USING AN ECOSYSTEM MODELING APPROACH TO ASSESS THE MANAGEMENT OF A MEXICAN COASTAL LAGOON SYSTEM

MANUEL J. ZETINA-REJÓN, FRANCISCO ARREGUÍN-SÁNCHEZ, AND ERNESTO A. CHÁVEZ
Centro Interdisciplinario de Ciencias Marinas-I.P.N.
Apartado Postal 592
La Paz 23000, Baja California Sur
México
mzetina@ipn.mx

ABSTRACT

The Huizache-Caimanero coastal lagoon system supports an economically important artisanal shrimp fishery and a less valuable finfish fishery. We analyze the response of the fisheries and the ecosystem to changes in fishing effort. To do this we use Ecosim—a dynamic version of Ecopath, which is a steady-state model emphasizing natural rates of growth and consumption of marine populations. We examine changes in each group's biomass and determine which fishing strategies optimize yields on the basis of economic, social, and ecological criteria. We find that two of the four exploited fish groups, centropomids and gerreids, are underutilized; the other two, ariids and mugilids, are near the maximum sustainable yield. We find that the shrimp resource is overexploited. Our simulations suggest that the optimal management strategy occurs with a small increase in effort in the finfish fishery (1.24 times) combined with a small reduction of effort (0.8 times) in the shrimp fishery. This strategy enhances fishery yields of centropomids and gerreids, thereby decreasing the biomass of finfish and resulting in fewer (lower biomass of) shrimp predators. Simulations suggest that applying the optimal fishing strategy increases economic profits by ten percent.

INTRODUCTION

The shrimp resources of the Huizache-Caimanero lagoon system are important ecologically, economically, and socially. This lagoon complex is a nursery area for penaeid shrimp. The area has supported an important shrimp fishery since ancient times. Nearly 90% of the total shrimp catch in this lagoon is made up of one species, *Litopenaeus vannamei* Boone 1931. Three other minor species of shrimp are also caught in the fishery: *L. stylirostris* Stimpson 1874, *Farfantepenaeus californiensis* Holmes 1900, and *F. brevirostris* Kingsley 1878.

Shrimp catches in the Huizache-Caimanero lagoon system reached 1,500 metric tons in the 1980s (de la Lanza and García-Calderón 1991) and had one of the highest yields per unit area compared with other coastal lagoons (Edwards 1978), but catches have declined in the last decade. A finfish fishery in the area exploits four groups: centropomids, ariids, gerreids, and mugilids. On the basis of economic value and catch volume, however, the finfish fishery is less important than the shrimp fishery.

An Ecopath mass balance model (Christensen and Pauly 1992) has been developed by Zetina-Rejón (2000) using available information for the Huizache-Caimanero lagoon system. This model describes the trophic structure and energy flow among the major functional groups in the ecosystem. In this paper, we use the model to evaluate the status of the current fisheries and to explore optimization of fishing strategies based on ecological, economic, and social criteria.

MATERIALS AND METHODS

Study Area

The Huizache-Caimanero lagoon complex is located on the Pacific coast of Mexico in the south of Sinaloa state (fig. 1). A narrow channel separates the two lagoons, and a barrier island separates the lagoons from the Pacific Ocean. Each lagoon receives intermittent flows from two small rivers connected by narrow, winding channels, permitting the transport of fresh water out of the lagoon during the rainy season (June to January). A contorted channel, permanently open, allows shrimp postlarvae and other marine species to enter the lagoons shortly after spawning. Tides are semidiurnal, with a range of 0.85 m. The average area of the system is 175 km^2, and is reduced dramatically to 65 km^2 in the dry season (Soto 1969). Water temperature ranges from 20° to 40°C, and precipitation varies between 800 and 1,200 mm per year (de la Lanza and García-Calderón 1991). Mangrove swamps and other halophytes surround the lagoon complex.

The Shrimp Fishery

Shrimp are caught by means of artificial barriers, locally known as *tapos*, which are placed in tide channels. This method catches subadult shrimp during their emigration to the sea. Each tapo has two or more heart-shaped collectors pointing downstream so that shrimp are caught inside at ebb tide. There are platforms around the collectors on which fishermen stand and remove shrimps with scoop nets. During fishing operations there

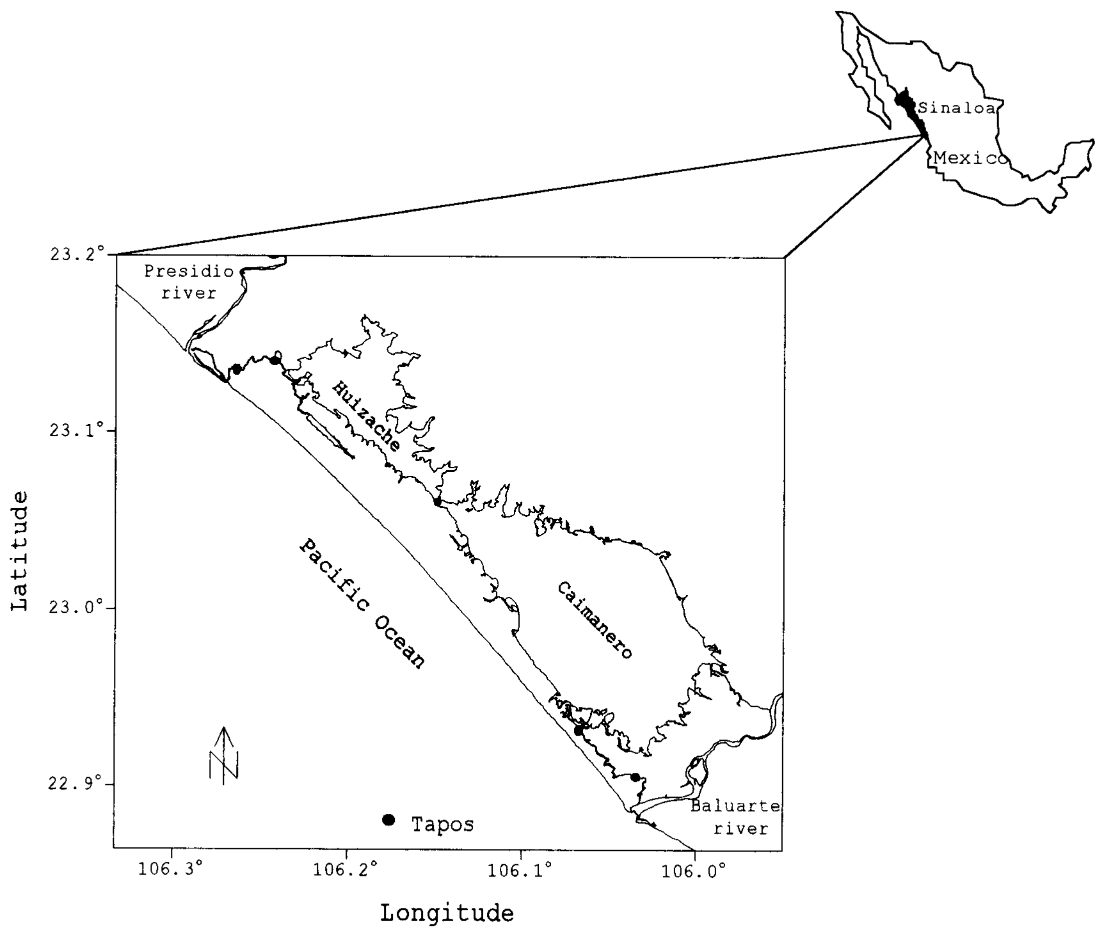

Figure 1. Huizache-Caimanero coastal lagoon system, with *tapos* indicated.

is no bycatch. The fishery lasts from mid-September to mid-April, when the tapos are closed.

Model Construction

Zetina-Rejón (2000) constructed a mass balance model for the Huizache-Caimanero coastal lagoon system by using Ecopath with Ecosim software (Christensen et al. 2000). The model includes 26 functional groups based on the economic or ecological importance of species. Two groups of primary producers (phytoplankton and macrophytes) and a detritus group were also included in the model (fig. 2). The Ecopath model (Polovina and Ow 1983; Polovina 1984; Christensen and Pauly 1992) uses a set of linear equations for all groups i in the system and assumes mass balance; that is, the production of the i group minus all predation on i minus nonpredatory losses of i minus export of i is equal to zero. This is formulated as:

$$B_i \cdot \left(\frac{P}{B}\right)_i \cdot EE_i - \sum_{j=1}^{n} B_j \cdot \left(\frac{Q}{B}\right)_j \cdot DC_{ji} -$$

$$B_i \cdot \left(\frac{P}{B}\right)_i \cdot (1-EE_i) - EX_i = 0 \qquad (1)$$

Where B_i = biomass of group i;

$(P/B)_i$ = 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 = ecotrophic efficiency, which is the part of the total production that is consumed by predators or exported out of the system;

B_j = biomass of predator j;

$(Q/B)_j$ = consumption/biomass ratio of predator j;

DC_{ji} = proportion of prey i in the diet of predator j;

EX_i = the export of group i, which in this study consists of catch if the group is exploited.

Since this equation is balanced, a term can be unknown and the model will estimate it. In addition, the diet composition of all consumers is required.

Simulation of Harvesting Strategies

We use Ecosim (Walters et al. 1997), the time dynamic version of Ecopath, to simulate changes in fishing rate for the exploited groups. Ecosim takes the set of linear equations used in Ecopath and re-expresses them as coupled differential equations where the term biomass accumulation may equal zero. Ecosim's basic equation is

$$\frac{dB_i}{dt} = f(B) - M_0 B_i - F_i B_i - \sum_{j=1}^{n} c_{ij}(B_i, B_j) + BA_{cc} \quad (2)$$

where B is biomass;

M_0 is the mortality rate (not due to fishing or predation);

F_i is the fishing mortality rate;

$f(B)$ represents the production function if the group is a primary producer or the growing function if the group is a consumer;

$C_{ij}(B_i, B_j)$ is the function to predict the consumption of the prey i by predator j;

BA_{cc} is the biomass accumulation term.

Ecosim uses some parameters additional to those used in Ecopath. These include vulnerability settings for all predator-prey interactions, which control the rate at which prey move between a vulnerable state and an invulnerable state. This vulnerability setting allows us to impose trophic flow, using either "top-down" or "bottom-up" control. The first control often leads to rapid oscillations of prey and predator biomasses, and the second often leads to unrealistically smooth biomass changes in prey and predator dynamics, which usually do not propagate through the food web. In this study, we used $v = 0.3$, which represents a mixed control, since we have no information on whether the system is controlled from the top down or from the bottom up.

An additional input is the maximum production/biomass ratio tolerated by any group. This value is used to limit the value of P/B when fishing or predation increases for a group. A maximum P/B value twice that of the original was used in this study.

Equation 2 permits us to simulate perturbations in fishing intensity (F_i) for any group to describe biomass changes, taking into account growth rate, consumption, and mortality not due to fishing. We use the equilibrium analysis to evaluate the changes resulting from different levels of fishing effort. This analysis takes the partial derivatives of the differential equations defined by Ecosim with reference to fishing mortality, and sets these equal to zero. Ecosim then finds the catch tendency and biomass values of all groups that would result from different fishing levels expressed as fishing mortality. The analysis was performed for each fleet separately—the shrimp fleet, which we modeled as a single-species fishery *L. vannamei* (since this is the most important and abundant species); and the finfish fleet, which catches four fish groups: centropomids, ariids, gerreids, and mugilids. For each exploited group, we explored the fishing mortality from $F = 0$ up to $F = 3\times$ (three times the original value).

In order to find F values that optimize management strategies, we used the fishing strategies optimization searching procedure included in Ecopath with Ecosim software version 4.0 (Christensen et al. 2000). This procedure takes into account the maximization of an objective function based on ecological, economic, and social criteria. The ecological criterion (E) is defined by the importance of each group in the ecosystem based on the inverse of the P/B ratio for each group, which is related to the longevity of the organism (Christensen 1995). The economic criterion ($) is defined as the total landed value of the catch minus the total operating cost. The social criterion (J) is assumed to be proportional to the index jobs/catch landed value for each fleet. Weighted values are assigned to each criterion depending on the management strategy to be evaluated. In this case, we tested several relative weights for each criterion, and found the best results with values of 1.9 for social and economic criteria and a value of 1 for the ecological criteria. The ecological criteria often imply reduced fishing effort for large, long-lived organisms, in this case represented by top predators, some of which are exploited in the finfish fishery.

The optimization routine uses the Davidson-Fletcher-Powell nonlinear estimation method, which iteratively maximizes the 3-criteria objective functions affecting the fleet structure and deployment through changes in fleet size. The relative fleet sizes are used to calculate relative fishing mortality rates for each fleet type. We assume that reducing a fleet type by some percentage results in the same percentage decrease in the fishing rates for all the groups that it catches. In this study, simulations were performed for period of 30 years. The optimization was started at year 5 to year 30, and the fleets were independently optimized at the same time.

The former simulation corresponds to an approach aimed at reaching a broadly defined goal, a policy assessment known as "open-loop." Additionally, Ecosim incorporates a "closed-loop" policy simulation to evaluate not only the biomass dynamics over time, but also the dynamics of the stock assessment and regulatory process. That is, a closed-loop simulation considers the uncertainty in biomass and fishing rate estimates. Assessment results are implemented through limitation of fishing effort. The closed-loop simulation permits one

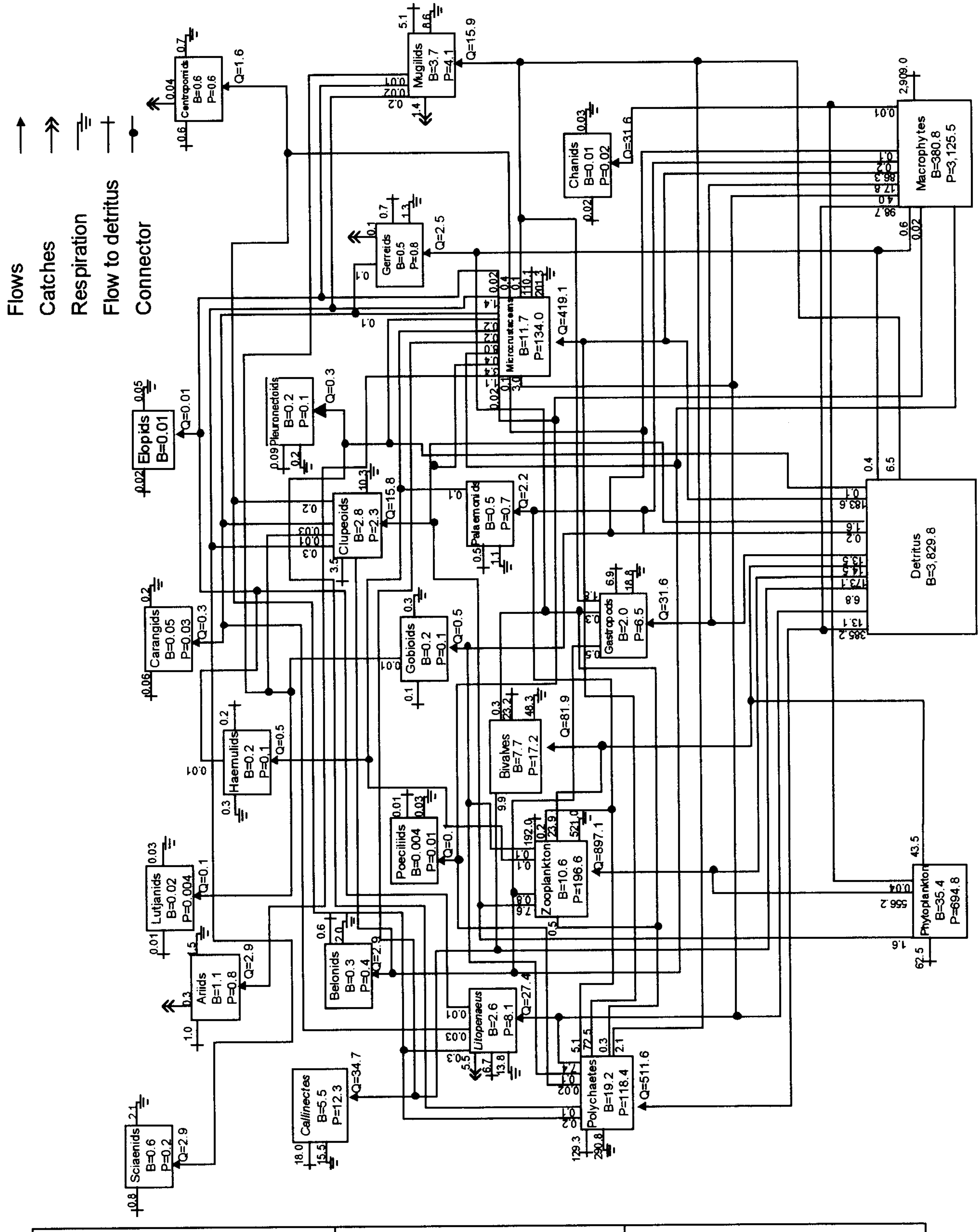

Figure 2. Box model representing major flows in Huizache-Caimanero coastal lagoon system, using Ecopath approach. B = biomass ($g \cdot m^{-2}$), P = production ($g \cdot m^{-2} \cdot year^{-1}$), Q = consumption ($g \cdot m^{-2} \cdot year^{-1}$). After Zetina-Rejón 2000.

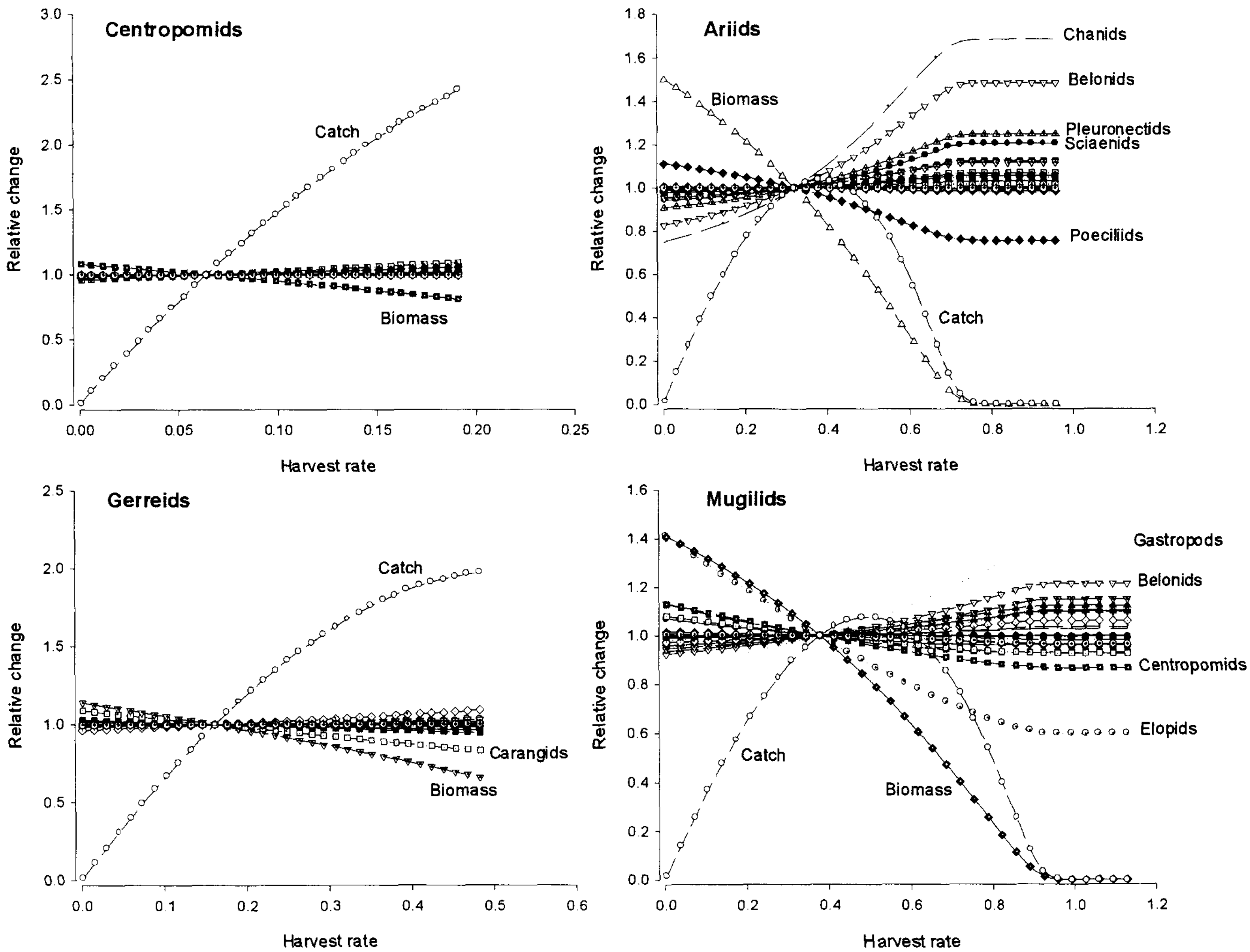

Figure 3. Simulation of changes in biomass and catches of exploited groups resulting from changes in fishing effort of finfish fleet. For each group the simulated harvest rate ranges from 0 up to 3 times the original value, which corresponds to the intersection point of all curves. The only other groups indicated are those with major changes in biomass.

to (1) decide how many closed-loop stochastic simulation trials to do (in this case 10); (2) set the accuracy of the annual assessment procedures coefficient of variation of annual biomass estimates (in this case 20%); (3) set the value or importance weightings for the F's imposed on various species by each fishing fleet (in this case the same impact was considered for all exploited groups); and (4) consider changes in catchability as the maximum annual increase (in this case a value of 0.1 was used). In this study, we use the closed-loop simulation results for analyzing the risk of exceeding upper and lower biomass bounds for any group—0.5 and 2.0 times the original biomass, respectively—as a consequence of implementing the optimized management strategy.

RESULTS

Although current catches of ariids and mugilids are near the maximum sustainable yield, changes in fishing effort do not appear to affect the biomass of centropomids and gerreids because current levels of exploitation are low, as indicated by equilibrium analysis (fig. 3). In contrast, simulations show that the shrimp fishery is overexploited (here defined as exploitation beyond the maximum biological production), as indicated by the current fishing effort on the right side of the curve that represents the maximum yield (fig.4). We find that changes in fishing effort not only directly affect the exploited groups but also indirectly affect other groups that interact with exploited species.

Changes in effort in the finfish fleet that intensively exploit ariids and mugilids seem to affect more groups than just the centropomids and gerreids, which are less exploited in the system. The groups affected by this fleet are from different trophic levels, including such top predators as elopids, carangids, and centropomids, as well as organisms from the second trophic level such as chanids,

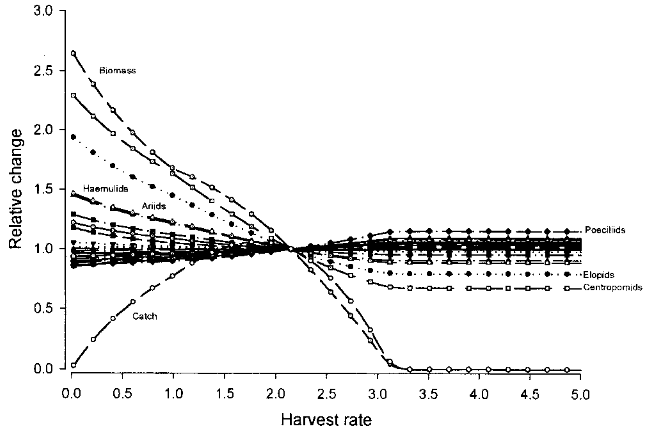

Figure 4. Simulation of changes in biomass and catches of exploited groups resulting from changes in fishing effort of shrimp fleet. For each group the simulated harvest rate ranges from 0 to 3 times the original value, which corresponds to the intersection point of all curves. The only other groups indicated are those with major changes in biomass.

poeciliids, and gastropods (fig. 3). The shrimp fleet, which is intense, impacts several groups in higher trophic levels, mainly top predators such as elopids, centropomids, ariids, and haemulids (fig. 4).

After the optimization routine was run during simulation, the resulting fishing effort for the finfish fleet suggests an increment of 1.24 times the original fish mortality, and for the shrimp fleet a reduction at 0.80 times the original value. We did not find any important reduction in the biomass of any group, but a small increase in shrimp biomass resulted from the reduced fishing effort even when uncertainty was considered (closed-loop). Also, the biomass of ariids and mugilids was slightly reduced as a consequence of the fishing effort in the finfish fishery (fig. 5).

Furthermore, in all cases we found changes in catches (figs. 6 and 7) after year 5 following the change in fish-

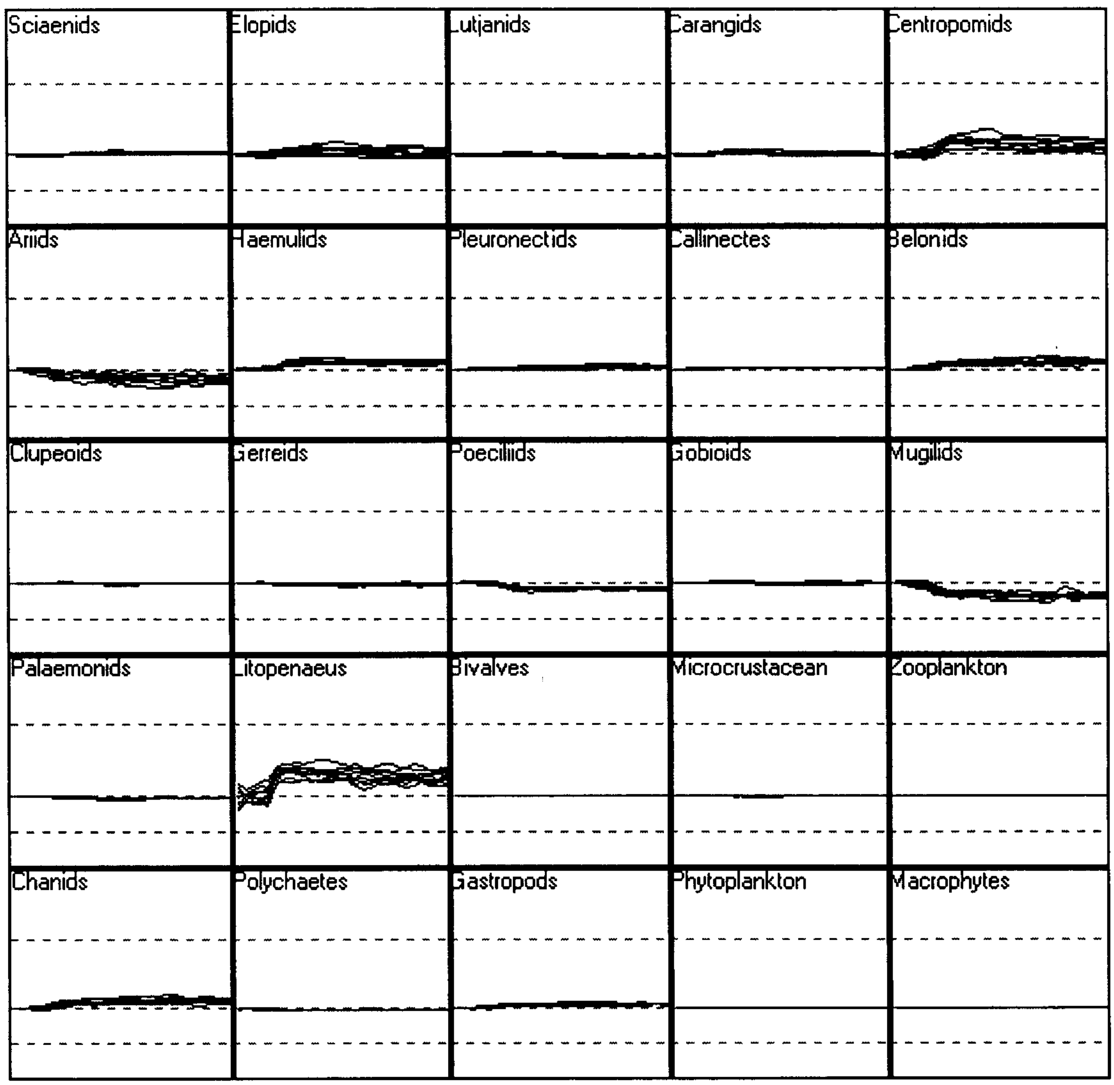

Figure 5. Biomass trends of groups after optimization of management strategies considering economical, social, and ecological criteria and considering closed-loop policy simulation. Black lines represent uncertain biomass. Upper and lower dotted lines represent levels of biomass as 2.0B and 0.5B, respectively.

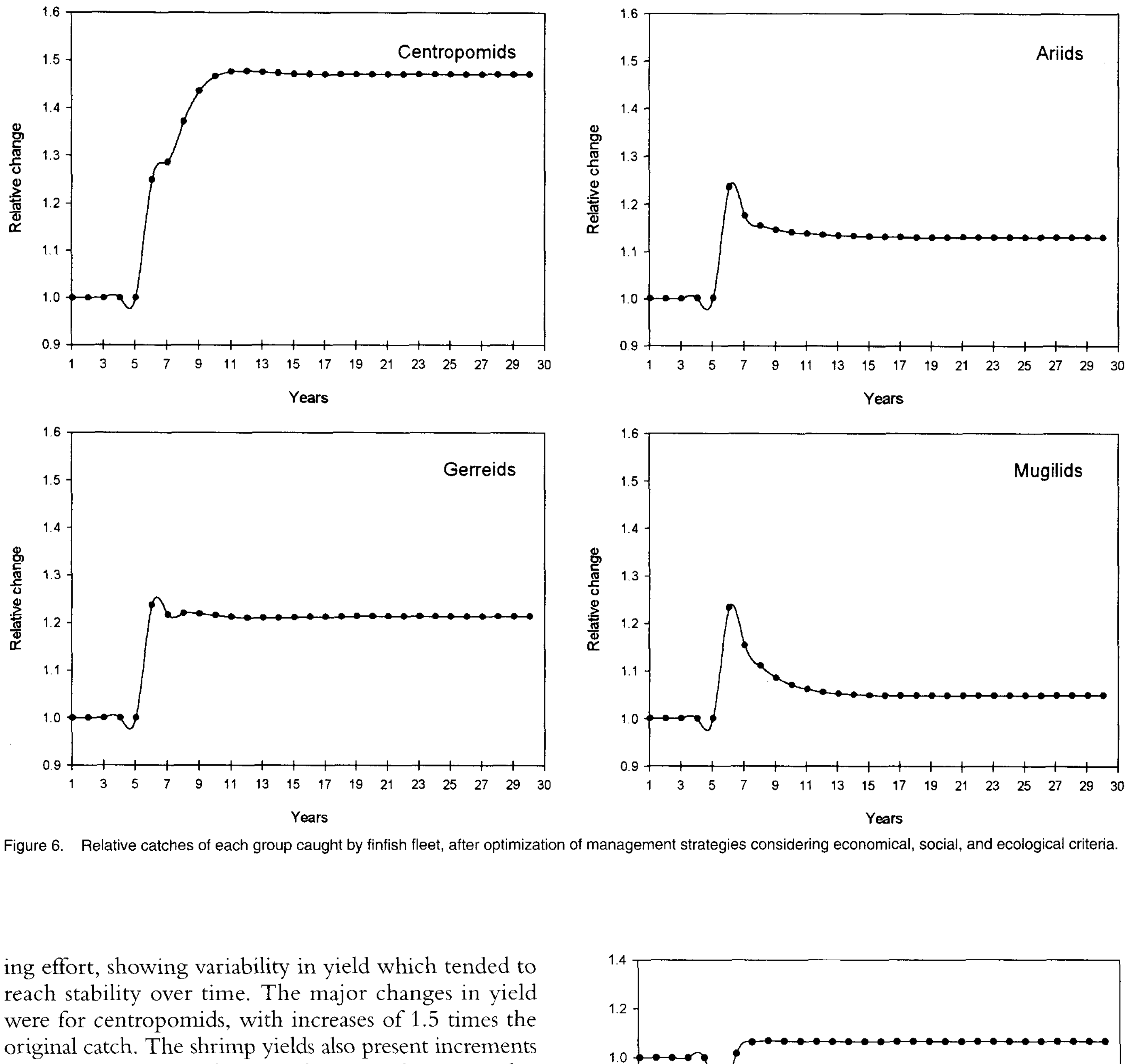

Figure 6. Relative catches of each group caught by finfish fleet, after optimization of management strategies considering economical, social, and ecological criteria.

ing effort, showing variability in yield which tended to reach stability over time. The major changes in yield were for centropomids, with increases of 1.5 times the original catch. The shrimp yields also present increments near 10%, important because shrimp is the most valuable resource in the area.

Outputs for the three criteria considered in this study, after the optimization procedure, were compared with initial values without optimization (current state). The results are shown in table 1 as relative values (optimized criteria value divided by initial value) for both policy assessments. The results of both procedures, open- and closed-loop, are consistent and suggest that the optimal management strategy can increase economic benefits by 10 percent. The other two criteria, social and ecological, were not reduced in either analysis (deterministic or stochastic).

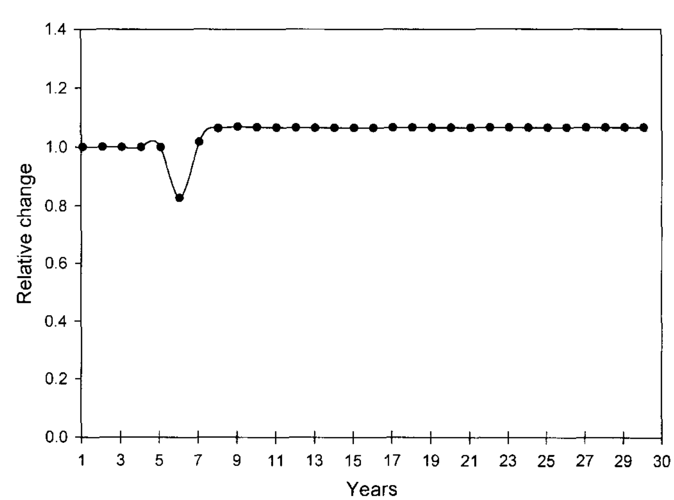

Figure 7. Relative catches by shrimp fleet, after optimization of management strategies considering economical, social, and ecological criteria.

TABLE 1
Relative Values of Each Criterion after Optimization of Fishing Management Strategies

	Criteria		
	\$ Economic	J Social	E Ecological
Open-loop assessment	1.13	1.06	1.02
Closed-loop assessment	1.09	1.05	1.02

DISCUSSION

Multispecies management has been a challenge because management efforts have traditionally focused on single species (Walter and Hoagman 1971; Pope 1979; Kirkwood 1982; Sainsbury 1982; Cushing 1984; Gulland and García 1984; Christensen 1998). Ecosystem-based approaches incorporating trophic structure offer a tool for understanding how ecosystems function and for evaluating which fishing strategies are optimal for areas with multiple interacting fisheries (Walter 1979; Polovina and Ow 1983; Polovina 1984; Christensen and Pauly 1992; Walters et al. 1997). Furthermore, simulation models have shown the relevance of the multispecies approach, since fishing has been shown to affect resources both directly and indirectly (Arreguín-Sánchez and Chávez 1995; Arreguín-Sánchez and Valero 1996; Christensen 1996; Arreguín-Sánchez and Manickhand-Heileman 1998), as well as ecosystem structure (Pérez-España and Arreguín-Sánchez 1999). The results of these model simulations can be used to make recommendations to optimize fishery management.

Recently, researchers have been discussing how ecosystem-based approaches can be used to guide fishery management (Pauly 1998; Field et al., this volume; Fluharty and Cyr, this volume). Discussions have focused on the application of tools to evaluate multispecies fisheries in order to develop a comprehensive framework for management (Arreguín-Sánchez, in press; Arreguín-Sánchez and Calderón-Aguilera, in press). This paper focuses on how to optimize fishing in a coastal lagoon system in which there are valuable shrimp resources and less valuable finfish resources.

We find that the two more valuable finfish resources (centropomids and gerreids) are underexploited, and that higher profits could result from increased fishing effort on them. This increased exploitation would reduce the biomass of finfish in the system, and there would be a concomitant reduction in the biomass of shrimp predators. A large increase in fishing effort for finfish, however, could deplete the other two fish groups: the ariids and mugilids. Furthermore, not only would the centropomids and gerreids be directly affected by large increases in fishing effort, but our results show that other groups would sustain an indirect negative effect (fig. 3). Our model predicts that the most heavily affected groups would be from the top and middle trophic levels.

The results of both equilibrium and optimization analyses were in agreement, suggesting that a small decrease in shrimp fishing effort and a small increase in finfish effort would be optimal. In fact, fishing efforts resulting from the optimization procedure are near the F_{MSY} indicated by equilibrium analysis (figs. 3 and 4). The use of ecological criteria in the optimization procedure reduces the possibility of biomass depletions; therefore the optimum fishing strategy did not greatly increase fishing effort for finfish. Our model predicts an increase (10%) in economic profit with the application of the optimal fishing strategy. This increase occurs in our simulations even after we account for uncertainty in the data estimates as well as the assessment procedures (closed-loop).

In our examinations of the vulnerability parameter, we observed lower changes in biomass estimations for bottom-up control ($v < 0.3$); whereas top-down control ($v > 0.3$) produced abrupt changes in biomass estimations. The lowest uncertainty was observed for the mixed control model ($v = 0.3$). Similar results have been reported by Arreguín-Sánchez (in press), who also suggests that assuming bottom-up control often leads to higher uncertainty in biomass estimates for groups from intermediate trophic levels, and top-down control can lead to higher uncertainty for biomass estimates for groups from higher trophic levels. Clearly, this is an area for further investigation, since the mechanisms behind the observed behavior could help explain what occurs in ecosystems where top predators have been removed by fishing. However, using a mixed control in the model produces less uncertainty in biomass estimates than bottom-up or top-down controls, and could help us to detect average biomass responses resulting from the implementation of optimum fishing strategies.

Our results show a practical application of trophic modeling to a coastal lagoon system. Furthermore, this method allows us to model the effects of various levels of fishing effort on target resources. This example highlights how assessments like these can predict the ways in which multispecies fisheries can affect each other. Multispecies modeling can be used to predict changes in biomass of all the groups in the ecosystem as a result of changes in fishing effort. Furthermore, this example shows how such modeling can be used to optimize fishing strategies, thereby enhancing economic profits from multispecies fisheries.

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