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# Exploration of harvesting strategies for the management of a Mexican coastal lagoon fishery☆

Manuel J. Zetina-Rejón*, Francisco Arreguín-Sánchez, Ernesto A. Chávez

*Centro Interdisciplinario de Ciencias Marinas, I.P.N., Av. Instituto Politécnico Nacional s/n Col. Playa Palo de Santa Rita, Apartado Postal 592, La Paz 23000, Baja California Sur, Mexico*

**Abstract**

Huizache–Caimanero is a tropical brackishwater lagoon in western Mexico where there has been an important shrimp fishery for a long time. Four other, less important fish groups in this ecosystem are also exploited. We use a previously constructed Ecopath model to explore harvesting strategies for multispecies management. Changes in fishing mortality were simulated using the search for optimum strategies implemented in Ecopath with Ecosim. Simulations covering a period of 30 years were run. Several scenarios were tested in which fishing rates were changed to optimize ecological, economical, and social criteria. The biomass of each group, catches, and values of economic, social, and ecological indicators were compared between scenarios. In general terms, scenarios considering economic and social criteria produced high fishing rates that would cause the depletion of several groups. When an ecological criterion was considered, the impact on biomass was reduced due to a conservative fishing strategy. We discuss about effects of input parameters in the searching routine.


*Keywords:* Shrimp fishery; Ecopath; Tropical lagoon; Simulation; Ecosim

## 1. Introduction

In recent years, a consensus has developed among fisheries biologists that ecosystem management must be implemented and the need to account for both the structure and function of ecosystems has been widely recognized (Christensen and Pauly, 1995; Christensen, 1996; Botsford et al., 1997; Jennings and Kaiser, 1998). As a consequence, multispecies management has been a challenge for fisheries biologists and legal authorities. The comprehensive management of exploited ecosystems requires explicit consideration of biological interactions in predator–prey systems. Such multispecies analyses are not new. Examples include extensions of the Beverton and Holt yield-per-recruit analysis (Murawski, 1984; Chávez et al., 1995) and the multiple stepwise regression technique (Arreguín-Sánchez et al., 1992). Another approach, multispecies virtual population analysis (MSVPA), has "conceptual simplicity" (Hilborn and Walters, 1992) and was initially applied to North Sea fisheries. However, the large amount of data required imposes a major constraint to its application elsewhere (Pope, 1979; Daan, 1987).

The Ecopath with Ecosim approach appears to be a useful tool to evaluate management strategies of fishing resources because it takes into account trophic relationships among the major biological components of the ecosystem. The model allow characterization of ecosystem trophic structure and simulated harvesting

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* Corresponding author. Tel.: +52-612-1225344; fax: +52-612-1225322.
*E-mail address:* mzetina@ipn.mx (M.J. Zetina-Rejón).

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strategies for exploited stocks in order to examine the impact of fishing effort (policy strategies) on target stocks, other groups, and the whole ecosystem. In this paper, we use a previously constructed Ecopath model for the Huizache–Caimanero lagoon complex to explore harvesting strategies for fisheries management using different policy optimizations based on three criteria: ecological, economic, and social.

## 2. Materials and methods

### 2.1. Study area

The Huizache–Caimanero lagoon complex is located on the Pacific coast of Mexico in southern Sinaloa state (Fig. 1). A narrow constriction separates the two lagoons and a barrier island separates them from the Pacific Ocean. Each lagoon receives intermittent flow from two small rivers connected by narrow and winding channels, permitting the transport of freshwater to the lagoon during the rainy season (June to September). A winding, permanently open channel allows entrance of shrimp postlarvae and other marine species. Tides are semidiurnal with a range of 0.85 m. The average area of the system is 175 $km^2$, decreasing to 65 $km^2$ during the dry season (Soto, 1969). Water temperature ranges from 20 to 40 °C, and precipitation between 800 and 1200 mm (de la Lanza and García, 1991). Mangroves and other halophytes surround the lagoon complex.

The ecosystem supports a large artisanal shrimp fishery since ancient times, which operates in inshore waters during the emigration of juveniles, using fixed gear named *tapos*, which consists of barriers that partially block the tidal channels. Nearly 90% of the total shrimp catch in this lagoon is made up of one specimen, *Litopenaeus vannamei* Boone 1931. Three other

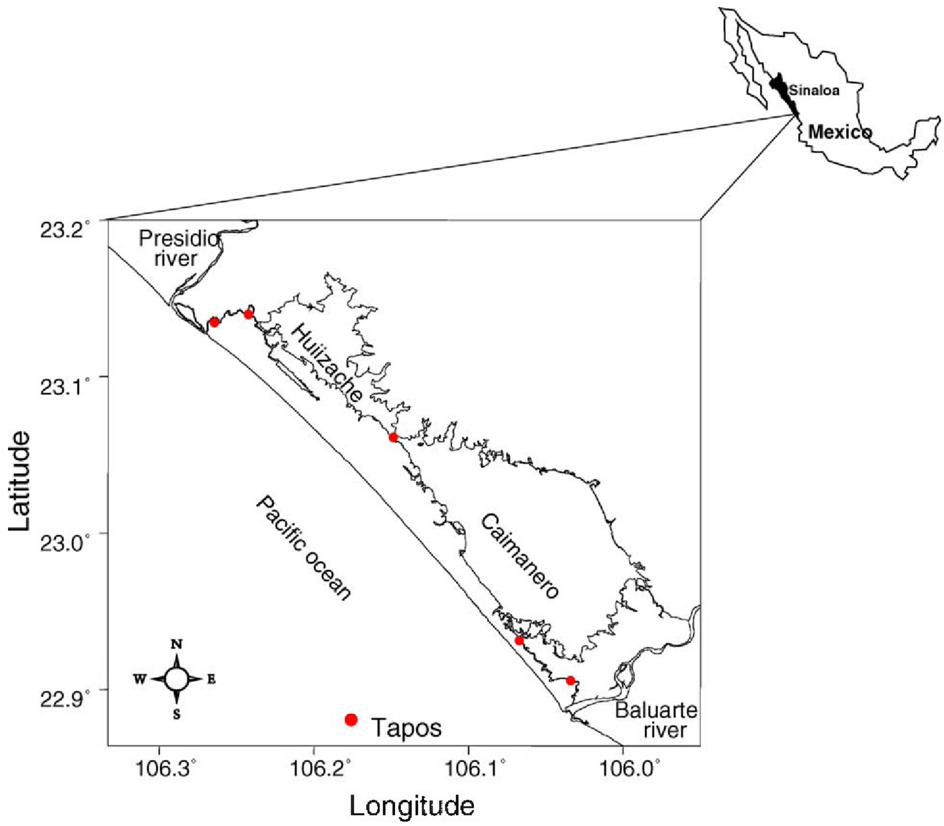


Fig. 1. Study area, the Huizache–Caimanero lagoon complex, Sinaloa state, Mexican Pacific coast.

minor species of shrimp are also caught in the fishery: *Litopenaeus stylirostris* Stimpson 1874, *Farfantepenaeus californiensis* Holmes 1900, and *Farfantepenaeus brevirostris* Kingsley 1878. Until the 1980s, annual production from this system was up to 1500 t (de la Lanza and García, 1991) and, amongst coastal lagoons; it showed the highest yield per unit of area (Edwards, 1978b). However, in the last decade, yields of shrimp have been greatly reduced, probably due to overfishing (Zetina-Rejón et al., 2001). Four fish resources (snooks, catfishes, mojarras, and mullets) are also exploited by an artisanal finfish fleet, but they are of less economic importance than the shrimp. High yields in the shrimp fishery conferred ecological, economic, and social importance to the ecosystem and several scientific studies have been conducted, mostly in the 1970s. Many of these studies focused on shrimp biology, ecology, and fishery (Edwards and Bowers, 1974; Sepúlveda, 1976, 1981; Edwards, 1978a; Blake and Menz, 1980; Menz and Bowers, 1980; Menz and Blake, 1980) and also other biological components of the system were studied (Gómez-Aguirrre et al., 1974; Amezcua-Linares, 1977; Edwards, 1978b; Warburton, 1978, 1979; Paul, 1981). Despite the available information, no multispecies context has been taken into account to manage exploited resources. Based on literature data, Zetina-Rejón et al. (2003) constructed a mass-balance model using the Ecopath approach (Polovina and Ow, 1983; Polovina, 1984; Christensen and Pauly, 1992) to describe the trophic structure and flows of biomass amongst the major functional groups of the ecosystem.

### 2.2. The Ecopath base model

The Ecopath approach uses a set of linear equations for all groups $i$ in the system assuming a mass balance with the form

$$B_i\left(\frac{P}{B}\right)_i - \sum_{j=1}^{n} B_j\left(\frac{Q}{B}\right)_j \mathrm{DC}_{ji} - B_i\left(\frac{P}{B}\right)_i (1-\mathrm{EE}_i) - \mathrm{EX}_i = 0 \qquad (1)$$

where $B_i$ is the biomass of group $i$; $(P/B)_i$ is the production/biomass ratio of $i$, which is equal to the total mortality coefficient ($Z$) under a steady-state condition (Allen, 1971); $\mathrm{EE}_i$ is ecotrophic efficiency; $B_j$ is biomass of predator $j$; $(Q/B)_j$ is consumption/biomass ratio of predator $j$; $\mathrm{DC}_{ji}$ is the proportion of prey $i$ in the diet of predator $j$; $\mathrm{EX}_i$ is the export of group $i$, represented here by fisheries catch data.

The model of Zetina-Rejón et al. (2003) comprised 26 groups consisting of 15 fish groups, 8 invertebrate groups, 2 groups of primary producers (phytoplankton and macrophytes), and a detritus group. The selection of groups was based on their ecological and economic importance. Most of the data used in the model construction came from the study area, however, the uncertainty was considering using "data pedigree" (Funtowicz and Ravetz, 1990) that serves a dual purpose by describing data origin, and by assigning confidence intervals to each input data based on the origin (Pauly et al., 2000), those confidence intervals were used in the Ecoranger routine to allow explicit consideration of uncertainties in the input data. Also, an overall pedigree index for the model was calculated, the index values scales from 0 for a model that is not rooted in local data up to a value of 1 for a model that is fully rooted in local data. The overall pedigree index for Huizache–Caimanero Ecopath model was 0.73 with a measure of fit of 5.02, indicating an acceptable quality model. A box model depicting the major flows of biomass is shown in Fig. 2.

### 2.3. Simulation and optimization of harvesting strategies

We used the Ecosim model (Walters et al., 1997) to simulate changes in the fishing rate of the exploited groups. Ecosim uses the set of linear equations used in the Ecopath model re-expressed as differential equations. The Ecosim basic equation is represented as

$$\frac{\mathrm{d}B_i}{\mathrm{d}t} = f(B) - M_0 B_i - F_i B_i - \sum_{j=1}^{n} c_{ij}(B_i, B_j) \qquad (2)$$

where $B$ is biomass; $M_0$ is the mortality rate not due to fishing or predation; $F_i$ is the fishing mortality coefficient; $f(B)$ represents the production function if the group is a primary producer or a growing function if the group is a consumer; $c_{ij}(B_i, B_j)$ is the function to predict consumption of the prey $i$ by predator $j$.

In order to find $F$ values that optimize different policy strategies, we used the "open loop policy" searching routine included in the Ecopath with Ecosim

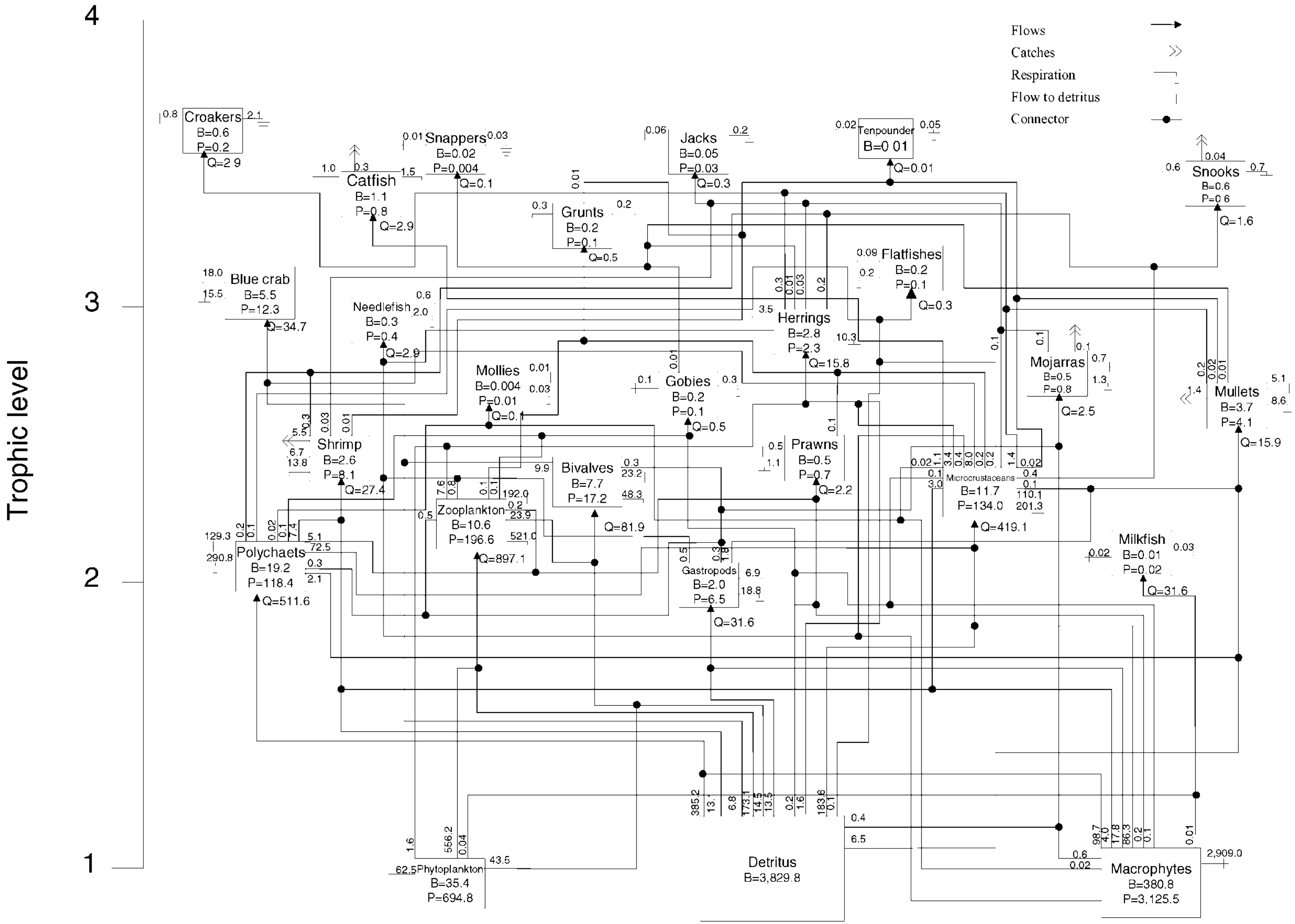


Fig. 2. Biomass flow diagram of the Huizache–Caimanero lagoon system. For simplicity, only flows >10% of total flows are represented. $B$ = biomass ($g\,m^{-2}$), $P$ = production ($g\,m^{-2}\,year^{-1}$), $Q$ = consumption ($g\,m^{-2}\,year^{-1}$).

software. This procedure takes into account the maximization of an objective function based on weighted values for ecological, economical, and/or social criteria. The ecological criterion ($E$) uses the inverse of the $P/B$ ratio for each group, and represents size and longevity, being high for long-lived and large-sized fish. The economic criterion ($) is defined as the net economic rent from the fisheries, which are of 70% for the finfish fishery and 75% for the shrimp fishery. The social criterion ($J$) is assumed to be proportional to catch value and is defined by the ratio of jobs to landed value for each fleet, in this study we use a value of 1 for the finfish fishery and 2.5 and for the shrimp fishery. Weighted values are assigned to each criterion depending on the policy strategy to be explored; we use a value of 1 for the criterion to be optimized and a low non-zero value (0.01) for the criterion not to be optimized. The optimization routine uses the Davidson–Fletcher–Powell nonlinear estimation method, which improves the objective function by changing the relative fishing rates. The routine runs the Ecosim model repeatedly while varying fishing rates; each run is evaluated until the procedure maximizes the objective function. Simulation was performed for a period of 30 years, and several scenarios were analyzed, including the three criteria, independently and combinations of them. Because nonlinear searching procedures can converge on a local maximum, not on the global maximum for the given objective function, we carry out several separate estimations using random values of $F$ as start to check results after each run to guarantee that routine reach the global maximum. Results for each criterion were compared between scenarios and with respect to the original value (Ecopath base scenario, without optimization) and expressed as the relative change after optimization. The results provide information about the way that fishing can proceed under specific optimizing criteria.

Ecosim requires some additional parameters to those used in Ecopath. These include a vulnerability setting for all predator–prey interactions, to simulate the rate at which the prey moves between a vulnerable state and a state where they are not accessible to predators. This setting of vulnerability allows trophic flow control, low values (e.g. 0.1) represent bottom up control and high values (e.g. 0.6) represent top down control. We analyze the effect of this setting because Ecosim outputs are particularly sensitive to this parameter (Walters et al., 1997). Other settings were kept as Ecosim default values.

The analysis of implementation of different fishing policies was performed using "closed loop policy" exploration, which incorporate observation error. The routine produces time series of biomass and objective function value components. Closed loop simulation models not only the ecological dynamics over time, but also the dynamics of regulatory process through incorporation of uncertainty in stock size estimations and/or improvements in fishing efficiency. We use the default values of 20% for variation in biomass estimations, catchability increases at a maximum of 10% per year, and the mean of the objective function values from 50 runs.

## 3. Results

Fig. 3 compares policy performance with increasing weight given to ecological criterion and to economic and social criteria increasing the weight for both simultaneously. As expected, we found an inverse relation between ecologic and socioeconomic goals. However, we found that with little increases in weights for ecological criteria (1.1 times respect to socioeconomic), a small increase is produced not only in ecological performance but also social and economic performance. Also, when we increase the socioeconomic criterion between the range of 1–1.9 times the ecological criterion, no major changes in ecological performance occurred.

The effects of flow control assumed in Ecosim on the estimation on $F$ during the optimization routine for the three criteria scenarios and for the compromise scenario which considers three criteria at the same time are showed in Fig. 4. We use three values of vulnerability, 0.1, 0.3, and 0.6 for bottom up, mixed, and top down control, respectively. In the ecological scenario, similar reductions in fishing mortalities for both fleets were found under the three types of flow control because ecological criterion tends to minimize all fishing mortalities to reduce effects on ecosystem structure. In other scenarios, the relative $F$ for the shrimp fleet was reduced in all scenarios assuming mixed and top down flow control but little increased was produced when bottom up flow control was assumed. In contrast, relative $F$ for finfish was increased in most

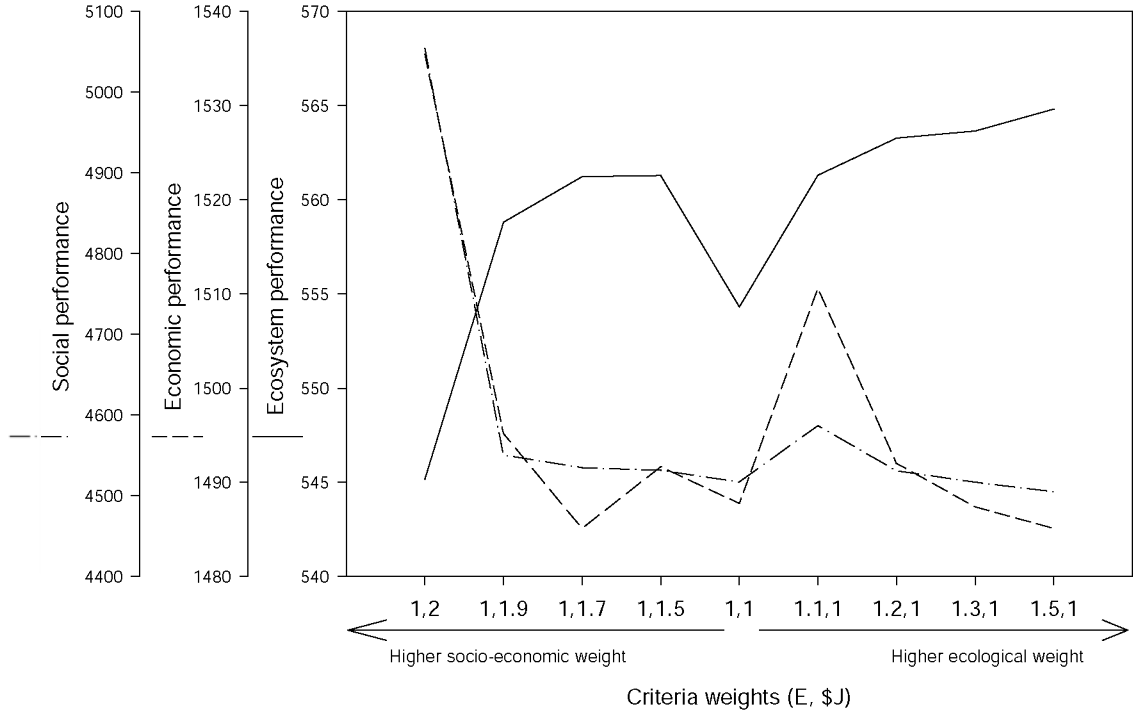


Fig. 3. Changes in policy performance with increasing weights. Higher weights to socioeconomic ($J) criteria are to the left and higher ecological (E) weights are to the right. Pair of values on x axis represent weights for ecological and socioeconomic criteria (E, $J). 1,1 represents equal weights for both criteria.

scenarios, but drastic changes were produced when we consider only one economic or social criterion. In the multi-objective scenario, assuming high vulnerabilities produced drastic changes in $F$ for the finfish fleet, and no apparent changes for both fleets $F$ were produced under bottom up conditions. Assuming mixed control under multi-objective scenario appears to be more reasonable, and we use this setting for subsequent simulations.

Relative annual biomass changes per group for different scenarios are shown in Fig. 5. Shrimp biomass increase in all scenarios due to the economic and ecological importance of this group and the relatively higher jobs per catch ratio. In general terms, the biomass of groups included in the finfish fishery is negatively affected when optimizing the economic and social criteria, due to the increase of fishing effort that would result of this. Optimization of the ecological criterion causes increases in the biomass of several groups, mainly those of higher trophic levels (TL) and minor reductions were produced for their preys; shrimp are also positively affected. The influence of the ecological criterion is evident when combined with other two criteria, minimizing negative biomass changes. More conservative biomass changes were found under the multi-objective scenario. Social and economic scenarios and their combination produce very similar changes.

Changes in the relative values of criteria after optimization under open and closed loop conditions are given in Table 1. These values represent relative changes of each criterion after optimization of policy criteria with respect to Ecopath original conditions. If values between open and closed loop are similar, then we can have more confidence in results. Values above 1 represents increases of the original performance and values below 1 represents reductions respect to original conditions. For example, when only the ecological criterion was optimized, the economic and social performance values are reduced to 94 and 95% of original value (with no optimization), respectively, and ecosystem stability increase 28% in open loop simulations.

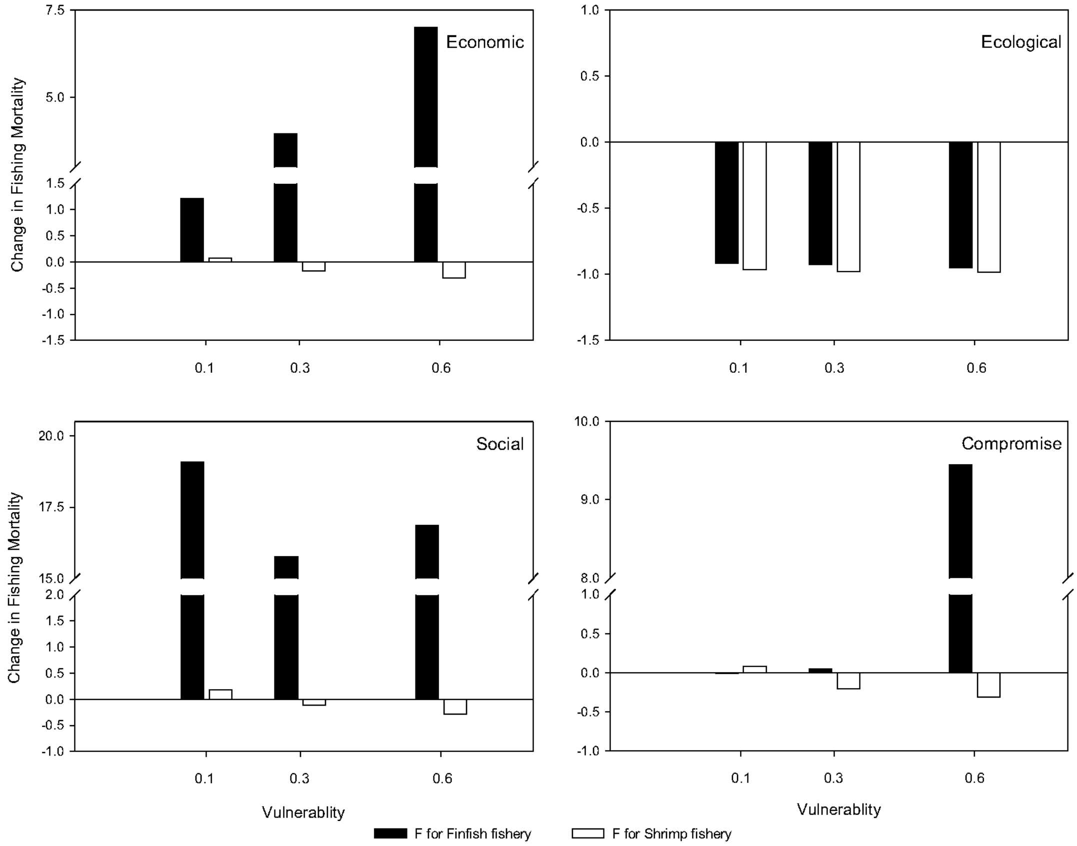


Fig. 4. Effects of flow control on the estimation of fishing mortality for finfish and shrimp fleets under different policy scenarios.

This pattern is preserved in closed loop simulations. However, optimizations of only economic or social criterion or their combination cause no major changes in ecosystem stability for both open and closed loop simulation conditions. When we combine ecological criteria with social and economic, we found increases around 10% in economic and ecological performance and no major change in social value. When the optimization of three criteria simultaneously was made, the economic value was increased around 10%.

Table 1
Relative changes in values of criteria after optimization of policies under open and closed loop conditions, in different scenarios

| Scenarios | \$ | *J* | *E* | \$, *J* | \$, *E* | *E*, *J* | \$, *E*, *J* |
|---|---|---|---|---|---|---|---|
| Open loop | | | | | | | |
| Net economic value | 1.19 | 1.15 | 0.06 | 1.19 | 1.07 | 1.09 | 1.14 |
| Social (employment) value | 1.13 | 1.18 | 0.05 | 1.17 | 0.98 | 1.00 | 1.05 |
| Ecosystem stability | 1.00 | 1.00 | 1.28 | 1.00 | 1.11 | 1.10 | 1.04 |
| Closed loop | | | | | | | |
| Net economic value | 1.16 | 1.16 | 0.06 | 1.16 | 1.04 | 1.05 | 1.10 |
| Social (employment) value | 1.12 | 1.15 | 0.05 | 1.14 | 0.98 | 1.00 | 1.04 |
| Ecosystem stability | 1.00 | 0.99 | 1.28 | 0.99 | 1.10 | 1.10 | 1.04 |

Criteria: \$ = economic, $J$ = social, and $E$ = ecological.

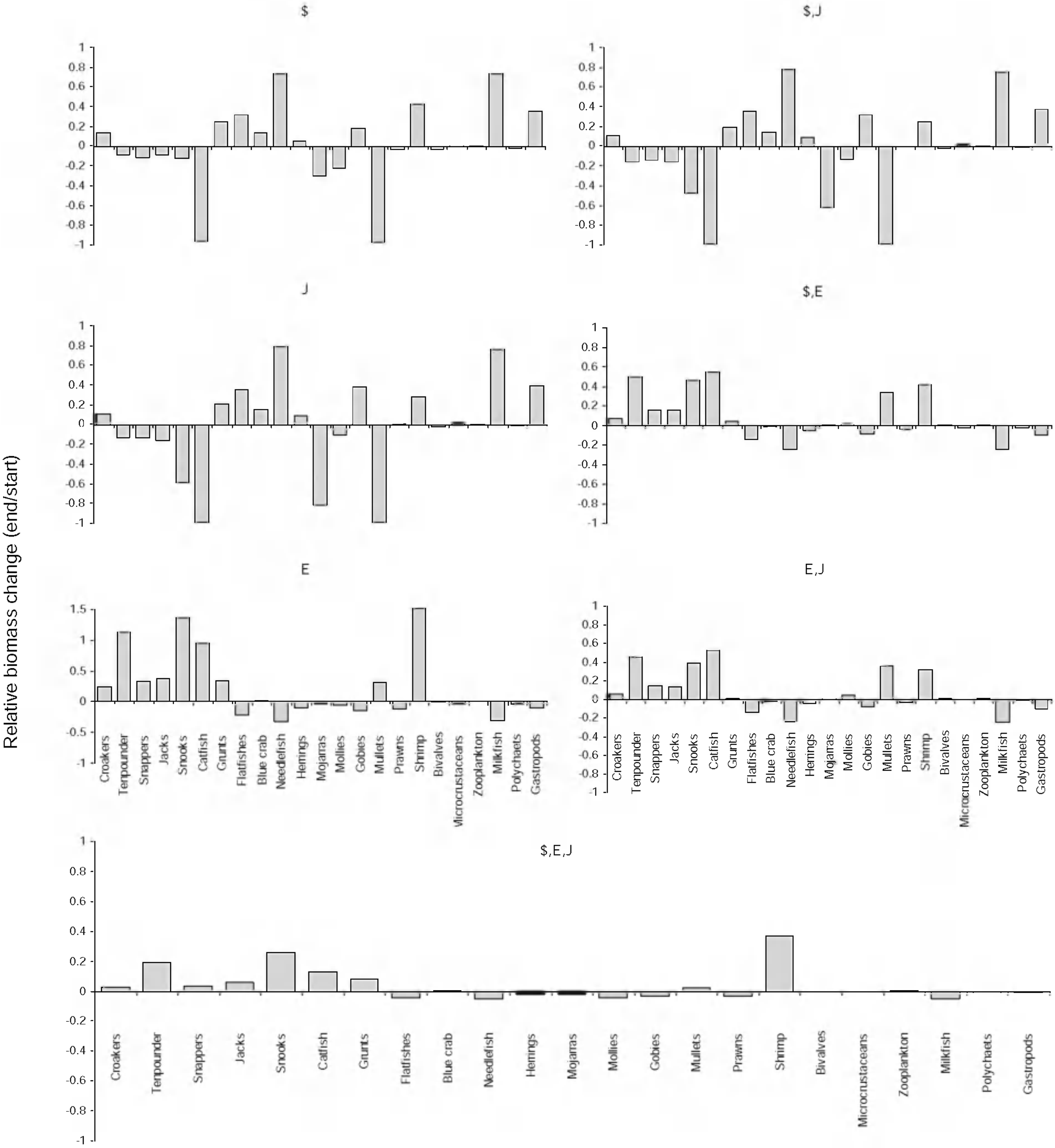


Fig. 5. Relative changes in biomass (end/start ratio) for 30 years simulation under different optimized strategies, economic ($), social (*J*) and ecological (*E*). Groups are sorted by trophic level (TL) from gastropods (TL = 2.0) to croaker (TL = 3.6).

Table 2
Overall objective function values for the base and optimized scenarios after open (OL) and closed loop (CL) simulations

| | Base | OL | CL | CL/OL |
|---|---|---|---|---|
| \$ | 0.42 | 0.5 | 0.42 | 0.84 |
| *J* | 0.45 | 0.53 | 0.4 | 0.75 |
| *E* | 1.0 | 1.28 | 1.28 | 1.00 |
| \$, *J* | 0.87 | 1.03 | 0.82 | 0.80 |
| \$, *E* | 1.42 | 1.56 | 1.48 | 0.95 |
| *E*, *J* | 1.45 | 1.55 | 1.45 | 0.94 |
| \$, *E*, *J* | 1.87 | 1.99 | 1.8 | 0.90 |

CL/OL represents the relative change of the overall value after incorporate uncertainty during implementation of the scenarios.

Values of the overall multi-criterion objective function for each scenario are given in Table 2. Values were improved during the nonlinear searching procedure on each scenario, based on the criterion or criteria considered. The outputs are weighted values computed from the three criteria considered (economic, social, and ecological). The resulting values of the function were compared to the value in the base scenario without optimization (Ecopath initial conditions). It was found that the ecological criterion makes the major contribution (1.0) to overall value when they are combined, and the economic and social criteria have nearly the same value (0.42 and 0.45, respectively). The social optimization scenario would have major value changes when uncertainty is considered (closed loop), while the ecological optimization scenario would not change in closed or open loop assessments. In general, all scenarios have the same overall value after closed loop simulations.

Fig. 6 shows group biomass trends during the closed loop simulation for different scenarios. The upper and lower biomass bounds, corresponding to 0.5 and 2.0 times the original biomass ($B$), were used as biological reference points for risk assessment. Economic and social optimization scenarios both have a negative impact on the biomass of catfish, snooks, mojarras, and mullets, which fall below $0.5B$. Combining the three

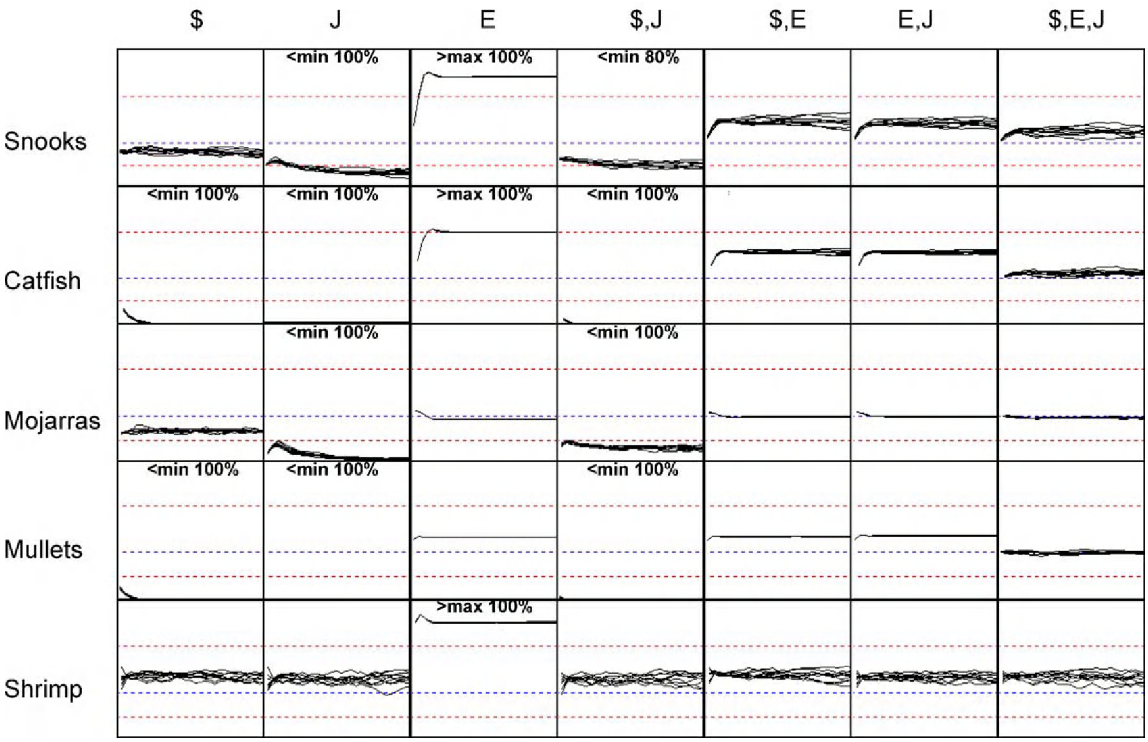


Fig. 6. Biomass trends of exploited groups after closed loop policy simulations. \$ = economic criterion, $J$ = social criterion, and $E$ = ecological criterion. Black lines represents biomass trends. Upper and lower dashed lines represent reference biological levels of biomass at $2.0B$ and $0.5B$, respectively. Percentages represent the number of runs in which biomass fall below reference biomass level.

criteria results in less negative impact of economic and social optimization of the groups caught by the finfish fleet. In all scenarios, the shrimp stock increases in biomass, reaching a maximum during the optimization of the ecological criterion, with a biomass greater than $2.0B$. Also, the shrimp stock varies more than the other groups in all scenarios.

## 4. Discussion

Multispecies management is big challenge not only for fisheries biologists, but for decision makers as well, since we often find disagreement between socioeconomic and ecological goals. When a high weight is given to socioeconomic aspect, the ecosystem stability could be in danger, and vice versa. However, we found in this work that is possible to find suitable weights for each criterion with no considerable losses in socioeconomic or ecological aspects, as we can show in Fig. 3. Vasconcellos et al. (2002) and Bundy (2002) show that when more weight is given to the ecological criterion, improvements in ecological performance occur at the expense of losses in socioeconomic performance, but they only examine changes in ecological and socioeconomic performance with increasing weight to ecological criterion and moreover using extreme values for this, from 1 to 100 times when socioeconomic weight was 1. Nevertheless, the weight assigned to each criterion needs to be explored in future studies.

It is well known that Ecosim simulations are highly sensitive to vulnerabilities used, here we found that the policy optimization routine is also highly sensitive to this parameter because fishing mortalities estimated can be dramatically different depending on the flow control assumed (vulnerabilities values). In many cases, when we work at the ecosystem level, there may not be sufficient evidence to decide what kind of flow control must be used, in those cases, like in Huizache–Caimanero ecosystem, the effects of assuming at least three values of vulnerabilities representing bottom up, top down, and mixed control should be required. One of the main uses in this kind of analysis is to detect some pattern in $F$ estimations for each fleet using several vulnerabilities values under different policy scenarios, no magnitudes as such. For example, we found in all scenarios, except for the ecological scenario, an increasing trend in finfish fishery effort which suggests that effectively this could be implemented. Zetina-Rejón et al. (2001) using a mixed flow control found that an increment of 1.24 times the original $F$ for finfish could lead to higher catches for this fishery with no important reduction in biomass of any group in the ecosystem. However, for the shrimp fishery depending on the flow control assumed results can indicate reduction or increment in $F$. Nevertheless, it is clear that in real situations, extreme scenarios like considering only one criterion to be optimized would not be probably, and the compromise scenario would be applicable to most situations, and in this case using a high vulnerability setting leads to drastic results with no practical application. Therefore, we suggest a mixed control would be a good start when there is not other evidence of flow control.

In general, in extreme scenarios, which consider only one criterion to be optimized, or extreme vulnerabilities, the suggested harvesting strategies were extreme and cause biomass depletion not only of the exploited groups but also other components of the ecosystems.

In this study, economic and social scenarios lead to similar results because the more profitable fishery (shrimp fishery) is also the one with higher jobs per catch ratio. Optimization of economic and social criteria results in an increase in fishing effort for the finfish fishery and a decrease for the shrimp fishery using a mixed trophic flow control. This is because shrimp are intensively exploited and better yields could result from a small decrease in fishing effort as demonstrated by Zetina-Rejón et al. (2001) using Ecosim equilibrium analysis. These authors also show that snooks and mojarras are under exploited by the finfish fishery, but catfish and mullets are near the MSY. However, if we consider only the socioeconomic aspect, this would result in harvesting strategies which maximize economic performance at the expenses of overexploit less valuable resources. In this case, the higher price of snooks and mojarras (US$ 5.43 and US$ 1.88 per kg, respectively) than catfish and mullets (US$ 0.92 and US$ 0.99 per kg, respectively). Also, optimization of economic and social criteria without consideration of the ecological structure causes a reduction in biomass of several groups, mainly top predators (Fig. 5). Here, the ecological optimization balances the effects of socioeconomic optimization. Mackinson

(2002) and Vasconcellos et al. (2002) have also found that economic and social scenarios produce similar results in terms of biomass changes; in addition, the last authors also found that predators from higher trophic levels are impacted negatively when social or economic values are optimized.

We found useful to compare performance of the criteria after optimization with performance at base conditions because this allow us to rank the policies strategies and choose the most appropriated in terms of improvements or weakenings.

We can conclude that Ecosim provide a great tool for policy exploration of harvesting strategies in multispecies management, however, exploration and interpretation of results must be addressed carefully, taken into account how input parameters can affect our results, particular attention should be for vulnerabilities and criteria weight used in the process of finding optimum strategies.

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