Available online at www.sciencedirect.com

SCIENCE DIRECT®

Ecological Modelling 172 (2004) 373–382

ECOLOGICAL MODELLING

www.elsevier.com/locate/ecolmodel

Optimal management scenarios for the artisanal fisheries in the ecosystem of La Paz Bay, Baja California Sur, Mexico[☆]

Francisco Arreguín-Sánchez[a,*], Agustín Hernández-Herrera[a], Mauricio Ramírez-Rodríguez[a], Horacio Pérez-España[b]

[a] *Centro Interdisciplinario de Ciencias Marinas del IPN, Apdo. Postal 592, La Paz 23000, Baja California Sur, Mexico*
[b] *Centro de Ecología Costera, Gómez Farías No. 82, San Patricio-Melaque 48980, Jalisco, Mexico*

Abstract

In La Paz Bay, two artisanal fisheries operate, one based on hook-and-line, targeting snappers and groupers, and the other mainly based on gillnets, targeting species such as tilefish and haemulids. A shrimp fishery, which is not permitted to expand, also operates. We analyzed various harvesting strategies with the Ecopath with Ecosim modelling software, using catch-and-effort data for target species to fit simulated biomasses. Optimal harvesting strategies for artisanal fisheries were explored using social, economic and ecological criteria. Several harvesting strategies were simulated: continuation of the current state of the fisheries, optimizing economic and social (employment) criteria, using maximum sustainable yield (MSY) as a goal of management, and optimization of an ecological criterion when necessary. Optimization of current fisheries and economic and social criteria, and the MSY resulted in depletion of some stocks and in no-realistic increases in fishing effort. Combinations of economic-ecological, social-ecological and economic–social–ecological criteria did not result in stock depletion. However, some of these scenarios resulted in unrealistic choices, especially large increases in gillnet fishing effort. Among the reasonable choices, a strategy of increasing the hook-and-line fishery effort by a factor of 1.5 and the gillnet effort by a factor of 2.8, appeared to be potentially applicable, to increase efficiency of the artisanal fisheries.

Keywords: Ecopath with Ecosim; Optimization; Harvesting; Artisanal fisheries; La Paz Bay; Mexico

---

1. Introduction

Artisanal fisheries in Mexico support around 40% of the total national catch, and represent an important source of employment. Recent estimates from the National Institute of Fisheries indicate the existence of more than 130,000 small-scale or artisanal fishing boats in the whole country. La Paz Bay is located on the southern end of the Peninsula of Baja California (Fig. 1) where artisanal fleets target demersal species associated with the rocky substrate there. According to Ramírez-Rodríguez (1997), there are around 400 fishers using 7-m vessels with engines of 40–60 hp. Hand-held hooks, hook-and-lines and gillnets are the most important fishing gears. Diving and the use of fixed nets are other common fishing methods of less importance in the Bay.

The species caught can be grouped by their economic importance (Ramírez-Rodríguez and Rodríguez, 1991; Abitia-Cárdnas et al., 1994; Ramírez- Rodríguez, 1996); the target finfish species are snappers (Lutjanidae) and groupers (Serranidae);

[☆] Manuscript PFITEC-17 (EMECS 3) for Ecological Modelling, May 2003.

[*] Corresponding author. Tel.: +52-612-25344; fax: +52-612-25322.
E-mail address: farregui@ipn.mx (F. Arreguín-Sánchez).

0304-3800/$ – see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolmodel.2003.09.018

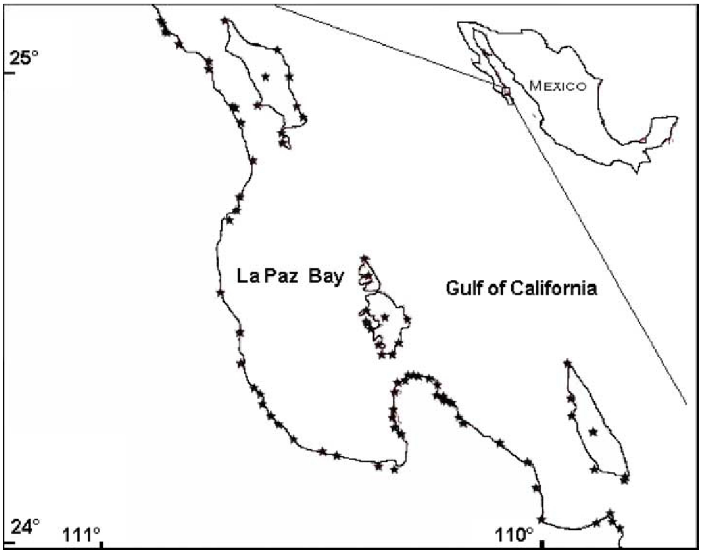

Fig. 1. Location of La Paz Bay, on the southern peninsula of Baja California, Mexico. Stars indicate known landing areas of the artisanal fleets.

secondary species include tilefish (Malacanthidae), jacks (Carangidae) and others (Table 1). Catches of target species fluctuate during the year, and fishers do not follow rigid fishing patterns. Most fishers operate without an individual license under a practically open access scheme. Limits to fishing are frequently implemented through minimum legal sizes, based on local information and experience with similar stocks in adjacent regions. However, there are serious difficulties in implementing more specific management measures, which are needed in view of the following identified problems in the artisanal fisheries.

- the annual catches tend to decrease;
- the number of fishers is continually increasing;
- there are several different fleets;
- gillnets are claimed to be inefficient and to cause mortality of non-target species;
- habitats are being altered as a result of operation of some fishing gear;
- there are conflicts with other users of the coastal zone;
- illegal fishing occurs;
- there is growing interest in conservation, particularly around islands, which are the preferred fishing grounds;
- the market is unpredictable and fluctuates with no apparent pattern;

Table 1
Catches (metric tons) of the most abundant fish species caught by the artisanal fleet in La Paz Bay, Mexico

	Snappers	Groupers	Mojarras	Parrotfish	Haemulids
1992	117.949	113.750	7.211	18.431	11.278
1993	107.826	52.973	6.289	6.912	5.395
1994	169.425	108.868	5.264	5.511	4.347
1995	176.241	121.706	13.349	6.399	**24.513**
1996	**205.184**	**128.120**	**36.463**	8.011	12.891
1997	138.463	108.024	13.750	**20.457**	3.140
1998	145.920	66.366	3.482	13.238	1.661

Bold numbers indicate highest catch.

There is also a limited shrimp fishery in the Bay. Trawling is generally prohibited, but a few boats operate under special licenses. It is unlikely that further development of this fishery will take place.

Rational management involves the consideration of all fisheries activities and finding a balance between economic and social benefits within the framework of ecosystem conservation. One of the major problems is to find quantified solutions. The modelling software Ecopath with Ecosim (Christensen and Pauly, 1992; Walters et al., 1997; Pauly et al., 1999) provides a convenient tool to explore such possibilities. The aim of this contribution is to explore some harvesting strategies for the artisanal fishery; particularly on sustaining stock biomass and optimizing economic and social benefits on snappers and groupers as target (highest priced) species.

2. Material and methods

A previously constructed Ecopath model for La Paz Bay (H. Pérez-España, unpublished data) was used as the base for Ecosim (Walters et al., 1997) simulations of harvesting strategies. The mass-balanced model for La Paz Bay (Fig. 2) considers 22 functional groups: 3 for marine mammals; 10 for fishes; 3 for macro-crustaceans, 2 for demersal invertebrates, zooplankton, and as primary producers phytoplankton, benthic producers and detritus (Table 2). The artisanal fishery was divided in two groups: short longlines and hook-and-line (Art hook), which mostly target on snappers, groupers and tilefish; and gill nets (Art gnet), which exploit a number of coastal species such as haemulids, mojarras and parrotfishes (Villavicencio, 1985; Ramírez-Rodríguez and Rodríguez, 1991; Ramírez-Rodríguez, 1991, 1996, 1997).

Ecopath model is based on a set of linear equations as follows (Christensen and Pauly, 1992), one for each group in the ecosystem, assuming mass-balance; that is, the production of the group is equals to the sum of all losses by predation, non predatory losses and export. The generalized mass-balanced equation for each group is:

$$B_i \cdot \left(\frac{P}{B}\right)_i \cdot \mathrm{EE}_i = \sum_{j=1}^{n} B_j \cdot \left(\frac{Q}{B}\right)_j \cdot \mathrm{DC}_{ji} + B_i \cdot \left(\frac{P}{B}\right)_i \cdot (1 - \mathrm{EE}_i) + \mathrm{EX}_i \tag{1}$$

where B_i is biomass of group i; $(P/B)_i$ is production/biomass ratio of i, which is equal to the total mortality coefficient (Z) under steady-state conditions (Allen, 1971; Merz and Myers, 1998); EE_i is ecotrophic efficiency which is the part of the total production that is consumed by predators or exported

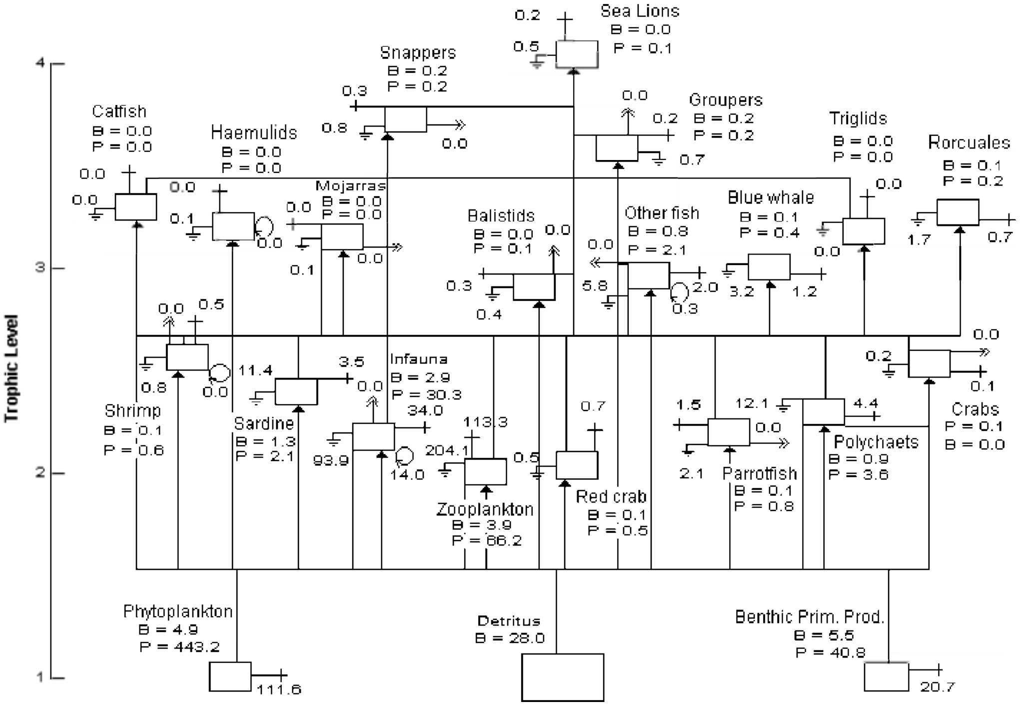

Fig. 2. Flows of biomass for the mass-balanced model of the ecosystem of La Paz Bay, Mexico. Biomass is in g/m^2 and flows in g/m^2 per year.

Table 2
Species or groups of species representing pools of the trophic ecosystem model for La Paz Bay

Group	Comments	*B*	*Q/B*	*P/B*	EE
Phytoplankton	All species larger than 38 μm	13		2	
Benthic primary producers	All algae present within the 5 m depth.	16, 8	2	2	
Zooplankton	All species larger than 505 μm except jellyfish	5		2	
Shrimp	*Penaeus californiensis*	18	2	2	
Red crab	*Pleuroncodes planipes*	6	2	2	
Infauna	Organisms larger than 5 mm, except polychaeta	7	2	2	
Polychaeta	All benthic polychaeta	9	2	2	
Snappers	All species of Lutjanidae	10	2	2	
Groupers	All species of Serranidae		2	2	
Mojarras	All species of genus *Eucinostomus* spp.	18	12	12	
Parrotfish	All species of Scaridae	10	14	14	
Triggerfishes	All species of Balistidae	10	14	14	
Sardines	All species of Clupeidae		15	15	12
Searobins	*Prionotus stephanophrys*	18	12, a	12, 1	
Catfish	genus *Galeichthys* spp.	18	2	2	
Haemulids	Genero *Orthopristis* spp.	18	2	2	
Other fishes	Families Labridae, Pomacentridae y Haemulidae (except *Orthopristis* spp.)	10	2	2	
Crabs	genus *Callinectes* spp.		2	2	
Sea lions	*Zalophus californianus*	17	17, 4		
Blue whale	*Balaenoptera musculus*	19, 3	20		
Bryde's whale	*Balaenoptera edenii*	19, 3	20		
Detritus	Detritus	21			

Sources of data are given. *B*: biomass, *Q/B*: consumption/biomass ratio; *P/B*: production/biomass ratio, EE: ecotrophic efficiency. Numbers in the right columns correspond to references below (taken from Pérez-España, unpublished).
1. Schmitter (1992); 2. Chávez et al. (1993); 3. Valles-Jiménez and Urbán (unpublished); 4. Aurioles-Gamboa (1996); 5. De Silva-Dávila (unpublished); 6. Mathews et al. (1973); 7. García-Domínguez (1991); 8. Hernández-Carmona et al. (1990); 9. Bastida-Zavala (1991); 10. Pérez-España et al. (1996); 11. Ramírez-Rodríguez (1997); 12. assumed by author; 13. Martínez-López (unpublished); 14. Aliño et al. (1993); 15. Vega-Cendejas et al. (1993); 16. Cruz-Ayala (1996); 17. Aurioles-Gamboa and Zavala-González (1994); 18. Pérez-Mellado and Findley (1985); 19. Flore-Ramírez et al. (1996); 20. Olivieri et al. (1993); 21. Pauly et al. (1993).

out of the system; B_j is the biomass of predator *j*; $(Q/B)_j$ is the consumption/biomass ratio of predator *j*; DC_{ji} is the proportion of prey *i* in the diet of predator *j*; EX_i is the export of group *i*, which in this study consists of fisheries catch when a group is exploited.

Based on Eq. (1) the Ecosim model (Walters et al., 1997) describes the dynamics of groups in the ecosystem through the equation

$$\frac{dB_i}{dt} = f(B) - M_0 - F_i B_i - \sum_{j=1}^{n} c_{ij}(B_i, B_j)$$

where *f(B)* is a function of B_i when species *i* is a primary producer, and for consumers $f(B) = g_i \sum_{j=1}^{n} c_{ji} \cdot (B_i, B_j)$, where g_i represents the growth efficiency, and $c_{ij}(B_i, B_j)$ is the function used to predict consumption from B_i by B_j, and represents the probability of encounters between prey and predators, as well as physiological behavior such as satiation.

Harvesting strategies were tested against four major criteria: (1) continuation of the current state; (2) optimizing economic benefits in terms of net profits; (3) maximum sustainable yield (MSY) for snappers and groupers as goal for management, defined as the yield obtained under $0.5B_0$, where B_0 is the initial biomass; and (4) optimizing social benefits, based on the job/catch value ratio, because artisanal fisheries are an important occupational activity and the number of fishers is increasing. Within all these scenarios, we consider also the conservation of ecosystem structure.

Ecosim uses a nonlinear optimization procedure known as the Davidson-Fletcher-Powell (DFP) method to iteratively improve an objective function by changing relative fishing rates. DFP runs the Ecosim model repeatedly while varying these parameters; in the search output display. The parameter variation scheme used by DFP is known as a

Table 3
Input data used for the construction of the trophic model for La Paz Bay

Group	*B*	*P/B*	*Q/B*	EE	EX
Phytoplankton	4.459	85.746	0.000	0.982	
Primary benthic producers	4.924	8.073	0.000	0.766	
Zooplankton	4.013	14.852	85.307	0.560	
Shrimp	0.075	6.717	19.760	0.974	0.006
Red crab	0.066	7.708	24.476	0.243	
Infauna	7.913	8.397	49.461	0.831	0.024
Polychaeta	1.983	5.195	21.110	0.805	
Snappers	0.200	0.724	6.155	0.334	0.042
Groupers	0.148	1.110	5.370	0.893	0.017
Mojarras	0.015	1.002	7.818	0.643	0.001
Parrotfish	0.146	5.549	30.291	0.008	0.004
Triggerfishes	0.026	5.519	28.498	0.032	0.004
Sardines	1.199	1.583	14.548	0.933	0.001
Searobins	0.007	0.631	4.291	0.718	
Catfish	0.004	0.299	10.685	0.442	
Haemulids	0.013	1.401	10.106	0.317	
Other fishes	0.864	2.782	12.607	0.825	0.009
Crabs	0.057	2.019	8.479	0.963	0.002
Sea lions	0.021	2.616	25.154	0.109	0.006
Blue Whale	0.141	2.314	33.773	0.031	0.010
Bryde's whale	0.093	2.474	26.811	0.083	0.019
Detritus	28.000				

B: Biomass, *Q*: consumption, *P*: production, EE: ecotrophic efficiency, EX: exportation. Biomass is given as g dry weight (dw) per m^2; rates as g (dw) per m^2 per year (from Pérez-España, unpublished).

'conjugate-gradient' method, which involves testing alternative parameter values so as to locally approximate the objective function as a quadratic function of the parameter values, and using this approximation to make parameter update steps (Christensen et al., 2000).

Ecopath inputs were taken from Pérez-España (unpublished data) but referred here as Tables 2 and 3 for inputs and their sources, and in Table 4 for prey–predator matrix. Data for this model resulted in a pedigree index of PI = 0.515. This index is understood as a coded statement categorizing the origin a given input specifying the likely uncertainty associated with the input. The measure of fit is seen to describe how well rooted a given model is in local data. The pedigree index ranges between 0 and 1 (Christensen et al., 2000; Pauly et al., 2000).

Catch values were obtained from statistical records reported by the ministry of fisheries (SEMARNAP, 1998) as landed prices. Costs were represented as proportions as shown in Table 5.

Time series of catch-per-unit-effort and effort for snappers and groupers were used to calibrate simulated biomasses. Data come from local daily receipts collected by the local federal office and recorded through the data bank SIMAVI (Ramírez-Rodríguez and Hernández-Herrera, 1999) for 1992–1998. Other catch data coming from the artisanal fishery were not used because the above species are the target ones, and others could not reflect relative abundance. A time series for the shrimp fleet was not available.

The social index (job/catch value) was calculated using data reported by SEMARNAP (2000) and takes the following values: 0.5 for shrimp, and 2.0 for the artisanal fisheries. As an ecological criterion, we used the inverse of the production/biomass (*P*/*B*) ratio, per group, as a measure of the potential growth/recovery.

Optimization under the above conditions is done by a formal optimization method that searches temporal patterns for fishing rates that would maximize particular performance measures for management described here as open loop simulation (OLS). Each criterion (economic, social and ecological) was assigned the same relative importance for the optimization process during OLS in order to reflect conditions close to the real ones since there is not an specific fishing policy for the operation of the artisanal fisheries. The results provide general guidance on the direction in which the system is heading. A closed loop simulation (CLS) was also approached, assuming density-dependent catchability effects. The basic idea of this fishing policy search is that management will be based on the control of relative fishing effort by fleet type. For this we consider a maximum annual increase in catchability of 0.05 for the artisanal fleets and a zero value (0) for shrimp fleet. These values were used to calculate changes in fishing power over time. The relative impact of fleets on target groups was assigned by giving a weighting factor of 3 for the shrimp fleet relative to a value of 1 for the artisanal fleets. These weighting factors represent the relative importance of the species-specific fishing rates by fleet and directly affect the catchability coefficients.

CLS also considers uncertainty in group biomass, for which a CV = 20% was considered for all groups. Outputs can be referred to some biological reference point (BRP), here defined as a limit BRP = 0.5B_0

Table 4
Prey/predator matrix showing diet composition for La Paz Bay trophic ecosystem model, Mexico (taken from Pérez-España, unpublished)

Prey/predator[a]	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	21
1. Phytoplankton	0.881	–	0.195	0.140	–	–	–	–	–	–	0.59	–	–	–	–	–	–	–
2. Benthic primary producer	0.020	0.289	–	0.040	–	–	–	–	0.833	0.196	–	–	–	–	0.212	–	–	–
3. Zooplankton	–	–	0.039	0.050	–	–	–	0.208	–	0.010	0.41	0.220	0.157	0.096	0.050	0.048	–	0.402
4. Shrimp	–	0.010	–	–	–	0.113	–	–	–	0.080	–	0.137	–	–	0.019	0.105	–	–
5. Red crab	–	–	–	–	–	–	–	–	–	–	–	0.495	–	–	0.011	–	–	–
6. Infauna	–	0.254	–	0.095	0.25	0.251	0.010	0.742	0.157	0.443	–	0.052	0.206	0.289	0.651	0.100	0.108	–
7. Polychaeta	–	0.200	–	0.016	–	–	–	0.041	0.010	0.110	–	–	0.386	0.064	0.019	0.157	–	–
8. Snappers	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.012	–
9. Groupers	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.248	–
10. Mojarras	–	–	–	–	–	–	–	–	–	–	–	–	–	0.063	–	–	–	–
11. Parrotfish	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.006	–
12. Triggerfishes	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.001	–
13. Sardines	–	–	–	–	–	–	0.594	–	–	–	–	0.039	–	–	–	–	0.003	0.550
14. Searobins	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.006	–
15. Catfish	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.001	–
16. Haemulids	–	–	–	–	–	–	–	–	–	–	–	–	–	0.051	–	–	–	–
17. Other fishes	–	–	–	–	–	0.636	0.386	0.010	–	0.058	–	0.057	0.113	0.010	0.029	–	0.615	0.049
18. Crabs	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.010	–	–	–
19. Sea lions	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
21. Bryde's whale	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
22. Detritus	0.099	0.247	0.766	0.659	0.65	–	0.010	–	–	0.103	–	–	–	0.030	–	0.590	–	–

[a] The blue whale, group number 20, feed 100% on zooplankton and has not predators in the system.

Table 5
Fishing costs related to the operation of the fleets operating in La Paz Bay, on the southern Peninsula of Baja California, Mexico

Fleet	Fixed costs (%)	Effort-related costs (%)	Sailing-related costs (%)	Profit (%)
Shrimp	10	20	50	20
Art hook	5	7	30	58
Art gnet	5	10	20	65

i.e. 50% of the original biomass. The basic concept for simulations was that no group can decrease below this level of biomass. Simulations were developed for the period of 10 years and in all cases, covering time series of catch per unit of effort (CPUE) available and assuming no changes in the shrimp fleet.

3. Results

An Ecosim model was developed incorporating data on CPUE and effort. The simulated biomass of snappers and groupers reflected reasonably well their relative biomass represented by CPUE. However, this was not the case for other groups. The high variation in CPUE for the non-target species may be because CPUE is probably not a good index of stock abundance, or there is another factor affecting stock abundance (e.g. a forcing factor, habitat modification or limits for fishing on traditional grounds). Thus, in this analysis, we use only data for snappers and groupers to calibrate biomass tendencies (Fig. 3).

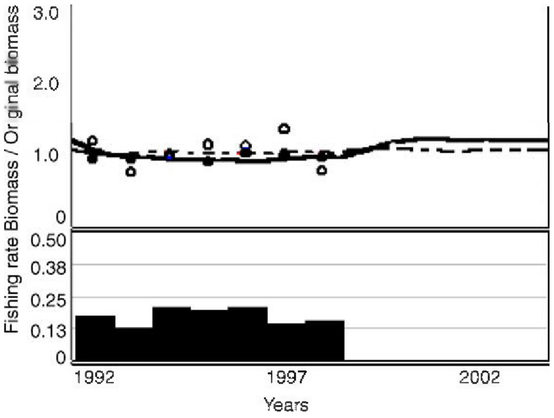

Fig. 3. Fitting independent data on relative biomass as CPUE (dots) to Ecosim-simulated biomass (lines) of target species in La Paz Bay, Mexico. Shaded area represents the historic fishing pattern. Black dots and dashed line represent snappers; open dots and lines, groupers.

Once the model was calibrated both, OLS and a CLS, were developed without optimization in order to represent a continuation of the current situation, considering that fishing can be controlled through the fleets; and as a reference for comparison with other scenarios. Under the current situation, three groups become depleted: haemulids, mojarras and crabs.

The MSY criterion, applied to snappers and groupers, results in increased fishing mortality to lower their biomass equivalent to $0.5B_0$, assuming that this value reflects the MSY situation. However, this strategy causes depletion for haemulids, mojarras

Table 6
Ratio between fishing effort under various criteria at the end of the simulated harvesting strategy and that in the initial Ecopath model (Final *F*/original F), La Paz Bay, Mexico

	Initial Ecopath model	MSY on snappers and groupers	Economic	Social	Economic and ecological (1,4)	Social and ecological (1,5)	Economic, social and ecological (1,1,8)	Economic, social and ecological (1,1,9)	Economic, Social & Ecological (1,1,10)
Total[a]	1.707	1.718	3.262	2.843	**1.006**	**1.019**	1.022	**1.013**	**1.009**
Economic[a]	2.396	2.376	3.273	2.402	**1.215**	**1.306**	1.684	**1.414**	**1.258**
Social[a]	2.872	2.879	2.127	2.861	**1.275**	**1.452**	1.802	**1.486**	**1.346**
Ecological[a]	0.823	0.816	0.809	0.821	**0.985**	**0.970**	0.935	**0.966**	**0.980**
Art hook[b]	2.213	2.350	2.514	2.234	**1.427**	**1.811**	1.703	**1.517**	**1.574**
Art gnet[b]	19.887	19.887	26.449	19.887	**1.055**	**1.028**	5.446	**2.801**	**1.005**

Bold numbers indicate those scenarios considered as realistic alternatives.

Numbers in parentheses are weighting factors used during simulations for each criterion.

[a] Measure of relative performance.

[b] Measure of relative fishing effort.

and crabs below $0.5B_0$. The F value for snappers was 0.71 per year and for groupers 0.85 per year. Once MSY was achieved, OLS and CLS were performed to compare outputs with other scenarios (Table 6).

For the economic criterion, optimization implies strong fishing pressure on snappers, and the biomass for haemulids, mojarras and crabs declines below $0.5B_0$. This is also an undesirable outcome.

We explored several scenarios that combine economic and social criteria until an output was found that did not deplete any group below $0.5B_0$. After CLS, F values for snappers and groupers become 0.43 and 0.21 per year, respectively. These values are almost the same as current fishing mortality values.

For the social criterion alone, that is, optimizing jobs, depletion of five stocks, including snappers and groupers, occurs. As in the previous case, we looked for a positive scenario, based on OLS. Several weighting factors were tested for optimization of ecological and social criteria (Table 6).

4. Discussion

Concerning Ecosim simulations, parametrization from Ecopath, as a mass balanced solution assumes that ecosystem picture represents a relatively stable ecosystem; mostly when a short time series of relative abundance is used to calibrate the model. This is also reflected by the relative low values of catchability with time variation, since this assumes few changes in catch efficiency. In this sense outputs from scenarios represent a scheme of the possibilities of using Ecopath with Ecosim as an exploratory tool. A more rigorous analysis would be required before it should be used for management purposes.

The results show that optimization of the current fishing fleet represents a high risk of depletion for several stocks, even with MSY as a goal for management of the main target species. Evidently, these scenarios are not desirable.

Economic and social optimization, in particular, yields situations in which the biomass of some groups in the ecosystem falls bellow $0.5B_0$. In both cases adding more weight to the ecological criterion in the optimizations resulted in a combination in which no group was under depletion risk. OLS provides options on the way that fishing can be directed under specific circumstances; in the present case, we can either optimize the economic and ecological criteria; optimize the social and ecological criteria; or optimize a combination of economic, social and ecological criteria.

The current (non-optimized) fisheries allow maintenance of the ecosystem structure because fishing is not causing a negative impact. However, optimizing exploitation rates on the major species would not be a good management choice.

Economic or social optimization as goal of management is not appropriate because they cause several stocks to become depleted and would increase the fishing effort by the gillnet fleet to unrealistic levels (Table 6). However, both criteria provide more realistic schemes when combined with a properly weighted ecological criterion (1:4 and 1:5, respectively). Table 6 shows the ratio of fishing effort between application of optimization criteria and the initial Ecopath value. The hook-and-line fleet could be increased by 40–80%, and the gillnet fleet 3–5% to achieve optimization.

While these increments in effort seem reasonable, the scenarios require that snappers and groupers continue to be the target species while others remain as secondary species. This is probably not a good scheme because there is a risk of approaching the MSY scenario, at least for hook-and-line fleet, with accompanying depletion of other stocks.

In the multiple criteria scenario, we first used weighting factors of 1, 1 and 8 for the economic, social and ecological criteria, respectively. The result suggested that fishing effort be increased by a factor of 1.7 times for the hook-and-line fleet, and 5.4 for the gillnet fleet. CLS showed that there was a risk of only 1% of depletion of haemulids (Fig. 4). Despite such insignificant risk, this scenario is probably unwise because an increment of five times the fishing effort of the gillnet fleet seems unrealistic, particularly because this fleet catches secondary species.

Two other scenarios were constructed by increasing the ecological weighting factor (to 9 and 10). Both scenarios (Table 6) suggest increasing the fishing effort of the hook-and-line fleet by a factor of 1.5. A corresponding effort increase by a factor of 2.8 for the gillnet fleet occurs with a weighting factor of 9 for the ecological criterion, and no change in that fleet with a weighting factor of 10. It is clear that these two scenarios are preferred to the previous.

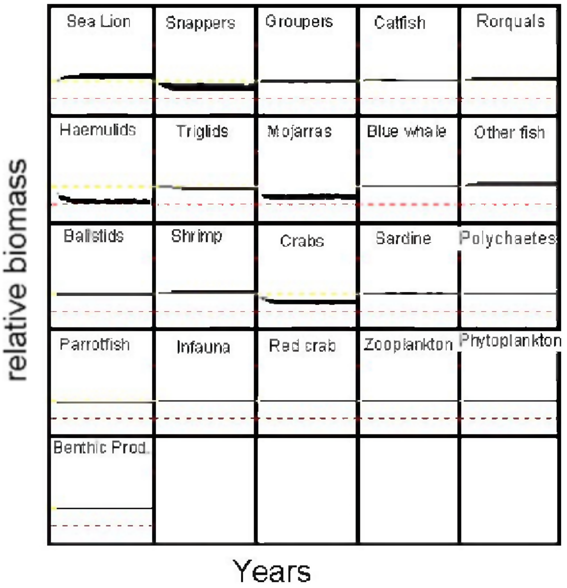

Fig. 4. Output of closed loop simulation after optimization of combined economic–social–ecological criteria, for the ecosystem of La Paz Bay, Mexico. Weighting factors were 1, 1 and 9, respectively. Y-axis represents relative abundance of biomass; dashed line the $0.5B_0$ stock size, being B_0 the original biomass; X-axis represents time of simulation in years.

In the process of seeking optimal choices, when the weighting factor of one criterion is increased, the performance of other criteria decreases. Based on optimized Ecopath outputs as reference values, a weighting factor of 9 for the ecological criterion appears to be the more reasonable option because it is close to the current situation. This option implies that the hook-and-line fleet can increase fishing effort by around 50%, while gillnet effort can increase by a factor of about three.

We conclude that the performance of the artisanal fisheries could be improved by adjusting the fishing effort of the fleets. The expectations are that their economic performance will increase by 40%; social performance will increase by about 50%; and ecological performance (ecological criterion concerning maintenance of current ecosystem structure) will decrease by a small amount (3.4%). We think that the ecological risk is not significant within the framework developed in this analysis.

There are two assumptions for these positive outcomes: first, that the interest of management of artisanal fishing in La Paz Bay is strongly focused on snappers and groupers, and that other groups are of secondary importance. Some schemes would change if more emphasis were placed on other species. Second, interpretation of the simulations is based on independent management of the two artisanal fleets. However, in practice, the same fishers operate in both fleets, or alternate between them during the year. A last consideration refers to the shrimp fleet, which was not changed in any scenario. If current policy concerning this fleet changes, results of the simulations would also change.

Acknowledgements

The authors thank the National Council of Science and Technology, CONACyT, for support given through project 34865-B; the National Polytechnic Institute, through project CGPI-980056 and CGPI 20020287, COFAA and EDI; as well as to the INCO-DC Concerted Action 'Placing Fisheries in their Ecosystem Context' (ERBIC18CT97175).

References

Abitia-Cárdnas, L.A., Rodríguez-Romero, J., Galván-Magaña, F., De la Cruz-Agüero, J., Chávez-Ramos, H., 1994. Lista sistemática de la ictiofauna de la Bahía de La Paz, B.C.S., México. Ciencias Marinas 20 (2), 159–181.

Aliño, P.M., McManus, L.T., McManus, J.W., Nañola, Jr., C.L., Fortes, M.D., Trono, G.C., Jacinto, G.S., 1993. Initial parameter estimations of a coral reef flat ecosystem in Bolinao, Pangasinan, Northwestern Philippines. In: Christensen, V., Pauly, D. (Eds.), Trophic Models of Aquatic Ecosystems. ICLARM Conference Proceedings, vol. 26. pp. 252–258.

Allen, K.R., 1971. Relation between production and biomass. J. Fish. Res. Bd. Can. 28, 1573–1581.

Aurioles-Gamboa, D., 1996. Ecología poblacional y alimentaria del lobo marino de California en la Bahía de La Paz, B.C.S., Golfo de California. Informe I de Proyecto CONABIO. CICIMAR-IPN.

Aurioles-Gamboa, D., Zavala-González, A., 1994. Consumo anual de alimento de la población de lobo marino (Zalophus californianus) en el Golfo de California y su relación con la pesquería de sardina. XIX reunión internacional para el estudio de los mamiferos marinos. Programa y Resumenes. UABCS, La Paz, B.C.S., México. 6 p.

Bastida-Zavala, J.R., 1991. Poliquetos (Annelida: Polychaeta) del sureste de la Bahía de La Paz, B.C.S., México: Taxonomía y aspectos biogeográficos. Tesis de licenciatura. Depto de Biologia Marina. UABCS. La Paz, B.C.S., México. 158 pp.

Chávez, E.A., Garduño, M., Arreguín-Sánchez, F., 1993. Trophic dynamic of Celestum Lagoon, Southern Gulf of Mexico. In: Christensen, V., Pauly, D. (Eds.), Trophic Models of Aquatic Ecosystems. ICLARM Conference Proceedings, vol. 26, pp. 186–192, 390.

Christensen, V., Pauly, D., 1992. Ecopath II—a software for balancing steady-state ecosystem models and calculating network characteristics. Ecol. Model. 61, 169–185.

Christensen, V., Walters, C.J., Pauly, D., 2000. Ecopath with Ecosim Version 4, Help system©. University of British Columbia, Fisheries Centre, Vancouver, Canada and ICLARM, Penang, Malaysia.

Cruz-Ayala, M.B., 1996. Variación espacio-temporal de la ficoflora y su abundancia relativa en la Bahía de La Paz, B.C.S., México. Tesis de maestría. CICIMAR-IPN. La Paz, B.C.S. México. 99 pp.

Flore-Ramírez, S., Urbán, J.R., Villarreal-Chávez, G., Valles-Jiménez, R., 1996. Spatial and temporal changes in the cetacean community structure at Bahía de La Paz, B.C.S., México (1988–1991). Ciencias Marinas 22 (3), 151–173.

García-Domínguez, F., 1991. Distribución, abundancia, reproducción y fauna asociada de la almeja roñosa, Chione californiensis en la Ensenada de La Paz, B.C.S., México. Tesis de Maestría. CICIMAR-IPN. La Paz, B.C.S. México.

Hernández-Carmona, G., Casas-Valdéz, M.M., Fajardo-León, C., Sánchez-Rodríguez, I., Rodríguez-Montesinos, E., 1990. Evaluación de *Sargassum* spp. en la Bahía de La Paz, B.C.S., México. Inv. Mar. CICIMAR. 5 (1), 11–18.

Mathews, C.P., Granados, J.L., Arvízu, J., 1973. Results of the exploratory cruises of the Alejandro de Humbolt in the Gulf of California. (reports of California cooperative oceanic fisheries investigations), vol. XVII, July 1971–June 1973.

Merz, G., Myers, R.A., 1998. A simplified formulation for fish production. Can. J. Fisheries Aquatic Sci. 55 (2), 478–484.

Olivieri, R.A., Cohen, A., Chávez, F.P., 1993. An ecosystem model of Monterey Bay, California. In: Christensen, V., Pauly, D. (Eds.), Trophic Models of Aquatic Ecosystems. ICLARM, International Council for the Exploration of the Sea, DANIDA. Manila, pp. 315–322.

Pauly, D., Soriano-Bartz, M.L., Palomares, M.L.D., 1993. Improved construction, parametrization and interpretation of steady—state ecosystem models. In: Christensen, V., Pauly, D. (Eds.), Trophic Models of Aquatic Ecosystems. ICLARM Conference Proceedings, vol. 26, pp. 1–13, 390p.

Pauly, D., Christensen, V., Walters, C., 2000. Ecopath, Ecosim and Ecospace as tools for evaluating ecosystem impact of fisheries. ICES J. Marine Sci. 57, 697–706.

Pérez-España, H., Galván-Magaña, F., Abitia-Cárdenas, L.A., 1996. Temporal and spatial variations in the structure of the rocky reef fish community of the southwest Gulf of California, Mexico. Ciencias Marinas 22 (3), 273–294.

Pérez-Mellado, J., Findley, L.T., 1985. Evaluación de la fauna acompañante del camarón capturado en las costas de Sonora y norte de Sinaloa, México. In: Yáñez-Arancibia, A. (Ed.), Recursos Pesqueros Potenciales de México: La Pesca Acompañante del Camarón. Progr. Univ. de Alimentos, Inst. Cienc. del Mar y Limnol., INP. UNAM, México D.F., pp. 201–254.

Ramírez-Rodríguez, M., 1991. Redes agalleras en Bahía de La Paz, B.C.S. Rev. Inv. Cient. Ser. Cienc. Mar. UABCS, México 2 (2), 65–74.

Ramírez-Rodríguez, M., Rodríguez, M.C., 1991. Composición específica de la captura artesanal de peces en Isla Cerralvo, B.C.S., México. Invest. Mar. CICIMAR, México 5 (2), 137–141.

Ramírez-Rodríguez, M., 1996. Pesquería de escama. In: Casas-Valdez, M., Ponce-Diaz, G. (Eds.), Estudio del Potencial Pesquero y Acuícola de Baja California Sur. Centro de Investigaciones Biológicas del Noroeste y Centro Interdisciplinario de Ciencias Marinas del IPN, México, vol. 1, pp. 287–304.

Ramírez-Rodríguez, M., 1997. La producción pesquera en Bahía de La Paz, B.C.S. In: Urbán-Ramírez, J., Ramírez-Rodríguez, M. (Eds.), La Bahía de La Paz, Investigación y Conservación. Univ. Aunón. Baja California Sur, Cent, Interdisc. Cienc. Mar. IPN, SCRIPPS Instit. Oceanpogr. Mexico, pp. 273–282.

Ramírez-Rodríguez, M., Hernández-Herrera, A., 1999. Sistema automatizado para el manejo de avisos de arribo (SIMAVI 1.0). CICIMAR, CRIP La Paz-INP, CIMEX. México, 32 pp. (mimeo).

Schmitter, S.J.J., 1992. Aspectos autoecológicos de los triglidae (Pisces: Scorpaeniformes) en la costa occidental de Baja California Sur, México. Tesis de maestría. CICIMAR-IPN. La Paz, B.C.S., México.

SEMARNAP, 1998. Anuario estadístico de pesca 1997. Secretaría de Medio Ambiente, Recursos Naturales y Pesca. México. 241 pp.

SEMARNAP, 2000. Carta Nacional Pesquera. Diario Oficial de la Federación. 28 Agosto del 2000, México.

Vega-Cendejas, M.E., Arreguín-Sánchez, F., Hernández, M., 1993. Trophic fluxes on the Campeche Bank, México. In: Christensen, V., Pauly, D. (Eds.), Trophic Models of Aquatic Ecosystems. ICLARM Conference Proceedings, vol. 26, pp. 206–213.

Villavicencio, C., 1985. Abundancia y distribución de la ictiofauna demersal de importancia econímica en la Bahía de La Paz. Tesis Profesional, Univ. Autón. Baja California Sur, México, 57 pp.

Walters, C., Christensen, V., Pauly, D., 1997. Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. Rev. Fish Biol. Fish. 7, 1–34.