary.

Ecological criteria	Units	Oregonian Province	Transition Zone	Californian Province
Coastline characteristics				
Sandy beach	km of coastline	39.7	22.1	7.5
Rocky coast (low exposure)	km of coastline	45.1	18.6	20
Rocky coast (high exposure)	km of coastline	43.8	21.8	2.2
Substrate type and depth				
Soft sediment (0–30 m)	km^2	133.4	101.5	56.3
Hard sediment (0–30 m)	km^2	117.6	24.7	22.6
Soft sediment (30–100 m)	km^2	725.8	218.1	192.8
Hard sediment (30–100 m)	km^2	80.3	34.6	13.4
Soft sediment (100–200 m)	km^2	538.5	215.7	93.3
Hard sediment (100–200 m)	km^2	···	25	3.8
Soft sediment (>200 m)	km^2	777.6	606.7	551.2
Hard sediment (>200 m)	km^2	···	50.1	7.9
Additional features				
Emergent rocks (nearshore)	no. <2 km from shore	216	208	95
Emergent rocks (offshore)	no. >2 km from shore	12	5	1
Submerged rocky features (pinnacles, ridges, seamounts)	km^2	20.2	91.6	13.7
Submarine canyons	km^2	3.4	115.6	17.1
Dominant plant communities				
Giant kelp	km^2	55.2	20.2	6.2
Surfgrass	km^2	46	23	11
Eelgrass	km^2	1	0.3	0.7
Breeding seabirds				
California Brown Pelican	km of coast†	0.5	10.1	9.4
Pelagic Cormorant	km of coast†	115.7	39.7	37
Double-crested Cormorant	km of coast†	0.5	0	8.5
Brandt's Cormorant	km of coast†	66.1	11	23.2
Common Murre	km of coast†	0.5	10.1	0
Pigeon Guillemot	km of coast†	76.6	29.6	39
Xantu's Murrelet	km of coast†	8.5	13.8	15.4
Tufted Puffin	km of coast†	0.5	10.1	0
Rhinocerous Auklet	km of coast†	8.5	0	0
Cassin's Auklet	km of coast†	21.1	14.2	7.4
Leach's Storm-petrel	km of coast†	12.2	10.1	4.2
Ashy Storm-petrel	km of coast†	1.1	0	0
Black Storm-petrel	km of coast†	0.5	10.1	0
Black Oystercatcher	km of coast†	121.4	49.6	40.6
Snow Plover	km of coast†	28.5	9.4	0
Western Gull	km of coast†	85.0	25.9	32.8
Pinnipeds				
Stellar (northern) sea lion	km of coast‡	6.4	0	0
California sea lion	km of coast‡	9	10.1	0
Northern fur seal	km of coast‡	6.9	0	0
Northern elephant seal	km of coast‡	28	6.4	0
Harbor seal	km of coast‡	76	40.2	20

† Kilometers of coast suitable for nesting.
‡ Kilometers of coast used by pinnipeds for hauling out.

Islands (Amuedo and Ivey 1967), a database of soft-sediment samples in the northern Channel Islands (USGS, *unpublished data*) and substrate maps of the sea floor around Channel Islands (MMS 1984). These sources were combined using a geographic information system (GIS) to develop a comprehensive substrate map of the Channel Islands National Marine Sanctuary, divided into soft substrate (e.g., mud, sand, gravel) and hard substrate (e.g., rock, boulder, bedrock). A bathymetric map of the Channel Islands (Waltenberger 1995) was then used to distinguish habitat types at the following depth intervals: shoreline, photic zone (0–30 m), upper continental shelf (30–100 m), lower continental shelf (100–200 m), continental slope (>200 m; Fig. 2).

Several dominant plant species, including giant kelp (*Macrocystis pyrifera*), surfgrass (*Phyllospadix* spp.), and eelgrass (*Zostera* spp.) form marine habitats used

by diverse groups of invertebrates, fish, mammals, and seabirds (Anderson et al. 1993). The potential distribution of giant kelp around the northern Channel Islands and Santa Barbara Island, covering an area of 81.6 km^2, was determined from aerial photographs of the region between 1980 and 1989 (Ecoscan 1989). Most of the kelp occurred on the southwestern coasts of San Miguel and Santa Rosa Islands.

Combined, the description of marine habitats in the Channel Islands included the intersection between sediments and depth and dominant plant communities that provide habitat for a variety of marine organisms (Table 2). Because organisms often use more than one habitat, it is important to include several habitats within each reserve in the network.

Vulnerable habitats

Vulnerable marine habitats, such as coral reefs, mudflats, rocky intertidal areas, and seagrasses, require protection from human threats and catastrophic events. To ensure that such habitats will be represented adequately in reserves, vulnerable habitats were considered explicitly in the Channel Islands reserve network siting process. For example, seagrasses, including eelgrass and surfgrass, are particularly vulnerable to human threats. These seagrasses provide several essential ecological functions, including substrate stabilization, primary production, and nutrient cycling (Phillips 1984) as well as habitat and food for a variety of plants, invertebrates, and fishes (McConnaughey and McRoy 1979).

Seagrass meadows are vulnerable to activities that disturb the sea floor, such as anchoring and construction, and catastrophic events, such as oil spills. Oil quickly adheres to the nonmucilaginous leaves of marine algae (Foster et al. 1971). In addition to direct impacts to seagrasses (e.g., Dean et al. 1998), there are various adverse effects of oil spills on invertebrate communities associated with them (e.g., Dean et al. 1996). Hydrocarbons persist longer in seagrass meadows, injury levels to invertebrate assemblages are higher, and recovery time is longer in shallow bays and seagrass meadows than in other marine habitats (Den Hartog and Jacobs 1980, Dean et al. 1996).

Eelgrass beds were mapped at six sites on Santa Cruz Island and two sites on both Anacapa and Santa Rosa Islands in 1994–1997 (J. Engle, *personal communication*). Intertidal surfgrass beds were mapped for the Bureau of Land Management using helicopter surveys (Littler and Littler 1979).

The scarcity and relatively small size (6 m^2 to 12 ha) of eelgrass meadows in the Channel Islands restricted the potential range of reserve locations. Given the criteria that reserves should include at least 30% of existing eelgrass meadows, and that large and contiguous reserves are most effective for conservation (Margules et al. 1988, Dayton et al. 2000), the SAP recommended potential reserve sites should include at least four of the 10 eelgrass meadows known in the Channel Islands. The lack of eelgrass meadows on San Miguel Island means that at least four reserves on Santa Rosa, Santa Cruz, and Anacapa Islands should include eelgrass habitat.

Species of special concern and critical life-history stages

One goal for marine reserves is to protect populations of special concern, which include species of economic importance, keystone species, declining, threatened or endangered species, and habitat-forming species. The MRWG identified 119 species of special concern in the Channel Islands, including plants, invertebrates, fish, seabirds, and marine mammals (Airamé et al. 2000). The list of species of special concern does not include a large number of mobile species (e.g., cetaceans) whose distributions greatly exceed the Sanctuary boundaries.

The distributions of species of special concern were not known for all species. However, some species, including seabirds (e.g., Hunt et al. 1980; Carter et al., *unpublished manuscript*) and pinnipeds (e.g., Stewart et al. 1993, DeLong and Melin 2000, Caretta et al. 2001), have been studied extensively on the Channel Islands and their distributions are known. The distributions of pinniped haul-outs and seabird colonies were among the criteria used to locate potential marine reserves within the planning region (Table 2). By explicitly identifying pinniped haul-outs and seabird colonies, the algorithm used to locate potential reserve sites identified areas of high pinniped and avian diversity along the island coastlines and on emergent rocks. In this way, the SAP weighted island coastlines and emergent rocks according to the distributions of pinnipeds and seabirds. Given sufficient data, other marine habitats could be weighted according to the distributions of a variety of species of special concern.

Exploitable species

Although the bulk of the southern California commercial landings of fin fish are from offshore fisheries such as Pacific mackerel (*Scomber japonicus*), Pacific bonito (*Sarda chiliensis*), and anchovy (*Engraulis mordax*; Cross and Allen 1993), the proportion of landings of nearshore species for commercial fisheries has been increasing (Dugan and Davis 1993). The overlap of northern species (e.g., yellowtail rockfish [*Sebastes flavidus*], lingcod [*Ophiodon elongatus*], and market squid [*Loligo opalescens*]) with southern species (e.g., California sheephead [*Semicossyphus pulcher*], white seabass [*Atractoscion nobilis*], and spiny lobster [*Panulirus interruptus*]) contributes to the great diversity of nearshore recreational and commercial fisheries in the

Channel Islands (>100 fish and >20 invertebrate species). Many exploitable species, particularly the nearshore groundfishes, could benefit from protection by fully protected marine reserves (Parrish et al. 2000, National Research Council 2001). Additionally, marine reserves have the potential to benefit depleted fisheries through export of larvae (e.g., Palsson and Pacunski 1995, Sluka et al. 1997, Murawski et al. 2000) and spillover of adult fish into nonreserve areas (e.g., Attwood and Bennett 1994, Johnson et al. 1999).

As an example, many rockfish (*Sebastes* spp.) have suffered recent declines throughout their ranges and several rockfish species (Pacific Ocean perch [*Sebastes alutus*], dark-blotched rockfish [*S. crameri*], cowcod [*S. levis*], bocaccio [*S. paucispinis*], canary rockfish [*S. pinniger*], and yelloweye rockfish [*S. ruberrimus*]) are considered overfished (<20% of their carrying capacity; Parrish et al. 2000, Pacific Fishery Management Council 2000, Leet et al. 2001). Rockfish are particularly vulnerable to commercial and recreational fishing because they are long-lived, have relatively slow growth, late maturity, and unpredictable annual recruitment (Horn and Allen 1978, Cross and Allen 1993, Love 1996, Love et al. 2002). Although efforts are underway specifically to address rockfish declines (California Code of Regulations, Title 14, Section 150.06 and Federal Register [2002]), establishing permanent refuges for rockfish and other vulnerable species may be necessary to reverse population trends and maintain viable populations of these species. Therefore, suitable rockfish habitats, including submerged rocky features such as pinnacles, ridges, seamounts, and submarine canyons, were added to the habitat types requiring sufficient representation within each biogeographic region (Table 2).

Invertebrate fisheries in the Channel Islands traditionally targeted abalone (*Haliotis* spp.; no longer harvested), spiny lobster, rock crab (*Cancer* spp.), and ridgeback prawns (*Sicyonia ingentis*). Red sea urchins (*Strongylocentrotus franciscanus*) emerged as the dominant fishery in the mid-1980s (Kritzer et al. 2000). Expanding fleets of squid boats target spawning aggregations of market squid on the nearshore shelves of the Channel Islands (Vojkovich 1998). Today, market squid and sea urchins dominate the fisheries, exceeding the market value of all other species, including fin fish (R. V. Leeworthy, *unpublished data*). Small, but growing, markets for turban snails, whelks, and sea cucumbers have developed in the last decade (R. V. Leeworthy, *unpublished data*). Given the historical expansion of invertebrate fisheries in the region, it is likely that fisheries will target additional species in the future. The SAP agreed that the range of representative habitats (Table 2) was sufficient to protect the most commonly exploited and potentially exploitable invertebrates.

Ecosystem functioning and linkages

It was difficult to determine the extent to which ecosystem linkages should constrain reserve design in the Channel Islands and the SAP did not identify a criterion for reserve siting based on ecosystem functioning and linkages.

Ecosystem services

Reserves have the potential to enhance habitats that provide refuges for species of special concern. For example, spiny lobsters can limit the abundance of sea urchins (a grazer) to levels that may allow kelp to persist (Lafferty and Kushner 2000). Reserves that enhance lobster density can indirectly provide a habitat for a diverse array of kelp forest species, many of which have economic importance (Lafferty and Kushner 2000). Thus, placing reserves in urchin barrens where fishing has reduced lobster populations may allow kelp forests to recover.

Reserves also provide relatively natural areas that can be compared to fished areas to determine the impacts of fishing on various species. Without reserves, it is very difficult to understand how marine ecosystems function in the absence of fishing. One particularly valuable research effort has been the annual monitoring of kelp forests and intertidal habitats conducted by the Channel Islands National Park (Davis et al. 1994). The Kelp Forest Monitoring Program provides a long-term annual description of the subtidal community at 16 monitoring sites throughout the Channel Islands. These data provide a baseline against which to evaluate reserves and, although the monitoring sites were not included as a formal criterion for reserve siting, the SAP recommended that some of the monitoring sites be included in reserves to allow researchers to track changes associated with protection over time.

Human threats and natural catastrophes

Most marine habitats are vulnerable to both natural and anthropogenic disturbances (e.g., large storms and oil spills). Over long periods of time and large areas, severe disturbances in marine ecosystems are not uncommon (Allison et al. 2003). High levels of site-specific threats might preclude certain areas from inclusion in a reserve network. Oil exploration, drilling, production, and transport all occur in the Channel Islands region and these activities are associated with a variety of potential threats. Projected oil development in the Point Conception and Santa Maria Basin areas could result in downstream contamination of the northern Channel Islands via the prevailing California Current.

The risk of shipwrecks, contributing to spilled oil or other contaminants, is substantial in the Channel Islands area. A major shipping lane lies in the Santa Barbara Channel along the northern shores of the northern Channel Islands (Fig. 1). The number of commercial vessels traveling between Point Conception and Long Beach, California, has increased from 8500 vessels per year in 1987 (Anderson et al. 1993) to >14 000 vessels per year in 2001 (M. McCutchan, *personal com-*

munication). The threat of an oil spill or other catastrophic event in the Channel Islands has a number of implications for reserve siting. One way to increase effectiveness of a reserve network is to allow for the impacts of catastrophic events by increasing the percentage of area in reserves. The minimum effective size of a reserve network is the size necessary to meet the goals for the reserve in a stable environment multiplied by an ''insurance factor'' that takes into account the frequency of severe disturbance to the environment (Allison et al. 2003). In the Channel Islands, the insurance factor was estimated as 1.2–1.8 times the size of a reserve network that meets the reserve goals in a stable environment (Allison et al. 2003). To achieve goals for conservation and fisheries, the SAP recommended a minimum reserve size of 30–50% of the planning region, multiplied by an insurance factor of 1.2–1.8, requiring minimum protection of ~36–54% of the planning region. For analytical purposes, targets of 30%, 40%, and 50% reserve areas were used in the algorithm for reserve siting. To minimize the likelihood that the total reserve area will be impacted simultaneously by a catastrophic event, the SAP recommended placing multiple reserves in each biogeographic province in the planning region.

Size and connectivity

The size, number, and spacing of reserves are interrelated. Ideally, the size of a single reserve depends on the potential dispersal distance, population growth rate, and fishing pressure on species of special concern (Carr and Reed 1998, Roberts et al. 2001). Individual reserves may be smaller if they are part of a network of reserves connected through dispersal of adults and larvae (Hastings and Botsford 1999). Given the wide range of life-history characteristics of species of special concern (e.g., annual to long-lived species of four phyla in the Channel Islands), it is nearly impossible to identify a reserve size that is optimal for all species. One way to achieve some level of connectivity among populations is to distribute a network of reserves throughout the planning region and to vary reserve spacing (Roberts et al. 2003). Future research on dispersal and connectivity in the Channel Islands region may provide the information required to incorporate this criterion effectively into reserve siting decisions.

In an effort to balance reserve size with enforcement constraints, the SAP recommended establishing one to four marine reserves in each biogeographic region. For example, the largest biogeographic region in the Channel Islands National Marine Sanctuary, the Oregonian Province, is ~2200 km^2. The recommendation to set aside at least 30–50% of all representative habitats in each biogeographic region, leads to a network of two to three reserves, each of ~200–550 km^2, in the Oregonian Province. In other planning regions, reserves for conservation and fisheries management may have to be larger (or smaller) and more (or less) numerous.

Application of Ecological Criteria

The SAP developed a suite of potential reserve network scenarios designs to meet goals for conservation and fisheries management using the range of effective reserve sizes and the ecological criteria discussed in this paper. Locating potential reserve sites required (1) selection and description of planning units in the planning region, (2) evaluation of potential reserve networks using the ecological criteria, and (3) selection of the best set of sites that provided the greatest degree of flexibility to accommodate various interests of stakeholders.

Choosing a suitable planning unit size

The Channel Islands planning region was divided into ~1500 planning units of 1 × 1 min (~1 × 1 nmi^2) following longitudinal and latitudinal lines (Fig. 2). Where they intersected the shore or the Sanctuary boundary, the boundaries of the planning units were irregular in length. The size of the planning units was selected, in part, because socioeconomic information on commercial and recreational use was collected at this scale. The ''cost'' of each planning unit was simply assigned as its size (in this case, the boundary length around the planning unit). It is possible to incorporate the actual cost of each planning unit, in terms of commercial and recreational revenue, however, the MRWG asked the SAP to provide a range of solutions optimal for conservation and fisheries management, without considering economic impacts. A separate panel of economists and social scientists collected and analyzed economic information on commercial and recreational activities in the planning region.

Describing planning units

Within each biogeographic region (Oregonian Province, California Province, or Transition Zone), planning units were assigned to a depth interval (shoreline, photic zone, upper and lower continental shelf, and continental slope; Fig. 2). The area covered by soft and hard substrates was estimated within each planning unit. Submerged rocky features, including pinnacles, ridges, seamounts, and submarine canyons, were located using bathymetric maps, and the percent cover of each feature was estimated. Areas covered by habitat-forming species, such as giant kelp, eelgrass, and surfgrass, were identified from aerial photographs and habitat maps. Finally, each planning unit was scored for the presence of persistent seabird colonies (16 species) and pinniped haul-outs (five species).

Existing reserves

Existing reserves in the Channel Islands were not included a priori in potential reserves. If existing re-

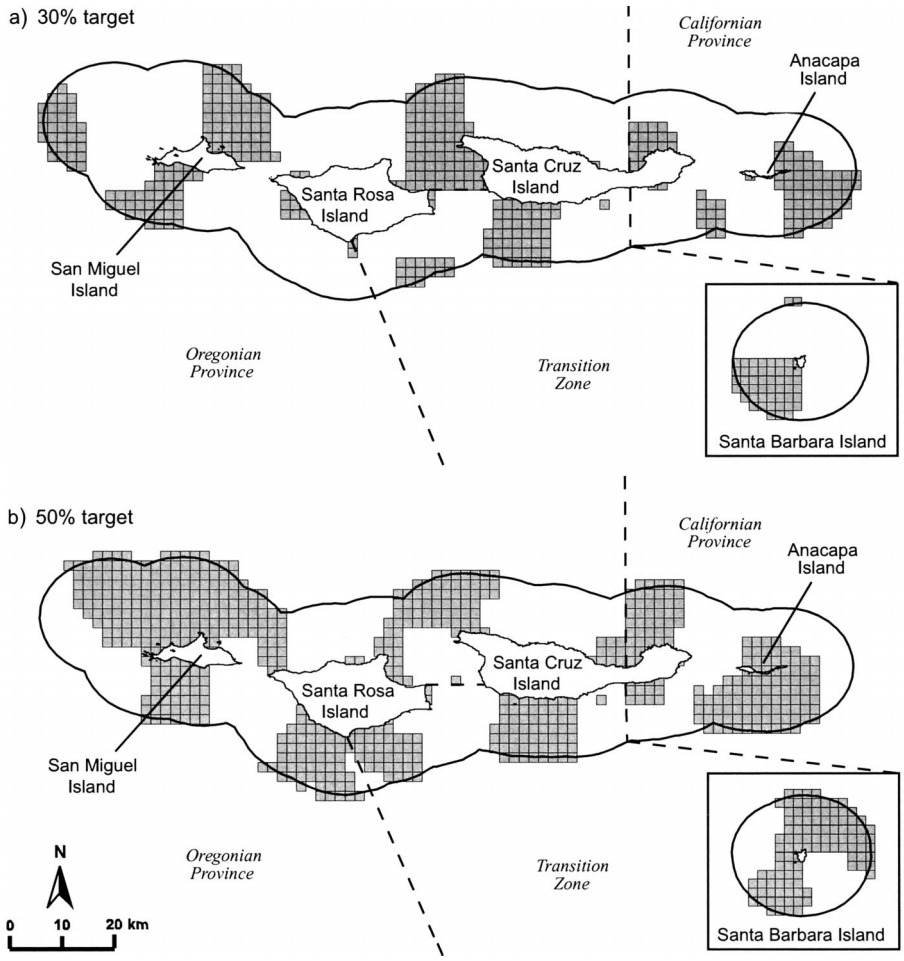

FIG. 3. Potential reserve designs for conservation and fisheries management in the California Channel Islands. Conservation targets were set at (a) 30% and (b) 50% of the total value for each of the ecological criteria listed in Table 2. Separate analyses were conducted for each of the biogeographic regions (dashed lines). Santa Barbara Island (insert) was included in the Transition Zone.

serves overlap proposed reserve sites, they will be incorporated into the proposed sites; if not, they will be evaluated and possibly removed in accordance with the Marine Life Management Act (AB 993).

The algorithm

Reserve siting algorithms have been used extensively in the context of terrestrial systems (e.g., Cocks and Baird 1989) to identify potential reserve networks that minimize cost while meeting specified ecological constraints, such as representation of some specified percentage of existing habitat or number of populations (Possingham et al. 2000). In contrast, there are few applications of mathematical siting algorithms to marine systems (but see Ward et al. 1999, Beck and Odaya 2000, Leslie et al. 2003). Potential reserve sites in the Channel Islands were located using Sites v. 1, an analytical tool for identifying regional-scale reserve networks (Andelman et al. 1999, Possingham et al. 2000). The program uses a greedy or simulated annealing algorithm to identify an efficient set of sites that collectively represent specified amounts of habitats, populations, or other features. The goal of the Channel Islands analysis was to identify potential sets of one to four reserves within each biogeographic region that meet the ecological criteria specified by the SAP, while minimizing total reserve network area. The model does not consider explicitly the spatial relationships among potential sites, however it provides flexibility to control the degree of clustering among reserves by using an adjacency constraint and minimizing the boundary length of the entire reserve system (by setting the boundary length modifier to a value of 1; Andelman et al. 1999, Possingham et al. 2000).

The analyses began by identifying the ecological criteria described in this paper as input parameters. Separate analyses were conducted for each biogeographic region to identify priority areas for conservation within

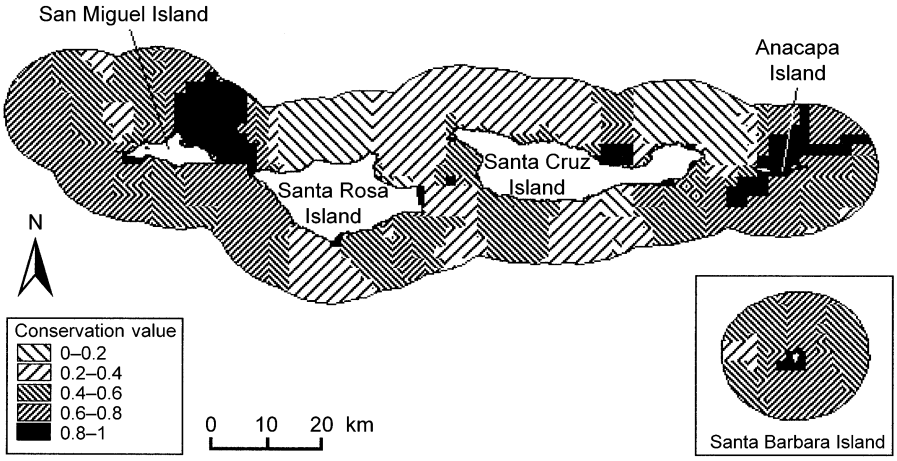

FIG. 4. Priority areas for conservation in the Channel Islands National Marine Sanctuary. Each planning unit is weighted by the number of times it was selected for a final solution out the total number of simulated annealing runs. The number of runs per bioregion is equal to the size of the region (e.g., 300–800 runs). Individual planning units can be compared on a scale of 0 to 1 by dividing the number of times each unit was selected for a final solution by the total number of runs in a particular bioregion.

each region. Targets of 30%, 40%, and 50% of each of the ecological criteria (e.g., habitats and features) were established for analysis. Given the input parameters, the program randomly generated an initial reserve system that included the target percentage of each habitat and feature. The program then calculated the cost of the reserve system (based on the boundary length of each planning unit). After the initial random reserve system was evaluated, the program randomly selected a planning unit that might or might not already be in the reserve system. The program evaluated the change to the value of the reserve system that would occur if this planning unit were added or removed from the system. The program repeated 1 000 000 annealing iterations. At each step, the new solution was compared to the previous solution, and the best one was accepted. The algorithm was run 300–800 times, in proportion to the size of each biogeographic region. Setting the number of runs equal to the number of planning units in a biogeographic region allowed comparison of results between regions.

Output data

Output data from the Sites model included (1) the solutions for each run, (2) the best solution of all runs, and (3) the summed solutions over all runs (or ''irreplaceability analysis'' discussed in Leslie et al. [2003]). The summed solutions describe the number of times each planning unit was selected for the final scenario out of the total number of runs. The data were grouped by biogeographic region and by percent of the region contained within the reserve network (i.e., 30%, 40%, and 50%). A large number of suitable solutions may satisfy a single set of input criteria. Each solution is given a score equal to the conservation value minus the cost (boundary length) of the reserve. The ''best'' solution of all runs is the scenario with the greatest conservation value and the lowest cost (Fig. 3).

The summed solutions over all runs described the number of times each planning unit was selected for the final scenario out the total number of runs (Fig. 4). The summed solutions were converted to percentages by dividing the number of times each planning unit was selected for the final scenario by the total number of planning units in the biogeographic region. For example, cells that were selected in 70%, 80%, or 90% of the runs were considered to have high conservation value, whereas those selected in 5% or 10% of runs were considered to have low conservation value. The MRWG used the summed solutions (Fig. 4), economic data, and personal knowledge to identify a set of potential reserve sites.

Cluster analysis

Numerous potentially suitable solutions may satisfy each specified set of criteria. Solutions with the highest conservation value were organized into distinct groups using cluster analysis. The Bray-Curtis similarity between solutions was calculated for the 100 top-ranking solutions. Solutions were divided into groups based on 60% Bray-Curtis similarity, producing approximately five groups per biogeographic region for each of three reserve network areas (e.g., 30%, 40%, and 50%). If the grouping algorithm produced more than five groups, the group with the lowest high score was removed from the analysis.

Solutions within each group were ranked according to conservation value. The best solution in each group was selected for consideration as a potential reserve network (e.g., Fig. 3). Thus, at the end of the analysis,

TABLE 3. Application of ecological criteria for marine reserve design.

Ecological criteria†	Application to the Channel Islands	Limitations
Biogeographical representation	Three major biogeographical regions were identified using data on biota and SST.	Boundaries of biogeographical regions are not fixed.
Habitat representation	Representative and unique marine habitats in each biogeographical region were classified using depth, exposure, substrate type, dominant plant assemblages, and a variety of additional features.	Data on the distributions of habitat types may be limited.
Habitat heterogeneity	This was not incorporated as a specific criterion, but the analysis required representation of 30–50% of all habitats within the smallest area possible, thus selecting areas of high habitat heterogeneity.	Data on the distributions of habitat types may be limited.
Vulnerable habitats	To insure adequate representation, vulnerable habitats were considered unique habitat types.	Data on the distributions of vulnerable habitats may be limited.
Species of special concern and critical life history stages	Island coastlines and emergent rocks were weighted according to the distributions of pinniped haul-outs and seabird colonies. The algorithm selected areas of high pinniped and bird diversity. Other species were not weighted due to insufficient data on their distributions.	Data on distributions and life-history characteristics of species of special concern may be limited.
Exploitable species	Habitats likely to support exploitable species, especially rockfishes (e.g., emergent rocks and submerged rocky features), were included for specific representation.	Data on distributions and life-history characteristics of exploitable species may be limited.
Ecosystem functioning and linkages	Not used	Determining the extent to which ecosystem linkages constrains reserve design may be difficult.
Ecosystem services	Locations of CINP kelp forest monitoring sites were not included as a formal criterion, but borders of potential reserves will be adjusted, if needed, to include some of those sites.	Sufficient information on ecosystem services may not be available.
Human threats and natural catastrophes	The reserve size needed to meet reserve goals in a stable environment (30–50%) was multiplied by a factor that accounts for the frequency of severe disturbances (1.2–1.8). No areas were excluded from the process.	Data on the frequency of severe disturbance may be limited.
Size and connectivity	At least one, and no more than four, reserves should be placed in each of the three biogeographical regions. For one region (650 nmi^2), two to three reserves (~60–160 nmi^2 each) was recommended.	Optimal number of reserves will generally depend on the size of each biogeographical region. Reserve placement will depend on dispersal among sites.

† Roberts et al. 2003.

the SAP presented the MRWG with a portfolio of 10 spatially explicit reserve network scenarios. The most dissimilar scenarios with the highest conservation value were chosen for consideration to provide a range of feasible options to the planning group.

Final decisions

Flexibility to explore alternative solutions is critically important for conservation planners because practical problems may overcome optimality (Cocklin 1989). Generally, conservation planners need to be able to evaluate a range of solutions that are reasonably good from an ecological perspective, in the context of other considerations, such as economics or political expediency (Possingham et al. 2000). The MRWG was given the opportunity to evaluate potential reserve scenarios in an interactive GIS that included socioeconomic information about major commercial and recreational activities in the Channel Islands. To facilitate consideration of diverse goals, the MRWG was able to adjust and evaluate potential reserve networks and modify potential reserve network boundaries within the framework of the GIS. Proposed changes to a reserve network were evaluated according to both ecological and economic criteria. If the proposed changes did not meet the ecological criteria, the SAP provided the MRWG suggestions for improving the reserve network. This flexible, iterative approach was essential because it allowed planners to evaluate a complex problem with diverse goals using the best available ecological and economic data.

CONCLUSIONS

The Channel Islands case study presented here illustrates the feasibility of using a simulated annealing

algorithm with data on representative and unique habitats, and distributions of vulnerable species, to identify reserve network scenarios with the potential to achieve both conservation and fisheries goals. The approach is flexible, and specific criteria may be added or deleted depending on reserve goals and the available data. The specific ecological criteria used to select the location, size, and number of reserves are defined by the specified objectives (e.g., the specific ecological features targeted within the geographic region being considered). Examples of potential ecological criteria include unique and representative habitats, species of concern, connectivity, vulnerable life history stages, and larval sources and sinks (Roberts et al. 2003). However, as we show here, in the absence of data on many of these criteria, it is possible to identify potential reserve networks using only a subset of the criteria (Table 3).

In the Channel Islands, as in many other marine regions of conservation interest, data on larval dynamics and population growth of particular species were scarce or nonexistent. In contrast, there were many sources of data on habitat distributions. We show that in such cases, a habitat-based approach may be an effective and practical alternative to identifying reserves based on individual species needs (Agardy 1997, Dayton et al. 2000). Protection of a substantial proportion of all habitats is likely to conserve many populations of concern, including exploited species, and therefore, will contribute to the fisheries goal. The SAP estimates that reserving 30% of all unique and representative habitats in the Channel Islands will conserve populations of ~80% of species of concern (Airamé et al. 2001).

There are limitations to using habitat as the only criterion for reserve design. These limitations result from a lack of data, and not from the general approach to reserve design described here. Habitat maps provide a snapshot of physical and ecological conditions at one point or interval in time. The static nature of most of the data on habitat distributions does not account for environmental variation and climate regime shifts. Two additional design considerations may reduce the probability that such large scale events will impact all reserved areas simultaneously. First, reserves should be placed in a network such that all reserves will not be affected by large scale events in the same way. In the California Channel Islands, the SAP recommended that one to four reserves be designated within each of three bioregions. Second, the risk of negative impacts on reserves from catastrophic events can be reduced by increasing individual reserve size and the overall network size. In the Channel Islands, this was done using an ''insurance multiplier,'' estimated as 1.2–1.8 times the size of a reserve network that meets the goals in a stable environment (Allison et al. 2003).

Another limitation of habitat-based reserve network siting is that habitat descriptors of species do not include the variable behaviors of individuals and populations. To incorporate the dynamic nature of biological and physical systems into reserve design, better understanding of the linkages between environmental shifts and life-history characteristics such as population growth and larval dispersal is needed. Although consideration of life-history traits in future reserve design efforts might increase the level of protection for certain species, a potentially effective reserve network that meets multiple objectives (e.g., conservation, fisheries management, education, and research) can be identified in the absence of such data. In fact, one benefit of marine reserves is to provide insurance against this type of scientific uncertainty (Roberts and Hawkins 2000). Using limited data, simulated annealing can provide resource managers with suitable tools to develop effective and acceptable solutions to complex conservation problems.

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