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Ecosystem-Based Analysis of a Marine Protected Area Where Fisheries and Protected Species Coexist

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Abstract The Gulf of California Biosphere Reserve (UGC&CRDBR) is a Marine Protected Area that was established in 1993 with the aim of preserving biodiversity and remediating environmental impacts. Because remaining vigilant is hard and because regulatory measures are difficult to enforce, harvesting has been allowed to diminish poaching. Useful management strategies have not been implemented, however, and conflicts remain between conservation legislation and the fisheries. We developed a transdisciplinary methodological scheme (pressure-state-response, loop analysis, and Geographic Information System) that includes both protected species and fisheries modeled together in a spatially represented marine ecosystem. We analyzed the response of this marine ecosystem supposing that conservation strategies were successful and that the abundance of protected species had increased. The final aim of this study was to identify ecosystem-level management alternatives capable of diminishing the conflict between conservation measures and fisheries. This methodological integration aimed to understand the functioning of the UGC&CRDBR community as well as to identify implications of conservation strategies such as the recovery of protected species. Our results suggest research hypotheses related to key species that should be protected within the ecosystem, and they point out the importance of considering spatial management strategies. Counterintuitive findings underline the importance of understanding how the community responds to disturbances and the effect of indirect pathways on the abundance of ecosystem constituents. Insights from this research are valuable in defining policies in marine reserves where fisheries and protected species coexist.

Keywords Ecosystem-based management · Geographical Information Systems · Local ecological knowledge · Loop analysis · Marine protected areas · Fisheries and protected species · Upper Gulf of California and Colorado River Delta Biosphere Reserve

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Fisheries have traditionally been managed using species-specific regulations for commercially important stocks and by protecting sites of biological, social, or economic interest. However, most fisheries have not achieved sustainability based solely on the use of these guidelines (Christensen and Pauly 1995; Botsford and others 1997). While species-specific planning has been limited by factors such as the lack of assessment of indirect effects and a poor understanding of socioeconomic processes (Sterman 2002; Fulton and others 2003; Ludwig and others 1993; Christie and others 2004; Beddington and others 2007), scientists have recently sought to develop new ecosystem-based

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management approaches and methodologies based on the assumption that the information of other ecological processes (such as species interactions, human impacts, and functional diversity) may provide important tools to solve both the problems faced by fisheries and the area's conservation issues, (Grumbine 1994; Loiselle and others 2000; Pauly and others 2000; Salomon and others 2001; Ortiz and Wolff 2002; Sala and others 2002; Pikitch and others 2004; Montaño-Moctezuma and others 2007).

The extreme climatic conditions, along with the lack of a connection with the open ocean, have led to particular physical characteristics in the Upper Gulf of California, such as ample tide intervals (10 m), shallow areas, extreme temperatures (8–30°C), and elevated turbidity, evaporation, and salinity indexes (Brusca 2004). These particular attributes are favorable for several species that promote a highly diverse ecosystem. Unfortunately, the biodiversity of the Upper Gulf of California has deteriorated due to human activities related to the diversion of water of the Colorado River for irrigation and municipal uses, as well as the increase in fishing activities (Sala and others 2004). Native peoples (Cucapa, Seri, and so on) have relied on natural resources from this area to gather food for centuries (Hale and Harris 1979). In recent years, however, the commercial harvest of these resources has increased dramatically. Artisanal and industrial fleets have mainly targeted shrimp, fish, and elasmobranches (Cudney and Turk 1998) and management strategies have focused on single-species regulations (seasonal and spatial closures, minimum size limits, fishing effort control, quotas) rather than a holistic ecosystem approach (Morales-Zárate and others 2004). Moreover, stock assessment, which is critical to achieving management goals, has commonly been based on unreliable and biased information in developing countries like México (Ortiz-Lozano and others 2005; Sáenz-Arroyo and others 2005).

Mexico has decreed that certain regions be labeled as marine protected areas (MPAs), with the aim of preserving the biodiversity of the area while also planning for the development fisheries in the area. In 1993, the Upper Gulf of California and the Colorado River Delta Biosphere Reserve (UGC&CRDBR), currently included on the UNESCO World Heritage list (IUCN 2005), was established to repair the damage done to one of the most diverse marine ecosystems on Earth. Although this MPA was intended to protect coastal resources, the application of its policies has not been effective in the recovery of fish or of protected species (Cisneros-Mata 2004). The limited success of the UGC&CRDBR regulations is due to several reasons: (1) the lack of understanding of ecosystem processes (Morales-Zárate and others 2004); (2) unreliable and biased information used to assess performance of the MPA; (3) changes in the amount of inflow from the Colorado River; (4) insufficient involvement of local communities in management and conservation decisions; (5) human activities controlled by remote economic forces; and (6) poaching. Since the fundamental objective of the UGC&CRDBR is the recovery of protected species, we analyzed the ecosystem response to specific conservation strategies that have been proposed to increase protected species abundances: (1) the reduction of by-catch in the gillnet and (2) the exclusion of devices on the trawl net. Our results show that understanding the functioning of the system contributes information valuable for proposing management alternatives that may diminish the conflicts between conservation measures and local fisheries.

Methods

To build the core model, quantitative and qualitative information was obtained about biological and social aspects of fisheries dynamics and conservation processes in the UGC&CRDBR. Quantitative data were extracted from the official database of government fishery agencies (technical reports) and from specialized scientific literature.

The pressure-state-response (PSR) conceptual framework was used to select environmental indicators that provide useful and simple evidence that is fast and cheap to collect (Fig. 1a). Two types of indicators were used: those describing the "state" of the biological community (biological resources) and those describing the fishing "pressure" on these species (fishing gear). Biological variables were used to identify species with similar roles in the marine ecosystem, i.e., most abundant, with proportional by-catch rates, main feeding habits, and importance as fishing resources (Arreguín-Sánchez and others 2002; Gladstone 2002). Since our approach analyzes fishery resources in the context of an MPA, we used the role of the local fisheries and the conservation status of each species to group biological variables. Pressure indicators were constructed with fishing gears and grouped based on gear selectivity and intensity of usage.

Loop analysis was used to represent the main relationships among biological and fishery variables. This method relies on a simple community matrix of positive interactions (→), negative interactions (—•), and no interactions (0) between model variables. The relationships among variables are depicted by a signed-digraph that represents the system (Fig. 2a). Biologically, a positive effect of one variable on another translates to ecological benefits or improved conditions (e.g., increase in prey abundance or in availability of fishing resources). The opposite is true in the case of negative relationships. These represent negative effects on the variable (e.g., greater number of predators, fewer fishing resources).

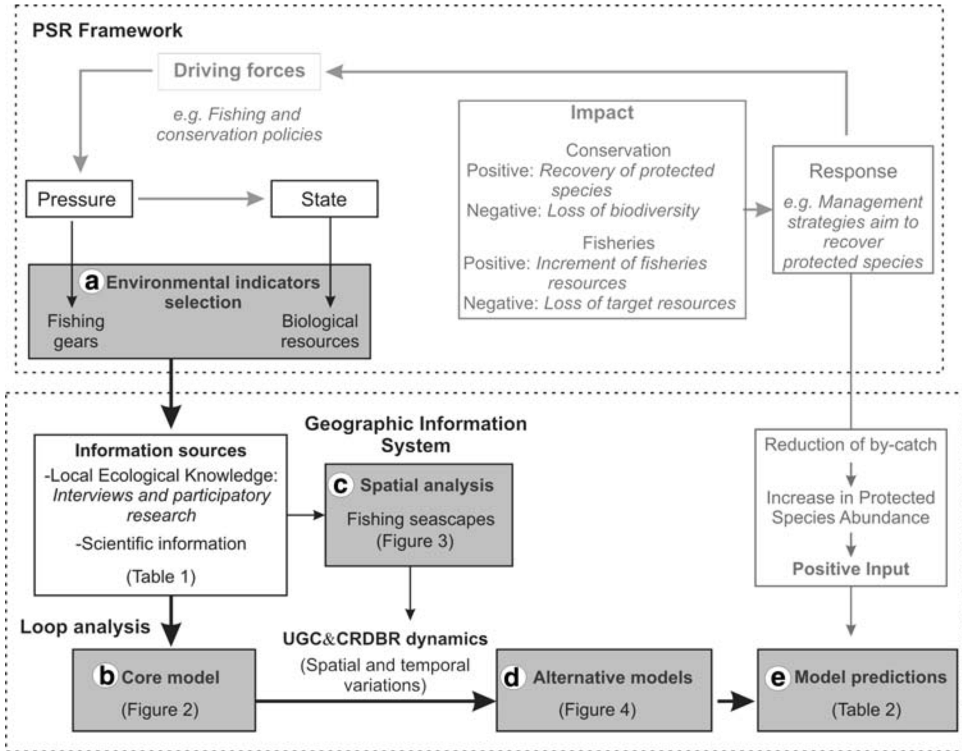

Fig. 1 Flow diagram showing the assembly of the analysis tools that were utilized: (1) pressure-state-response, (2) loop analysis, and (3) Geographic Information System. The assemblage is subdivided into five steps (*gray boxes*): (a) indicator selection, (b) core model, (c) spatial analysis, (d) alternative models, and (e) model predictions

Self-regulating effects are represented as links that begin and end at the same variable. They denote processes that regulate the variables (e.g., population density-dependent factors) or additional predators not specifically included in the system (Fig. 2b).

The direction of change in abundance of each variable after a disturbance is obtained from the inverse of the community matrix (A^{-1}) or prediction matrix (Levins 1974), which predicts the response of a positive or negative disturbance on each community member (Fig. 2c). Loop analysis models were tested for stability and "weighted" reliability in their predictions. We considered a model to be stable if (a) all characteristic polynomial coefficients had the same sign and (b) the Hurtwitz determinants were >0 (Puccia and Levins 1985). Weighted predictions allow the assessment of the probability of a given prediction. Weighted predictions >0.4 are considered to be reliable (Dambacher and others 2002). A detailed description of the functioning of loop analysis and its mathematical properties are provided by Puccia and Levins (1985) and Dambacher and others (2002). PowerPlay Digraph Editor version 2.0 and Maple version 5.00 were used to construct the signed digraphs and generate model predictions.

We constructed a core model to represent all the possible interactions between ecosystem members (Figs. 1b and 2). To identify the most important relationships among groups we used the species with higher percentages of occurrence in the stomach contents of different community members. Feeding information was acquired from published papers as well as nonpublished reports. Less frequent interactions were not included. For example, protected species prey on mollusks (M), fish (F), carnivore by-catch (CBC), and crustaceans (C), but only the first three groups (M, F, CBC) were the most common in the stomach contents of the protected species. Interactions among biological resources are mainly predator–prey relationships (←•), but connections among biological resources and fishing gear can be negative due to the incidental harvest effect of the gillnet on protected species (GN —• PS), carnivore by-catch (GN —• CBC), and the effect of the trawl net on carnivore by-catch (TN —• CBC) and fish (TN —• F). The effect of the trawl net on protected species was not included because it has been documented that the main effect of these nets is on habitat modification (García-Caudillo and others 2000; Arreguín-Sánchez and others 2002). Self-regulation effects on biological resources (e.g., M —• M) represent both cannibalism and density-dependent processes. Self-regulation effects on fishing gear (e.g., TN —• TN) include normative, technological, and socioeconomic aspects.

Local ecological knowledge (LEK) (ICSU 2000) was used to relate the anthropogenic variables (fishing gear) with the biological variables. LEK information was obtained from the extensive ethnographic study by Cudney and Turk (1998) which includes 117 structured interviews with fishers and 170 nonstructured interviews with fishers, cooperative societies, brokers, and UGC&CRDBR managers. This information comes from people who, on a daily

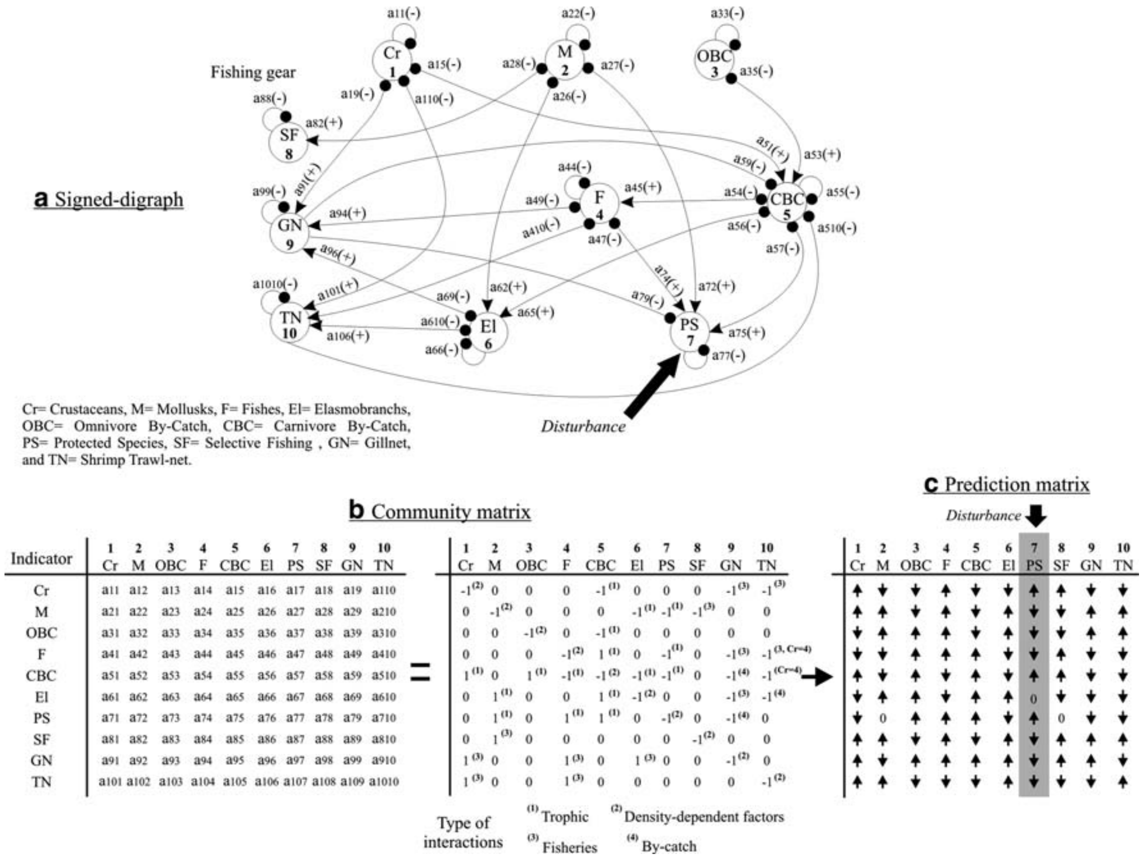

Fig. 2 **a** Core model signed digraph, **b** community matrix, and **c** prediction matrix for the Upper Gulf of California and the Colorado River Delta Biosphere Reserve. Matrix elements (a,i,j) were obtained from the signed digraph. Example: The interaction between protected species and mollusks is depicted by the matrix elements a27 (−) and a72 (+), which correspond to a negative and positive link, respectively. All self-effects are shown in the matrix diagonal, indicated as a11, a22, a33, etc. The prediction matrix indicates a positive disturbance (*black arrow*) that affects protected species and shows the response of each member of the community to this disturbance (*gray column* in prediction matrix). The indicators and their relationships were constructed from Table 1

basis and over long periods, interact with ecosystems for their benefit and livelihood (Berkes and Folke 2002).

To analyze UGC&CRDBR dynamics, alternative models were built considering the spatial and temporal variation in harvest regimes as well as the presence or absence of specific resources (Fig. 1d). In parallel, a spatial classification system based on the landscape ecology of aquatic environments (Hunsaker and Hughes 2002) was used to construct these alternative models for different fishing seascapes (Fig. 1c). We defined a fishing seascape as a region with a particular combination of fishery resources and human activities. In this way, the spatial variation of the fishing seascape was designed according to fisheries and conservation policies by overlaying artisanal and industrial fishing areas (Cudney and Turk 1998, CI 2002) and oceanic limits of the UGC&CRDBR. The percentage area of each seascape was calculated as well. This spatial analysis was conducted by a Geographic Information System (GIS), using Arc View 3.2a.

Seasonal changes in resource availability in a seascape determine shifts in fishing gear. These changes in target species can be identified by overlaying the main fishing seasons. Five fishing seasons were identified (Cudney and Turk 1998): (1) low fishing season (August and December), (2) shrimp (September–November), (3) fish (January–July), (4) mollusks (January–March and June–July), and (5) elasmobranches (May–July). The combination of seasonal changes in resource availability and fishing seasons was used to find the temporal variations in each fishing seascape.

According to the stakeholders, the main UGC&CRDBR conflict is the contradiction between conservation and fisheries; therefore, they suggested analyzing the resulting scenarios of the ecosystem response when either of two conservation strategies was enforced (e.g., the reduction of by-catch in the gillnet or the exclusion of devices on the trawl net). If these strategies succeeded, the survival rate of the protected species increased. The change in this parameter (an increase in protected species abundance) was used as positive input to help the system predict the response of each variable for a scenario where protected species recover (Fig. 2).

In agreement with Morse and others (2007), a spectrum of issues is required to classify disciplinary, multidisciplinary, interdisciplinary, or transdisciplinary research. In the case of this paper (transdisciplinary), team members combined research as a collective in three main parts of the research design. First, this occurred when the core model was drafted using scientific literature (Fig. 1a), complemented and more accurately designed with the stakeholders' perspectives (Fig. 1b). Five stakeholder workshops or collective interviews were organized to analyze the core model draft by technicians from local fishing institutes, by rangers of the protected area, and by fishery scientists. When all of the participants decided that the core model was accurate we proceeded to the second transdisciplinary step by asking local stakeholders to formulate questions that they would like to be addressed using the model. These inquiries were used as negative or positive inputs to get predictions (Fig. 1e).

Results

The information gathered through both the quantitative techniques (stomach contents) and the qualitative technique (workshops with four specialized groups and semi-structured interviews with five key informants) allowed for the integration of biological and social variables within the context of an ecosystem (Table 1). The visualization of the whole community served to shed light on the interactions between the prevailing fisheries in the area and the biological resources they depend on. For example, (1) main fisheries (selective fishing, gillnet, and shrimp trawl-net) exploit 28 species from four biological groups (fish, elasmobranches, mollusks, and crustaceans); and (2) gillnets and shrimp trawl-nets harvest similar resources, some as target species and others as by-catch—in contrast, selective fishing targets mainly mollusks, which represent the most diverse fishery (10 species) and have the lowest extraction rates (catch 1993–1998).

Four fishing seascapes were obtained from the spatial analysis of harvest resources and protection zones (Fig. 3). The resources that are harvested in each seascape vary depending on the area. Crustaceans were common in all seascapes, while protected species were similar for seascapes B, C, and D only. Temporal variations within seascapes generated 18 alternative models (two depicted in Fig. 4 and the rest in Fig. 5) that represent the combination of biological resources present in each seascape and the annual dynamics of fishing activities in the UGC&CRDBR. Main differences among the model structures of seascapes B, C, and D were (1) the absence of fish in seascape B, (2) the absence of elasmobranches in seascape C, and (3) the absence of mollusks in seascape D. The presence or absence of fishing variables (SF, TN, and GN) depended on the fishing seasons.

Model Predictions

Predictions obtained for the 18 alternative models suggest that a successful recovery of protected species will cause a different response for each seascape, suggesting that the same management strategy can have desirable results for some areas but adverse consequences for others. Results indicate that an increase in protected species might be beneficial for resources such as crustaceans and omnivore by-catch only in seascape B, since the abundance of these groups increases in this specific area (Table 2). Crustaceans, omnivore by-catch, and carnivore by-catch might not be affected by the same management options in fishing seascapes C and D (predictions = 0).

An increase in protected species might not be beneficial for mollusks and fish, since both resources tend to decrease in all seascapes (B–D) and seasons (five of five models). Consequently, artisanal fisheries (selective fishing) that depend on these resources will also decrease (Table 2).

The different responses of diverse seascapes to the analyzed management scenario were mainly due to the structure of the particular community that represents each seascape. For example, in model D.15 (Fig. 4), a successful management of protected species caused a decrease in carnivore by-catch due to direct predation. Because protected species also feed on fish, their abundances decreased, reducing predation pressure on carnivore by-catch. This indirect effect counterbalances the increase in predation pressure exerted by protected species. Thus, carnivore by-catch does not change, and neither does its prey (Cr and OBC). On the other hand, the response of the system in seascape B is due to the absence of fish (F) from this area in all models (Fig. 4). Predation pressure on carnivore by-catch (CBC) by protected species is not buffered by fish; therefore, carnivore by-catch decreases. This result suggests that if protected species recover, indirect food web effects will cause resources from lower trophic levels (Cr and OBC) to remain the same in most of the area (fishing seascapes C and D = 79%) and to increase in 9% of the area (seascape B).

Models grouped in the same seascape represent the temporal variation in community structure within areas. Significant predictions were consistent among models from the same seascape in all groups (Table 2). An exception was observed in the response of elasmobranches (El) in seascape D, where three of five significant models

Table 1 (a) Biological indicators and (b) fishing indicators selected for the Upper Gulf of California and the Colorado River Delta Biosphere Reserve, México

(a) Biological indicators: cumulative catch, 1993–1998 (17)[a]

Indicator	Species	Main feeding habits
By-catch		
Omnivore (NA)	11 species: mullet (*Mugil cephalus*), mojarra (*Eucinostomus* spp.), scallops (*Spondylus calcifer*, *Pteria sterna*, *P. rugosa*, *Atrina tuberculosa*, and *Spondylus princeps*), mussel (*Modiolus capax*), mother pearl (*Pinctada mazatlanica*), sea cucumber (*Isostichopus fuscus* and *Parastichopus parvimensis*)	Fish, polychaetae, algae, detritus, and microalgae (1, 2, 10, 13–16)
Carnivore (NA)	40 species:[a] flounder (*Paralichthys* spp.), trigger fish (*Pseudobalistes* spp), hake (*Merluccius productus*), gulf coney and grouper (*Epinephelus* spp.), guitarfish (*Rhinobatos* spp.), puffer (*Tetrodon annulatus*)	Fish and crustaceans (2, 3, 6, 9, 10, 13–16)
Target species		
Crustaceans (23,000 t)	5 species: shrimp (*Litopenaeus stylirostris* and *L. californiensis*) and crabs (*Callinectes belicosus*, *C. arcuatus*, and *C. toxotes*)	Filters feeders and carnivores (others crustaceans) (1, 2, 10, 13–15)
Mollusks (1800 t)	10 species: clam (*Argopecten circularis* and *Tibela stultorum*), oyster (*Crassostrea corteziensis*), winkle (*Hexaplex nigritus*, *Phyllonotus erythrostoma*, *Astrea undosa*, and *A. turbanica*), octopus (*Octopus bimaculatus* and *O. hubbsorum*), and jumbo squid (*Dosidicus gigas*)	Filters feeders and carnivores (other mollusks) (1, 2, 10, 14)
Fish (21,700 t)	5 species: milk fish (*Micropogonias megalops*), bass (*Cynoscion othonopterus*), mackerel (*Scomberomorus concolor*), gulf coney (*Epinephelus acanthistius*), and goldspotted (*Paralabrax auroguttatus*)	Carnivores (fish)(1, 2, 3, 6, 8–10, 13–16)
Elasmobranchs (8900 t)	5 species: sharks (*Squatina californica*, *Rhizoprionodon longurio*, and *Mustelus lunulatus*), guitarfish (*Rhinobatus productus*), and manta ray (*Dasyatis brevis*)	Carnivores (mollusks and fish)(1, 2, 7, 10, 13–15)
Protected species		
Protected species (NA)	7 species: totoaba (*Totoaba macdonaldi*) (I, III, V, VI), marine turtles (*Lepidochelis olivacea* and *Chelonia agassizi*) (II, V), vaquita marina (*Phocoena sinus*) (I, III, IV, V), dolphin (*Tursiups* spp. and *Delphinus delphis*) (V), and sea lion (*Zalophus californianus*) (V)	Carnivores (fish and mollusk) and omnivores (2–5, 10–15)

(b) Fishing indicators

Indicator	Fishing gear (fleet)	Target resources
Selective fishing	Hand-collected (artisanal)	Mollusks (1, 2, 8, 10)
Gillnets	Gillnets and hook (artisanal)	Crustaceans, fish, and elasmobranchs (1, 2, 8, 10)
Shrimp trawl-net	Shrimp trawl-net (industrial)	Crustaceans, fish, and elasmobranchs (2, 6, 8)

Note. NA, no information available. The seven biological indicators are grouped as by-catch, target species, or protected species. *Information sources*: local ecological knowledge (LEK) and ethnographic fishery literature, as follows. (1) Cudney and Turk (1998); five key informants: (2) O. Pedrín, with INP; (3) M. W. Cisneros-Mata, WWF; (4) R. Cudney; and (5) P. Turk, CEDO; (6) J. M. García, formerly with Conservation International; four specialized groups: (7) Shark Fisheries Team (CICESE); (8) managers, UGC&CRDBR; (9) research, CoBi; (10) research, CRIP-Guaymas. Specialized scientific literature: (11) Aurioles-Gamboa and Zavala-González (1994); (12) Cisneros-Mata and others (1995); (13) Arreguín-Sánchez and others (2002); (14) Morales-Zárate and others (2004); (15) FishBase (2006). (16). Technical reports. (17) SAGARPA, Technical Report 1993–1998. *Protected status*: (I) Convention on International Trade of Endangered Species (CITES 1973); (II) sea turtle fishing ban in federal waters (Diario Oficial de la Federación (DOF) 1990); (III) Official Mexican Norm 024 (DOF 1994); (IV) International Union for the Conservation of Nature (IUCN 1996); (V) Official Mexican Norm 059 (DOF 2001); (VI) Official Mexican Norm 063 (DOF 2007)

[a] Carnivores cumulative by-catch of <20 tons (1993–1998): highfin king croaker (*Menticirrhus nasus*), snapper (*Lutjanus* spp.), crevalle jack (*Caranx hippos*), sea bass (*Diplectrum pacificum*), gafftopsail pompano (*Trachinotus* spp.), trigger fish (*Balistes polylepsis*), ocean whitefish (*Caulolatilus* spp.), graybar and cortez grunt (*Haemulon* spp.), gulf grouper (*Mycteroperca jordani*), cusk-eel (*Lepophidium prorates*), roosterfish (*Nematistius pectoralis*), snowy grouper (*Serranus niveatus*), barracuda mexicana (*Sphyraena ensis* and *S. argentea*), leather jacket (*Oligoplites* spp.), bighead tilefish (*Caulolatilus affinis*), mahi-mahi (*Coryphaena hippurus*), ray (*Raja* spp., *Mobula* spp., *Gymnura marmorata*, and *Myliobatis californica*), threadfin (*Caranx otrynter*), blue bobo (*Polydactylus approximans*), other sharks (*Alopias* spp., *Carcharhinus leucas*, *Sphyrna* spp., *C. obscurus*, *Heterodontus* spp., *Negaprion brevirostris*, *S. mokarran*, *Isurus oxyrinchus*, *Galeocerdo cuvier*, *Carcharodon carcharia*, and *Carcharhinus limbatus*)

suggested that elasmobranch numbers would remain the same if protected species recover, while one model suggested an increase in abundance. Although elasmobranches are not directly connected to protected species, indirect effects of the food web may have an impact. Differences among models are mainly due to the negative effect of trawl-net (TN) on elasmobranches (El). This effect is present in models 14 and 15 and absent in models 16

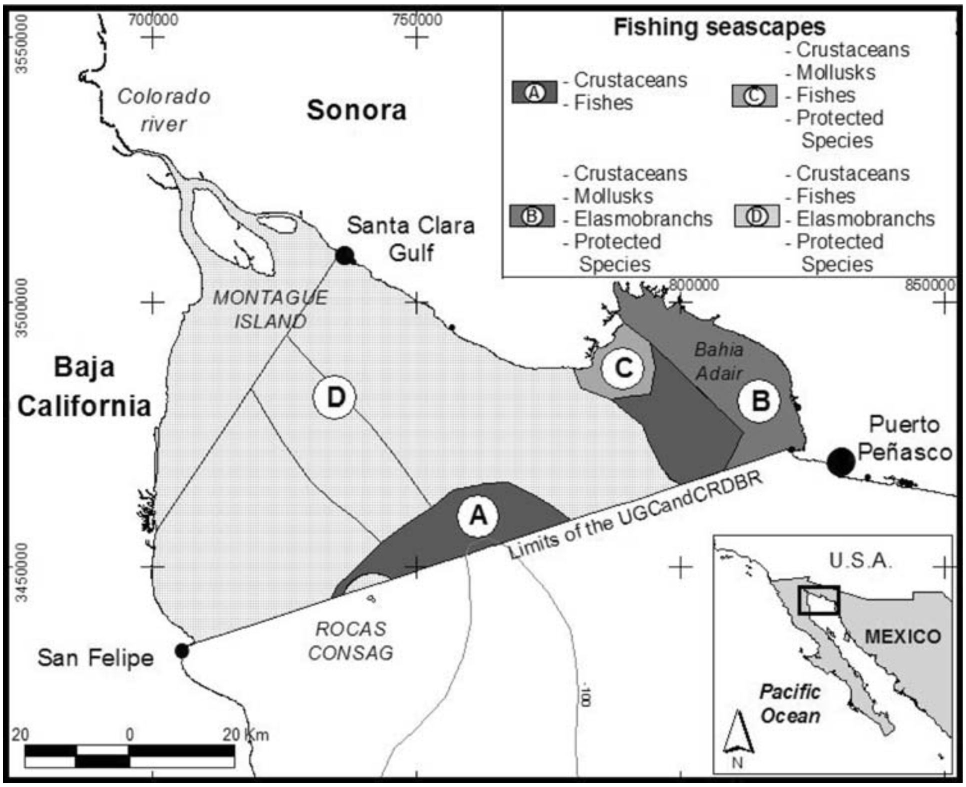

Fig. 3 Upper Gulf of California and the CRDBR regionalization according to space variations of biological resources. Fishing seascapes are denoted by letters, and the percentage cover of each seascape is A = 12%, B = 9%, C = 2%, and D = 77%

Fishing seascape (Spatial variations: Resources distribution)	Alternative models (Temporal variations: Fishing season)
A. Crustaceans and fishes	1. Crustaceans: Sep-Nov 2. Fishes: Jan-Jun 3. No fishing: Jul, Aug, and Dec
B. Crustaceans, mollusks, and elasmobranchs	4. Mollusks: Jan-Mar 5. No fishing: Apr, Aug and Dec 6. Elasmobranchs: May 7. Mollusks-Elasmobranchs: Jun and Jul 8. Crustaceans: Sep-Nov
C. Crustaceans, mollusks, and fishes	9. Mollusks-Fishes: Jan-Mar and Jun 10. Fishes: Apr-May 11. Moluscs: Jul 12. No fishing: Aug and Dec 13.Crustaceans: Sep-Nov
D. Crustaceans, fishes, and elasmobranchs	14. Fishes: Jan-Apr 15. Fishes-Elasmobranchs: May-Jun 16. Elasmobranchs: Jul 17. No fishing: Aug-Dec 18. Crustaceans: Sep-Nov

Cr= Crustaceans, M= Mollusks, F= Fishes, El= Elasmobranchs, OBC= Omnivore By-Catch, CBC= Carnivore By-Catch, PS= Protected Species, SF= Selective Fishing , GN= Gillnet, and TN= Shrimp Trawl Net.

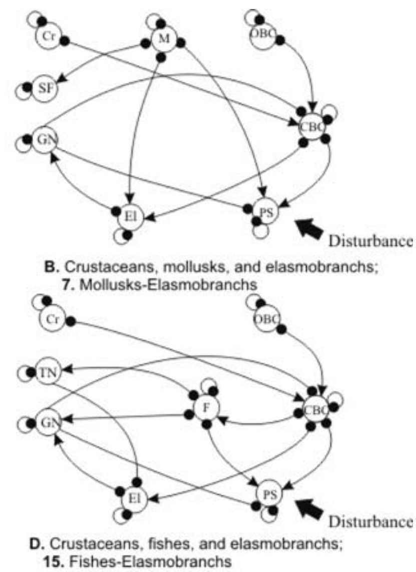

Fig. 4 Alternative models generated for the Upper Gulf of California and the CRDBR. The combination of fishing seascapes (denoted by letters) and fishing seasons yielded 18 alternative models. Models 7 and 15 are represented by signed digraphs as examples: model B.7 represents fishing seascape B, where crustaceans, mollusks, and elasmobranches are harvested and protected species are present; additionally, the number 7 indicates that elasmobranches and mollusks are captured in June and July only (fishing season). Signed digraphs for the rest of the models are given in Fig. 5

through 18 (Figs. 4 and 5). Although differences among model predictions might exist in seascape D, all predictions for this area (no change and increase) are beneficial for elasmobranches.

Fishing gear predictions were predominantly negative and were caused by the general decrease of target resources (Table 2). However, predictions from seascape C and D suggest that during the crustacean harvest season from September through November (Fig. 5: models 13 and 18), gillnet and shrimp trawl-net fisheries will remain the same (Table 3). Because fish (F) are not harvested during this season, the interaction between both trawl-net (TN) and gillnet (GN) with fish (F) is not present (Fig. 5: models 13 and 18). If protected species increase, predictions suggest that, in both models (13 and 18), all variables will remain the same (except mollusks and fish); therefore, gillnet and

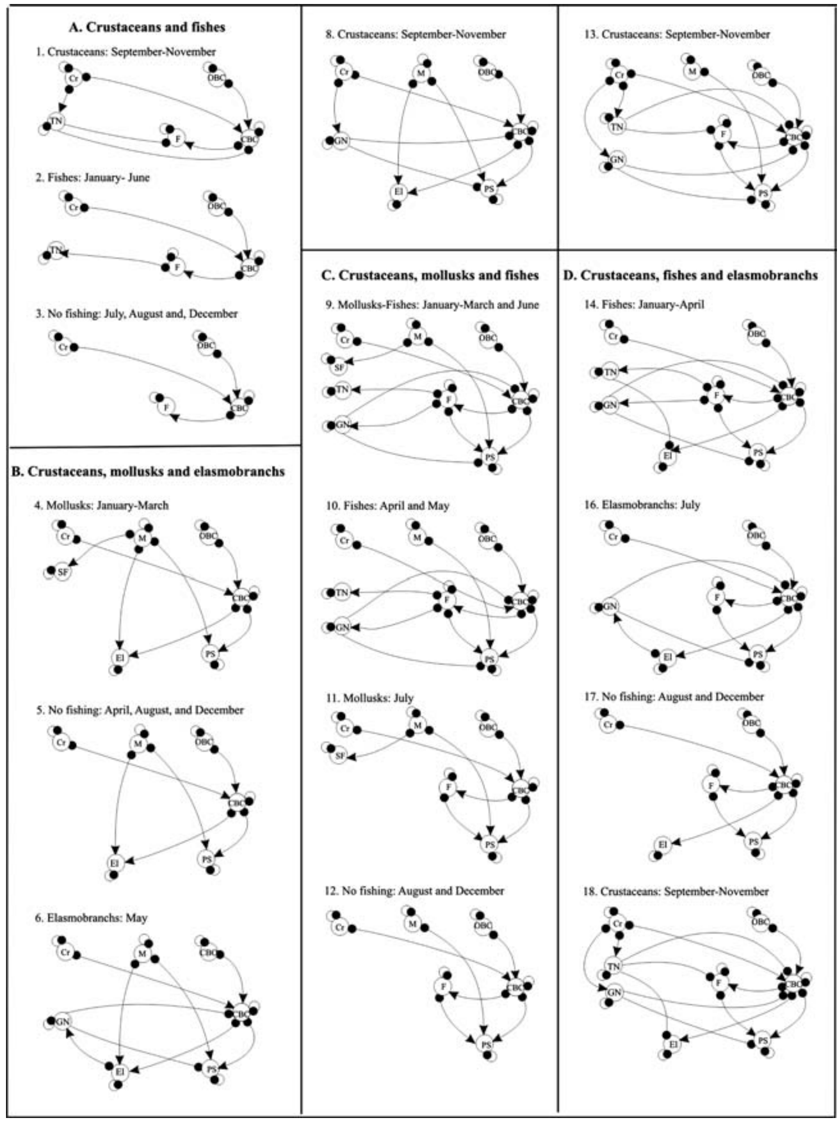

Fig. 5 Alternative models generated for the Upper Gulf of California and the CRDBR. The combination of fishing seascapes (denoted by letters) and fishing seasons yielded 18 alternative models. Example: model A.1 represents the first model from fishing seascape A, where fish and crustaceans are harvested. Temporal fishing seasons are denoted by numbers; model 1 represents the crustacean harvest that takes place from September through November. Models 7 and 15 are shown in Fig. 4

trawl-net fisheries will not change. The same is observed in model 16 (fishing seascape D), where the effects of the gillnet fishery on elasmobranches do not change (Table 3). These results suggest that harvesting crustaceans from September through November in fishing seascapes C and D is a management strategy that could enhance the coexistence between the sustainable use of harvested resources and the conservation of endangered species.

Discussion

The use of MPAs has been suggested as an ecosystem-based management (EBM) tool (Beddington and others 2007), but a holistic management approach has rarely been implemented, and conflicts between conservation efforts and local fisheries remain over single-species regulations. Our approach includes both protected species and fishery resources modeled together in a spatially represented marine ecosystem. This model allows a better understanding of how protected species and fisheries interact in a marine area where these activities coexist.

In the spirit of developing new EBM approaches, the assemblage of methods proposed in this study was useful for analyzing the implications of management policies within a complex ecosystem context, and it provides important tools to solve conflicts between fisheries and conservation measures.

In this work, we used a transdisciplinary approach (Morse and others 2007), defined as a research process where the team jointly define research questions and develop research designs that integrate theoretical knowledge and practical problem solving. For that purpose an assemblage of various analytical methods was used

Table 2 Model predictions considering a positive disturbance on protected species (reduction of by-catch in gillnet and implementation of excluding devices on trawl-net)

Fishing seascape prediction	B	C	D
Biological resource			
Omnivore by-catch	$\uparrow^{(2/5)}$–$\uparrow*^{(3/5)}$	$0^{(5/5)}$	$0^{(3/5)}$–$\uparrow*^{(2/5)}$
Crustaceans	$\uparrow^{(2/5)}$–$\uparrow*^{(3/5)}$	$0^{(5/5)}$	$0^{(3/5)}$–$\uparrow*^{(2/5)}$
Mollusks	$\downarrow^{(5/5)}$	$\downarrow^{(5/5)}$	NA
Carnivore by-catch	$\downarrow^{(2/5)}$–$\downarrow*^{(3/5)}$	$0^{(5/5)}$	$0^{(3/5)}$–$\downarrow*^{(2/5)}$
Fish	NA	$\downarrow^{(5/5)}$	$\downarrow^{(5/5)}$
Elasmobranchs	$\downarrow^{(5/5)}$	NA	$0^{(3/5)}$–$\uparrow^{(1/5)}$–$\uparrow^{*(1/5)}$
Fishing gear			
Selective fishing	$\downarrow^{(2/2)}$	$\downarrow^{(2/2)}$	NA
Gillnet	$\downarrow^{(2/3)}$–$\uparrow*^{(1/3)}$	$\downarrow^{(2/3)}$–$0^{(1/3)}$	$0^{(2/4)}$ –$\downarrow^{(1/4)}$ –$\downarrow*^{(1/4)}$
Shrimp trawl-net	NA	$\downarrow^{(2/3)}$–$0^{(1/3)}$	$0^{(1/3)}$–$\downarrow^{(2/3)}$

Note. Superscript numbers in parentheses: proportion of models from the same seascape that suggest the specified response. Example: Omnivore by-catch ($\uparrow^{(2/5)}$–$\uparrow*^{(3/5)}$): two of five positive predictions were significant and three of five were not significant (*). NA: scenarios where this indicator is not present in the system. (↑) Positive prediction (suggesting an increase in the group abundance); (↓) negative prediction (suggesting a decrease in the group abundance); (0) no change. Fishing seascape A does not appear because protected species are not present in this area

(driving forces-pressure-state-impact-response conceptual framework, LEK, loop analysis, and GIS).

The three methods (PSR, loop analysis, and GIS) have been applied individually to understand marine ecosystems (Ortiz and Wolff 2002; Montaño-Moctezuma and others 2007), for environmental planning of MPAs (Loiselle and others 2000; Gladstone 2002; Sala and others 2002), and to gather information on natural resources (OECD 1993). The PSR theoretical framework was important for integrating available social and biological information on the UGC&CRDBR and analyzing the variables as indicators of human activities and natural resources using data from a heterogeneous database. This integrative approach has not been used in this region before (McGuire and Valdez-Gardea 1997), nor has it been published elsewhere, to the best of our knowledge. Additionally, the PSR framework provided a simplified "multicause and multieffect" ecosystem analysis that highlighted the complex relationship between fisheries and protected species.

Table 3 Predictions from models that showed a different response within seascape C (model 13) and seascape D (models 14–18): the response of the biological and fishing indicators to a positive input on protected species is read down each column

Indicator model	C-13	D-14	D-15	D-16	D-17	D-18
Positive input on protected species						
Crustaceans	0	↑*	↑*	0	0	0
Mollusks	↓	NA	NA	NA	NA	NA
Omnivore by-catch	0	↑*	↑*	0	0	0
Carnivore by-catch	0	↓*	↓*	0	0	0
Fish	↓	↓	↓	↓	↓	↓
Elasmobranchs	NA	↑*	↑	0	0	0
Gillnet	0	↓	↓*	0	NA	0
Shrimp trawl-net	0	↓	↓	NA	NA	0

* No significant prediction

The use of diverse sources of information (quantitative and qualitative) allowed the incorporation of social and biological data, which were useful for filling in the gaps in our database and critically analyzing unreliable and biased information. In addition, the LEK provides convenient consensual management goals, since old and daily experiences from local people are considered to reduce the conflicts between conservation efforts and utilization of resources. The versatility of LEKs has been shown in studies of similar MPAs where conflict exists between fishing and no-take zones and exhaustive quantitative information is lacking. For example, in the Galapagos National Park, the sea cucumber and long-line fisheries are in constant conflict with conservation strategies (Awkerman and others 2006). The same conflicts have been reported in the Caribbean MPAs, where different fishery strategies (no fishing, regulated or zoned) have been put into practice to achieve conservation objectives (Geoghegan and others 2001). Another advantage of using LEK is that it includes literature from other disciplines, such as anthropology (Cudney and Turk 1998). In the present study, information obtained by LEK provided valuable information that is difficult to find in other sources (e.g., the harvest locations).

Analysis using the proposed ecosystem model of the management strategy, aimed at reducing protected species mortality, allowed us to understand the counterintuitive effects of this particular policy in the UGC&CRDBR. Ecological theory indicates that an increase in top predators, in this case an increase in the survival rate of protected species, will cause a decrease in the prey population. However, if the trophic web is highly connected, this trend is not necessarily followed because of indirect effects from other members of the community (Salomon and others 2001; Arreguín-Sánchez and others 2002; Montaño-Moctezuma and others 2007). Our results confirm these findings and emphasize the importance of knowing which indirect effects can cause counterintuitive changes in the ecosystem's response. It has been suggested that ecosystem-based management should focus on identifying the role of key interactions important to maintaining the ecosystem's services (Pikitch and others 2004). The findings of this work reveal how this MPA functions, as well how it responds to disturbances, and they help identify key interactions among species that are useful for propos ecosystem-based management alternatives. We found that fish (F) are key to the response of the system in 79% of the area (fishing seascapes C and D), because they counterbalance the negative impact of protected species on carnivore by-catch and, hence, on the other trophic levels. The presence of fish allows resources from lower trophic levels (Cr and OBC) either to remain the same or to increase when protected species recover. Fish have shown a tendency to decrease in the Gulf of California due to intensive fishing (Sala and others 2004). Since recovering protected species is a crucial goal of the MPA, our findings highlight the importance of protecting fish. Because fish will decrease directly as protected species increase, an alternative measure aimed at reducing carnivore by-catch will indirectly provide more food to fish, potentially promoting an increase in their abundance. Other studies have identified key species when analyzing the functioning of the system. Bodini and others (1994) suggest that the sea otter *Enhydra lutris* in the nearshore community of the Western Aleutian Islands should be considered a key species when designing management strategies, since this species functions as a buffer species that reduces the direct effects from a disturbance. Similar results have been presented by Estes and Duggins (1995) with the sea otter-kelp forest community in Alaska.

Loop analysis is static and does not consider variation in species interaction strength. We overcame this limitation by constructing alternative models that helped to include the variability among fishing seascapes. This suggestion has been recommended by Puccia and Levins (1985) and empirically tested by Montaño-Moctezuma and others (2007). Loop analysis assumes that the system is in moving equilibrium, so variables should have enough time to either return to the same equilibrium values or change to a new equilibrium, depending on the intensity of the disturbance. We believe that the moving equilibrium assumption could be valid for the models that represent fishing seascapes. However, the validity of this assumption for fishing seasons will depend on how fast the system recovers. Despite this, we decided to include alternative models representing the seasons to explore the system's response to each particular harvest scenario, since, in fact, none of the harvests take place at the same time within the same space. Interestingly, all predictions from seascapes B and C were similar in all models, suggesting that seasonal variations in structure do not have an effect on the response of the system to this particular disturbance. Similar responses among models indicate that, regardless of the harvested resource, each particular group (variable) will respond in the same way to the particular disturbance analyzed in the study, suggesting that spatial variations in community structure are more important than annual variations within the same site. Applied to management issues, this might suggest that if protected species recover, the effect of all harvest types in seascapes B and C should be added, cautioning managers about the cumulative potential effort that all fisheries have on the same resource, directly or indirectly.

Spatial and seasonal variations in model responses allowed us to detect which harvest scenarios might be in agreement with conservation policies aimed at recovering protected species. Predictions from seascape B suggest that no harvesting should be allowed in this area, since most of the biological resources as well as fishing gear decrease over time. Although crustaceans might increase, their fishery (gillnet) tends to decrease due to indirect effects. On the other hand, the crustacean fishery may be allowed in seascapes C and D, given that both biological and fishing variables remain the same with this particular management scenario. Crustaceans are harvested by either gillnet or shrimp trawl-net. Because the trawl-net has the negative effect of modifying the habitat (García-Caudillo and others 2000), the use of more benign fishery gear, such as the gillnet, should be encouraged. Reducing the impact of the trawl-net will also diminish the negative effect on carnivore by-catch, a strategy that was suggested in this document to enhance the recovery of fish.

Harvesting elasmobranches could also be a good alternative for seascape D. Although this group would be negatively affected by the gillnet, indirect effects will cause both variables (elasmobranches and gillnet) to remain the same. Although the artisanal mollusk fishery has the lowest extraction rates, it would be preferable to allow selective fishing compared to the more destructive trawl-net. Model predictions suggest that the former (selective fishing) competes for the same resources with protected species, so an increase in protected species has a direct negative effect on mollusks. The mollusk variable seems to be isolated from other variables and is connected only to protected species and harvest. This lack of connection prevents indirect effects from buffering the direct predation by protected species. These counterintuitive results suggest the importance of understanding how the community will respond to disturbances and the effect of indirect pathways on the abundance of ecosystem constituents. It also suggests a research question aimed at verifying whether mollusks are connected to the system through protected species only or by other unknown interactions important in diminishing direct effects.

The analysis of seascapes can be a useful tool for spatial management and can provide MPA administrators with alternative community scenarios to identify the exact pressure sources at each location, leading to focused and efficient management strategies that effectively reduce the human impact on marine systems. Furthermore, it provides the opportunity to perform experimental harvesting and adaptive management, tools that have been suggested as the most direct way to diminish uncertainty about fishery dynamics (Ludwig and others 1993).

Despite the multiple governmental strategies for the conservation of species that regulate the UGC&CRDBR (Cisneros-Mata 2004), spatial differences in system responses have rarely been suggested for this study area. Our approach suggests that if the coexistence of fisheries and protected species is the main goal of the UGC&CRDBR, specific management strategies for each particular site (fishing seascape) should be considered taking into account the differences among community structures.

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