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Simulated response to harvesting strategies in an exploited ecosystem in the southwestern Gulf of Mexico☆

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Abstract

The impact of some optimized harvesting strategies on ecosystem structure was investigated using a mass-balanced model of the ecosystem in the southwestern Gulf of Mexico, where there are four types of artisanal fisheries and a shrimp fishery that has collapsed. The Ecopath with Ecosim software was used to simulate harvesting strategies aimed at optimizing economic (profit), social (jobs), ecological (conservation of ecosystem structure) and shrimp-recovery criteria. As expected, the ecosystem changes that would ensue vary according to the combination of optimization goals. We found that for some scenarios, the extraction of biomass from a discrete trophic-level changes impacting ecosystem and catch structure. This was clearly observed through the tendency of the mean trophic level of the ecosystem and catch, as well as the fishing-in-balance index (FBI). A particular discussion was made about the collapsed shrimp fishery, where the impact of a specific shrimp-recovery strategy was evaluated. Collapse is strongly associated to physical variables and recovery based on trophic relationships is plausible but with a high ecosystem structure cost.

Keywords: Ecosystem response; Harvesting strategies; Shrimp collapse; Gulf of Mexico

1. Introduction

The continental shelf off Campeche, in the southwestern Gulf of Mexico, constitutes an ecosystem in which several human activities are undertaken, among the most important of which are the fishing and oil industries. In this area, the oil industry extracts around 70% of the nation's total oil and natural gas production. Before the oil industry was established in the early 1980s, fishing, particularly for shrimp, was the base of the regional economy. However, this fishery has collapsed; annual harvests have fallen from 27,000 t during early 1970s, to 3000 t or less in recent years (Arreguín-Sánchez et al., 1997a). The main problem is the decline of the pink shrimp (*Farfantepenaeus duorarum*) stock, which constituted in the past almost 90% of the total catch. Several hypothesis have been proposed to explain shrimp stock declination; one of them frequently argued by public is that

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suggesting an impact of the oil industry on recruitment, nursery areas and habitat degradation because pollution or physical damage. Another hypothesis underline a strong impact by the artisanal fleet on juveniles (Gracia, 1997). Recently Ramírez-Rodríguez et al. (2000) concluded that changes in oceanographic conditions over the last decades have affected recruitment and may be an important factor for the decline. Currently, fisheries in the area focus on other, less valuable species, particularly finfish and octopus, at the artisanal level.

Development of fishery management strategies requires an evaluation of the response of target species and of the ecosystem to exploitation. Cochrane (2000) has pointed out the necessity of evaluating alternative strategies under specific objectives in order to construct an appropriate framework for decision making. In this contribution, we attempt to evaluate the impact of different harvesting strategies (for economic, social and conservation goals) through the analysis of some ecosystem properties, using the ecosystem of the continental shelf off Campeche as a case study.

2. Material and methods

The ecosystem of the continental shelf off Campeche, on the southwestern Gulf of Mexico, has an area of 65,000 km^2 (Fig. 1). In this area are some 320 shrimp trawlers and more than 4400 boats belonging to the artisanal fleet.

The analysis is based on an improved version (Manikchand-Haileman et al., 1998) of the mass-balanced ecosystem model developed using Ecopath with Ecosim (Christensen and Pauly, 1992; Walters et al., 1997; Christensen and Walters, 2000). Basic

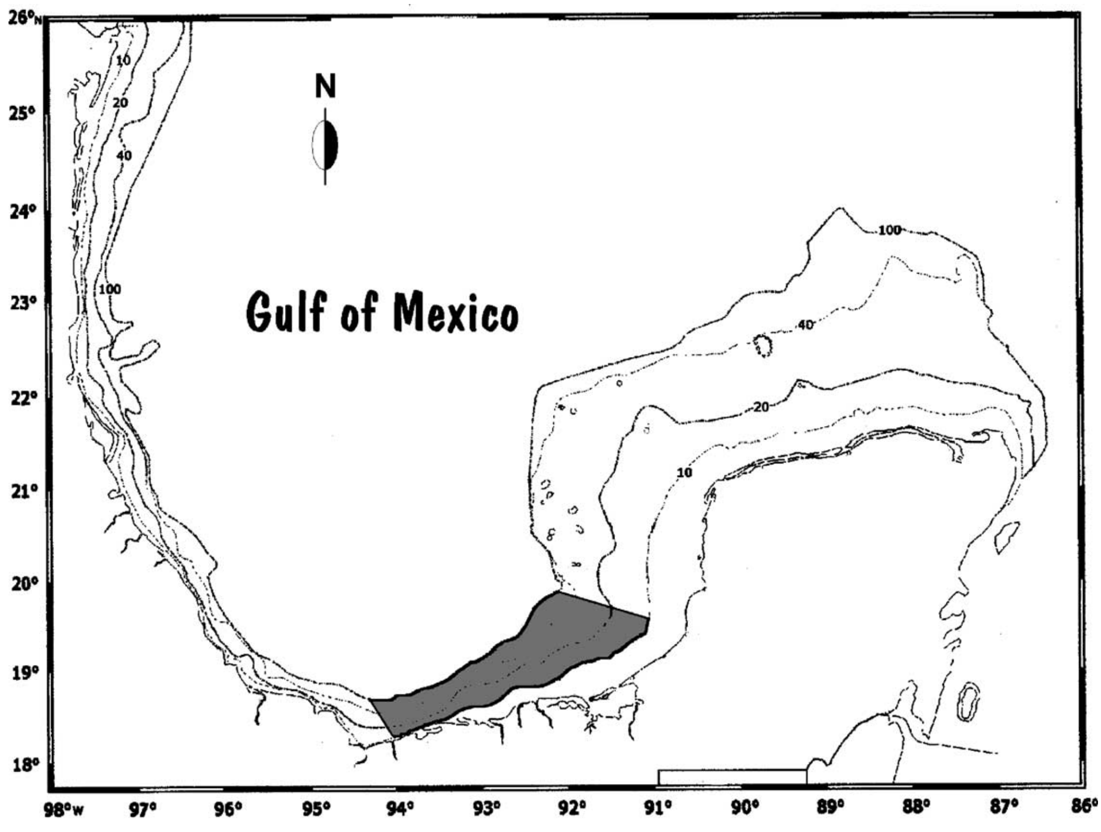

Fig. 1. Location of the study area (shaded) in the southwestern Gulf of Mexico. Numbers on lines indicates depth in fathoms.

data were collected from surveys during August 1988 to July 1994. We included as functional groups marine mammals (dolphins), sea birds and marine turtles; 12 groups of fish and sharks; and several invertebrate groups, including shrimp, octopus, squid, epifauna, infauna, zooplankton, and as primary producers, phytoplankton, benthic producers and detritus. The fisheries were divided into shrimp trawling and artisanal (Arreguín-Sánchez et al., 1997b; Gracia, 1997). The latter was divided in four groups: the demersal fleet (Art DEM HL) that mostly uses short longlines and manual hook-and-lines, targeting groupers and snappers; the pelagic fleet (Art PEL HL) which uses mainly gillnets to catch mackerels and jacks, and hook-and-lines for sharks; the beach seine fishery; and the octopus fleet, which uses live crabs as bait (Solís-Ramírez et al., 1997; Arreguín-Sánchez et al., 2000). The ecosystem model also incorporate changes in salinity as forcing factors that affect the shrimp stock (Ramírez-Rodríguez et al., 2000), as shown by Arreguín-Sánchez (2001).

Ecosim describes the dynamics of groups in the ecosystem through the equation

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

where $f(B)$ is a function of biomass B_i when species i is a primary producer, and for consumers $f(B) = g_i \sum_{j=1}^{n} c_{ij}(B_i, B_j)$, where g_i represents the growth efficiency, and $c_{ij}(B_i, B_j)$ is the function used to predict consumption from B_i to B_j, and represents the probability of encounters between prey (i) and predators (j), as well as physiological behavior such as satiation. c_{ij} is the consumption rate, M_0 other mortality not due to predation or fishing, F_i is the fishing mortality rate.

Harvesting strategies were based on optimization of one or combinations of five major criteria: economic benefits in terms of net present value of profits; social benefits in terms of employment generated by the fisheries and computed as the ratio of jobs/catch value; mandated rebuilding, which optimizes the recovery of depleted groups; and ecosystem benefits in terms of maintenance of ecosystem structure. Five combinations of such criteria were tested as shown in Table 1.

Catch values were obtained from statistical records (SEMARNAP, 1998) as landed prices. Costs were represented as indicated in Table 2:

Table 1
Strategies selected to simulate management scenarios for the fisheries on the southern Gulf of Mexico

Strategy	Symbol	Description
1	$	Optimize economic benefits only
2	J	Optimize social benefits in terms of jobs only
3	E	Optimize ecosystem benefits in terms of ecological quality/conservation only
4	MR	Mandated rebuilding (shrimp-recovery criterion)
5	$JE	Optimizing multiple criteria, i.e. economic, social and conservation of ecosystem structure (multiple criteria)

Time series of fishing mortality (1969–1994) and estimated biomass for shrimp were used to calibrate simulated biomasses. Data are from an age-based virtual population analysis (VPA) (unpublished data). Time series for artisanal fleets were not available.

The social index (job/catch value) was taken from SEMARNAP (2000) for Campeche, and has the following values: for shrimp 0.5, Art DEM HL 1.7, Art PEL 1.7, and Art beach seine and octopus 2.0. For the ecological criterion, we used the inverse of the P/B ratio, per group, as a measure of their potential growth/recovery. For the shrimp-recovering criterion, we tested several weighting factors and finally used a value of 6 with respect to other criteria, and a value of 1 for the shrimp group. Weighting factors on different criteria are used to explore potentially realistic scenarios. Testing different values yield different suggestions to control fleets operations. Values are given until realistic outputs resulted and we can select those which are closely related with our goals for management.

Following Christensen et al. (2000) optimization under the above conditions is defined here as an open

Table 2
Costs related to the operation of different fleets on the southern Gulf of Mexico

Fleet	Fixed costs (%)	Effort-related costs (%)	Sailing-related costs (%)	Profit (%)
Shrimp	10	40	30	20
Art DEM HL	5	10	30	55
Art PEL	5	35	20	40
Art beach seine	5	30	0	65
Octopus	5	5	40	50

loop simulation (OLS), which is a formal optimization method to search temporal patterns of fishing rates that maximize particular performance measures for management. It is a nonlinear optimization procedure known as a Davidson–Fletcher–Powell method (see the website: www.ecopath.org) designed to perform optimization by changing fishing rates during iterations. The results provide general guidance on the direction in which the system is moving.

A closed loop simulation (CLS) was also used; this framework for simulations assume density-dependent catchability. CLS allows evaluation of management based on the control of relative fishing effort by fleet type. For this we considered a maximum annual increase in catchability of 0.1 for the shrimp fleet, and 0.05 for the artisanal fleets. These values were used to calculate changes in fishing power over time. The relative efficiency of fleets on trophic groups was assigned by giving a weighting factor of 3 to the artisanal fleets. The weighting factor represents the importance of species-specific fishing rates and directly affects catchability coefficients. CLS also considers uncertainty in the biomass of groups, here assigned as CV = 20% for all groups, and outputs can be referred to some biological reference point (BRP), here assigned a limit of BRP = 0.5, representing 50% of the original biomass, i.e. no group will decrease below this level during simulations.

Simulations were developed for period of 30 years. Once optimization of a given criterion was made, the resulting ecosystem structure was used to compute ecosystem attributes. From the analysis of such

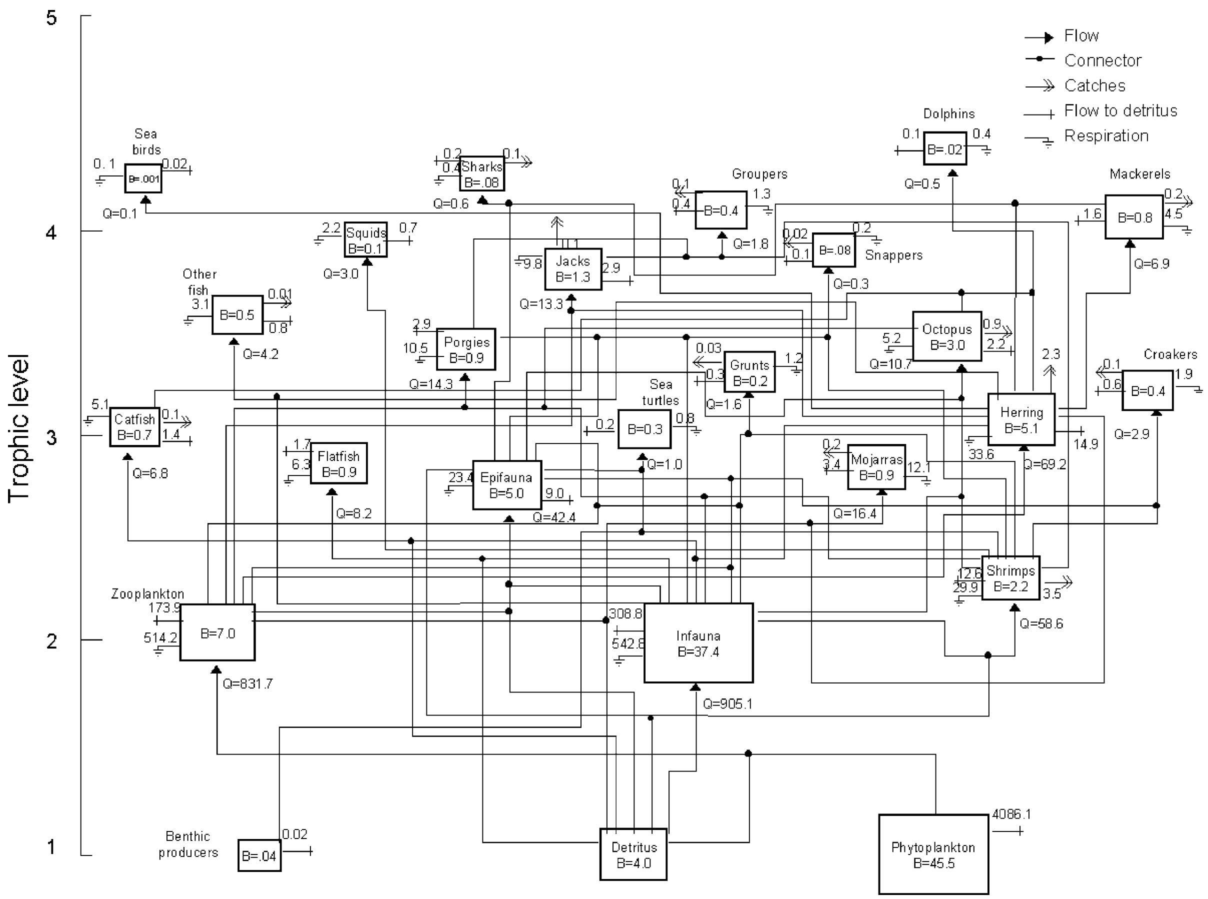

Fig. 2. Flow diagram of the southwestern Gulf of Mexico ecosystem. Biomass is given in $g\,m^{-2}$ and rates as $g\,m^{-2}$ per year. Flows contributing more than 15% to diets are shown.

attributes, we discuss the impact of harvesting strategies on the ecosystem.

3. Results

Flows of biomass for the improved ecosystem model can be observed in Fig. 2. Simulated shrimp biomass fits reasonably well with independent data on relative biomass and fishing patterns, with exception of the last few years. According to Ramírez-Rodríguez et al. (2000), changes in salinity explain more than 50% of the stock variation. When salinity was included as forcing factor, the simulated shrimp biomass more closely matched the observed biomass during the last few years (Fig. 3). Ecosystem parameters from the Ecopath model were taken as a baseline to compare the impact of harvesting strategies on the ecosystem, assuming as significant those changes higher than 5%. Additionally, two scenarios, CLS without optimization and the inclusion of time-series data, were also compared in order to separate specific effects of harvesting strategies.

Ecosystem characteristics resulting from the harvesting strategies are shown in Table 3. Significant differences were observed in gross efficiency, total catch, market values and costs, as derived from catch structure. An interesting aspect was the increase in mean trophic level of the catch when applying the ecological and shrimp-recovery criteria.

Harvesting strategies did not significantly affect ascendency. However, overhead associated with export in the social criterion scenario; and internal flow, associated with capacity in the shrimp-recovery scenario, were significantly affected (Table 4).

Trophic structure, in terms of biomass at each trophic level, showed significant change when applying the ecological and social criteria. The catch structure at all trophic levels was affected in all the scenarios (Table 5).

Transfer efficiencies (Table 6), cycling (i.e. Finn's index) and path length (Table 7) were not significantly altered; but primary production required (PPR) to sustain catch was significantly affected in all scenarios (Table 8).

4. Discussion

The observed changes in ecosystem structure during harvesting strategy simulations are associated with removal of biomass by fishing. The impact at different trophic levels (Table 5) results from differences in the use of the resources. For example, economic and social optimization favors higher priced species. Catches of low trophic-level groups, where shrimp is the

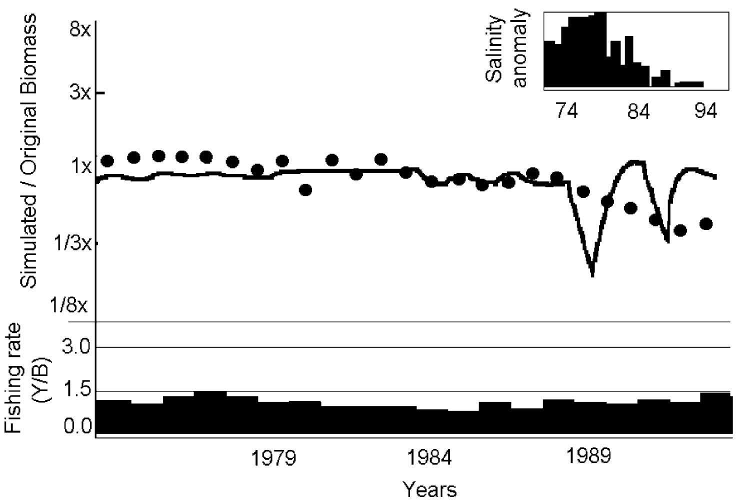

Fig. 3. Fitting Ecosim-simulated (line) vs. VPA-independent (dots) biomasses for the shrimp fishery in the southwestern Gulf of Mexico. Bars on the bottom represent fishing mortality. Salinity pattern, expressed as anomaly (top right), was used as forcing factor.

Table 3
Ecosystem statistics for Ecopath and harvesting strategies

Parameter	Ecopath	Ecopath CL	Ecopath TS	$JE	MR	$	E	J
Sum of all consumption	1999.60	2000.35	1994.50	1990.22	2020.75	1984.20	1997.32	1979.55
Sum of all exports	3460.13	3459.07	3463.73	3475.57	3445.43	3485.50	3468.86	3496.22
Sum of all respiratory flows	1208.58	1209.20	1204.40	1198.58	1220.44	1194.41	1203.84	1189.60
Sum of all flows into detritus	4624.70	4624.41	4625.31	4630.61	4624.75	4635.26	4631.05	4641.08
Total system throughput	11293.00	11293.00	11288.00	11295.00	11311.00	11299.00	11301.00	11306.00
Sum of all production	5057.00	5057.00	5055.00	5058.00	5060.00	5058.00	5060.00	5059.00
Mean trophic level of the catch	2.82	2.85	2.82	2.89	**3.24**	2.89	**3.59**	2.91
Gross efficiency (catch/net primary production)	0.00162	0.00155	0.00161	**0.00251**	(**0.00123**)	**0.00365**	**0.00208**	**0.00429**
Calculated total net primary production	4668.70	4668.70	4666.87	(4666.9)	4666.87	(4,666.9)	(4666.9)	(4666.9)
Total primary production/total respiration	3.86	3.86	3.88	3.89	3.82	3.91	3.88	3.92
Net system production	3460.13	3459.50	3462.47	3,468.28	3446.42	3472.46	3,463.02	3477.27
Total primary production/total biomass	41.40	41.39	41.43	41.61	41.01	41.79	41.64	41.98
Total biomass/total throughput	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total biomass (excluding detritus)	112.76	112.80	112.66	(112.16)	113.806	(111.68)	(112.07)	(111.16)
Total catches	7.56	7.22	7.50	**11.73**	**5.73**	**17.04**	**9.72**	**20.00**
Connectance index	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
System omnivory index	0.17	0.17	0.17	(0.17)	0.17	0.17	(0.16)	0.17
Total market value	191.82	**171.94**	189.14	**344.73**	**30.13**	**334.56**	**(90.70)**	**409.50**
Total shadow value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total value	191.82	**171.94**	189.14	**344.73**	**30.13**	**334.56**	**(90.70)**	**409.50**
Total fixed cost	9.13	**8.14**	8.99	**15.75**	**0.76**	**15.40**	**(2.31)**	**18.54**
Total variable cost	90.46	**80.60**	89.11	**153.43**	**5.70**	**149.70**	**(20.62)**	**179.12**
Total cost	99.59	**88.74**	98.11	**169.18**	**6.45**	**165.10**	**(22.93)**	**197.66**
Profit	92.23	**83.20**	91.03	**175.56**	**23.68**	**169.46**	**(67.77)**	**211.84**

$: optimizing economic yield; E: optimizing the ecological criterion; J: optimizing the social criterion; $JE: optimizing multiple criteria. CL: close loop simulation without optimization; TS: including time series. Biomass is in $\mathrm{g\,m^{-2}}$, and flows $\mathrm{g\,m^{-2}}$ per year. Numbers in parenthesis indicate negative impact. Bold numbers show impact greater than 5% of Ecopath value.

Table 4
Ascendency and related statistics computed for harvesting strategies in the southwestern Gulf of Mexico

Scenario	Ascendency	Overhead	Capacity
Ecopath			
Internal flow	6361.0	12750.0	19111.0
Export	4415.3	1583.0	5998.3
Respiration	3022.6	3096.0	6118.6
Totals	13798.9	17429.1	31228.0
Ecopath CL			
Internal flow	6362.7	12752.1	19114.8
Export	4415.5	1579.2	5994.7
Respiration	3023.4	3100.4	6123.8
Totals	13801.6	17431.7	31233.3
Ecopath TS			
Internal flow	6356.9	12749.1	19106.0
Export	4417.1	1579.3	5996.5
Respiration	3015.9	3092.2	6108.1
Totals	13789.9	17420.6	31210.5
$JE			
Internal flow	6349.3	12773.7	19123.0
Export	4426.6	1615.6	6042.2
Respiration	3011.6	3037.2	6048.8
Totals	13787.5	17426.5	31213.9
MR			
Internal flow	6397.0	12954.5	**13351.8**
Export	4415.9	1565.7	5981.7
Respiration	3036.8	3191.2	6228.0
Totals	13849.8	17711.5	31561.3
$			
Internal flow	6318.5	12799.3	19117.8
Export	4411.3	1691.7	6103.0
Respiration	3006.1	2996.8	6003.0
Totals	13735.9	17487.9	31223.8
E			
Internal flow	6358.5	12828.6	19187.1
Export	4438.9	1586.2	6025.1
Respiration	3022.7	3053.2	6078.9
Totals	13820.1	17467.9	31291.0
J			
Internal flow	6309.1	12823.5	19132.6
Export	4419.2	**1717.5**	6136.6
Respiration	3010.1	2936.2	5964.2
Totals	13738.4	17477.2	31233.5

Units are in flowbits. Bold numbers indicate significant change.

highest priced species, increase, while catches of high trophic-level groups decrease. The opposite occurs using the ecological criterion: increased catches of high trophic-level groups and reduced catches of lower level groups. Optimization of social and economic criteria results in high yields; the shrimp-recovery criterion results in the lowest yields.

These results are realistic. Economic and social criteria are directly connected with catch value, and the high value of shrimp implies low relative costs, while relative low-value species caught by artisanal fleets are associated with low operational costs. Note that depletion of the shrimp stock during the last years of the simulation implies important changes in the use of fish resources of different trophic levels over that period in order to maintain a stable ecosystem structure.

In the shrimp-recovery strategy, the control of the stocks was attempted by managing fishing effort, despite the affects of salinity changes in the area. This implies a reduction of fishing mortality on shrimp, and a combination of reduced and increased fishing mortality by the different artisanal fleets, in order to remove predators and competitors. Initially, the combination of weighting factors resulted in illogical options, e.g. increasing fishing effort on octopus by a factor of eight, and depletion of other stocks. We attempted several combinations of weighting factors (within criteria and groups) to select a plausible combination that resulted in more logical patterns of fishing activity, tending to avoid depletions for any group (Fig. 4). These combinations imply changes of internal flows and are the reason for the significant difference between the internal flow values of the shrimp-recovery strategy and those of the base Ecopath model (Table 4). The shrimp-recovery strategy produces an increase in shrimp biomass over the last years of simulation, despite the stress imposed by the forcing factor.

Significant changes in catches (±5% of initial value) at all trophic levels occurred only under the economic and social criteria, being negative for higher trophic levels in both cases. The optimization of multiple criteria (economic, social and ecological) produces a significant reduction in biomass of top predators, but increments in catch at all trophic levels. The shrimp-recovery strategy shows significant changes in catches for almost all trophic levels, being negative for $TL = 2$ and $TL = 6$ and positive for $TL = 3$ and $TL = 4$. However, the sum of all catches was negative.

Table 5
Distribution of biomass (top) and catch (bottom) at discrete trophic levels for the ecosystem in the southwestern Gulf of Mexico, for different harvesting strategies

Trophic level	Ecopath	Ecopath CL	Ecopath TS	$JE	MR	$	E	J
VII	0.001	0.001	0.001	0.001	0.001	0.001	0	0.001
VI	0.015	**0.014**	**0.014**	**0.014**	**0.014**	0.015	0.008	0.014
V	0.256	0.255	0.255	(**0.249**)	0.271	0.255	(**0.196**)	(**0.248**)
IV	4.155	4.152	4.159	3.988	4.182	4.008	(**3.501**)	3.859
III	14.923	14.936	14.923	14.751	15.297	14.247	(**14.842**)	(**14.002**)
II	47.874	47.9	47.766	47.613	48.496	47.611	47.983	(**47.493**)
I	45.539	45.539	45.539	45.539	45.539	45.539	45.539	45.539
Sum	112.763	112.797	112.657	112.155	113.800	111.676	112.069	111.156
VII	0.00	0.00	0.00	0.00	0.00	0.00	0.001	0.00
VI	0.004	0.004	0.004	**0.005**	(**0.003**)	(**0.001**)	**0.017**	(**0.002**)
V	0.049	0.049	0.049	**0.076**	0.049	(**0.039**)	**0.204**	**0.056**
IV	0.799	0.807	0.8	**2.437**	**1.193**	**1.74**	**5.22**	**2.591**
III	4.206	4.127	4.184	**5.097**	**4.420**	**11.063**	4.048	**12.394**
II	2.502	2.229	2.465	**4.112**	(**0.131**)	**4.196**	(**0.231**)	**4.955**
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	7.56	7.216	7.502	**11.727**	(**5.796**)	**17.039**	**9.721**	**19.998**

For meaning of symbols, see Table 1. Units are in $g\,m^{-2}$.

Table 6
Changes in mean transfer efficiency (%) for different harvesting strategies in the southwestern Gulf of Mexico ecosystem

	Ecopath	Ecopath CL	Ecopath TS	$JE	MR	$	E	J
From PP	12.8	12.9	12.8	13.8	13.4	13.5	16.7	13.9
From D	12.3	12.3	12.3	14.4	12.9	14.3	14.9	15.1
Total	12.5	12.5	12.5	14.1	13.1	14.1	14.5	14.8

PP: primary production; D: detritus.

The changes above are consequences of the changes in fleets operation that resulted from each scenario, and are shown in Fig. 5 as the mean trophic level of the ecosystem (MTLE) and catch (MTLC), as well as the fishing-in-balance index (FIB). The ecological criterion exhibits a clearly different pattern from the economic, social and multiple criteria, which follow similar patterns. The economic criterion (and social as consequence) always produces the largest changes because this scenario resulted in highest

Table 7
Complexity attributes of the southwesterm Gulf of Mexico ecosystem for different scenarios of harvesting strategies

Parameter	Ecopath	Ecopath CL	Ecopath TS	$JE	MR	$	E	J
Throughput cycled (excluding detritus)	42.03	42.03	41.64	41.64	41.64	41.64	41.63	41.64
Predatory cycling index	2.06	2.06	2.04	2.05	2.02	2.05	2.04	2.06
Throughput cycled (including detritus)	8.30	8.30	8.23	8.18	8.21	8.17	8.20	8.14
Finn’s cycling index	4.49	4.48	4.48	4.51	4.48	4.51	4.49	4.53
Finn’s mean path length	2.42	2.42	2.42	2.42	2.42	2.41	2.42	2.41
Finn’s straight-through path length	1.65	1.65	1.65	1.65	1.65	1.64	1.65	1.64
Finn’s straight-through path length	2.31	2.31	2.31	2.31	2.32	2.31	2.31	2.30

Table 8
PPR to sustain fisheries on the ecosystem of the southwestern Gulf of Mexico

Scenarios	No. of paths	TL	PPR	Catch	PPR/catch	PPR/total PP (%)
Ecopath	42050	2.82	300.32	7.56	39.72	6.43
Ecopath CL	42050	2.85	302.59	7.22	**41.94**	6.48
Ecopath TS	42050	2.82	297.72	7.5	39.68	6.38
$JE	42050	2.89	(**282.37**)	**11.73**	(**24.08**)	(**6.05**)
MR	42050	**3.24**	**285.12**	**5.80**	**49.18**	**6.11**
$	42050	2.89	(**231.78**)	**17.04**	(**13.6**)	(**4.97**)
E	42050	3.59	**4250.64**	**9.72**	**437.29**	**91.08**
J	42050	2.91	**502.74**	**20.0**	(**25.14**)	**10.77**

TL: trophic level. Other symbols as in Table 1.

catches impacting net rent. In the shrimp-recovery strategy, MTLC increase slowly with time, while MTLE remains almost constant except for the last years when shrimp biomass decreases, probably in relation to the stress imposed by the forcing factor. The FIB index tends to increase over time, because the shrimp-recovery strategies make use of higher trophic-level resources and involve reduction in exploitation of lower level species including shrimp.

As suggested by Pauly et al. (1998, 2000), MTLC, MTLE and the FIB index reflect changes in ecosystem structure. Under the ecological criterion in Fig. 5, there is a reduction in the biomass of higher trophic-level groups (Table 5), which is the reason for low values of

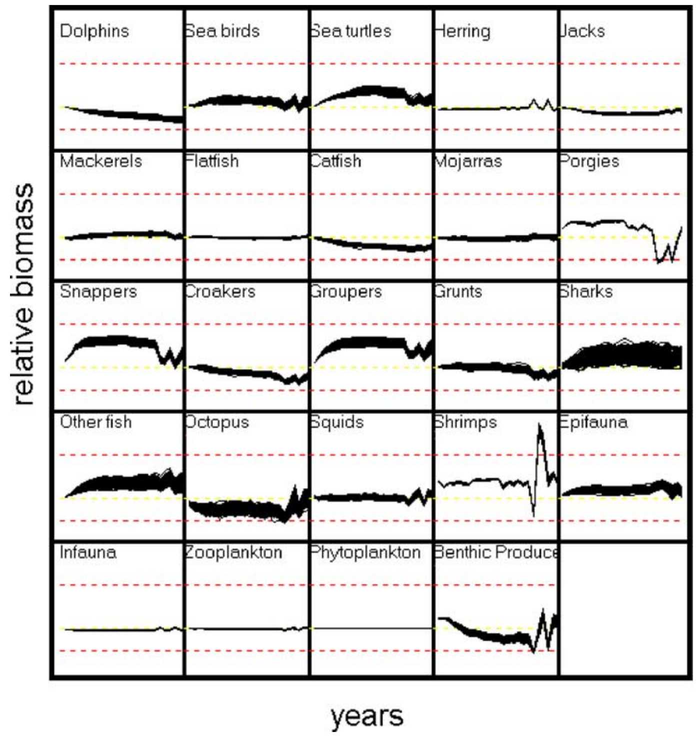

Fig. 4. Output of the CLS, showing the impact of the shrimp-recovery strategy on the ecosystem groups. *X*-axis represent simulated time, and *Y*-axis the relative biomass size. The density of black lines represents uncertainty in each group. Dotted lines represent 0.5 and 2 times the current biomass as BRPs. The risk of falling below 0.5 (lower dotted line) of the original biomass for any group is limited to 40% for porgies, which, however, recover at the end of the simulated time period.

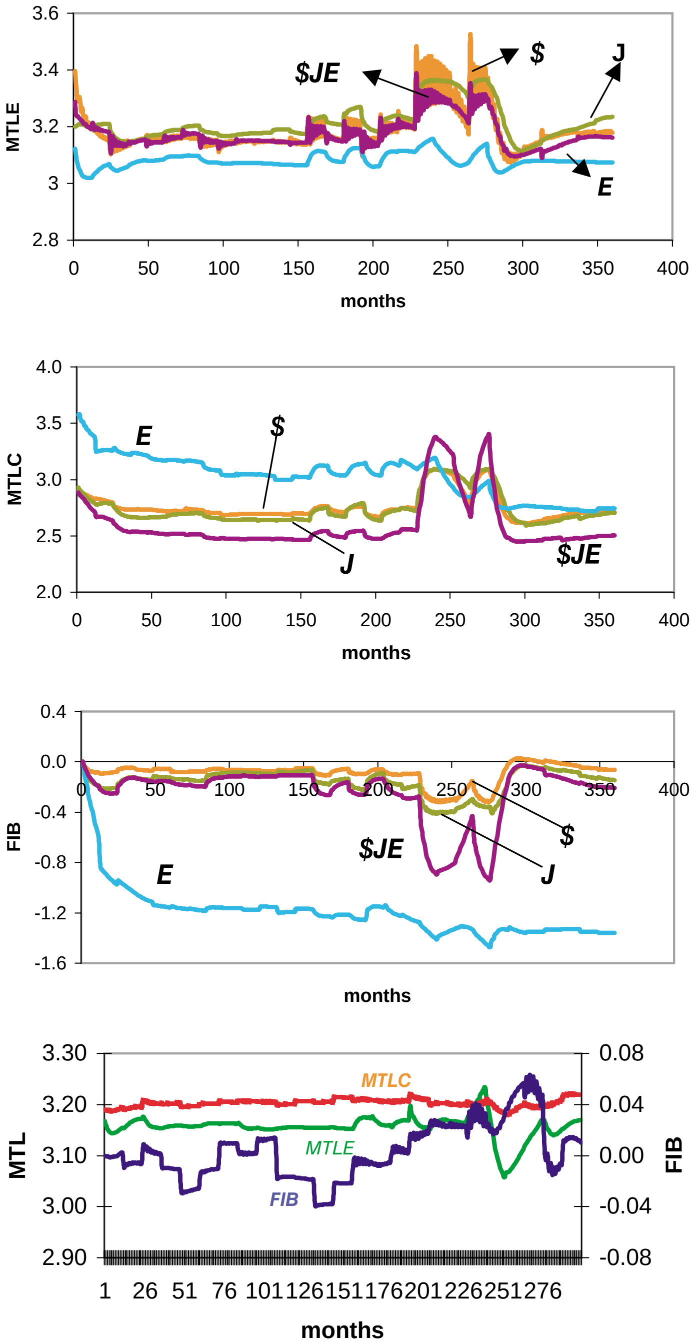

Fig. 5. Mean trophic level of the ecosystem (MTLE) and catch (MTLC), and FIB showing the effect of different harvesting strategies on the ecosystem of the southwestern Gulf of Mexico. J: social index; E: ecological criterion, $: economic index, and $JE represents multiple-criteria optimization.

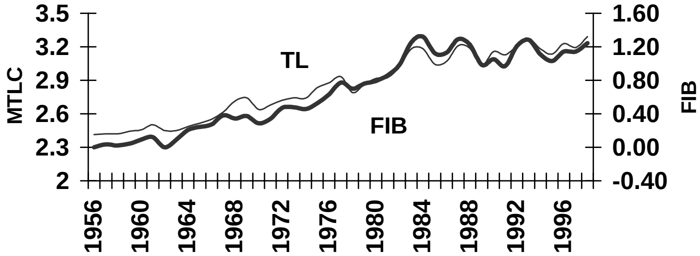

Fig. 6. Mean trophic level of catch (MTLC), and FIB for the continental shelf in the southern Gulf of Mexico, computed on the base of historical records of catch.

MTLE compared with those for other strategies, and the lower and declining tendency for MTLC and the FIB index.

MTLC and FIB indexes were also computed for historical catch data for fisheries off Campeche (Fig. 6). Both tend to increase as a consequence of low catches of shrimp in the last two decades, when fishers were obliged to switch to other species. The next priority groups in economic value in the area are octopus, the fishery for which has very low operating costs, red snapper and red grouper; all are active predators. Positive slopes for MTLC and FIB indexes derived from historical catch records, as also occur in some simulated strategies, indicate a fishing-up-the-food-web process from low trophic-level shrimp to higher trophic-level predators.

PPR to sustain catches (Pauly and Christensen, 1995) shows significant changes for all scenarios (Table 8). PPR under the ecological and social criteria shows an increase. For the ecological criterion, PPR increases by an order of magnitude, with the result that, under this scenario, fishing requires 91.1% of the total primary production of the system. This indicates the high ecosystem cost, in terms of energy (expressed by PPR/catch) in order to maintain the ecosystem structure. The social criterion scenario is associated with a PPR increase of 10.8%. Other scenarios involve a reduction of PPR to sustain catches of different energetic cost, a relatively large reduction under the shrimp-recovery criterion and a relative small one under the economic criterion.

We can conclude that depletion of shrimp stock in the southern Gulf of Mexico has caused an impact in the structural attributes of the ecosystem. Forcing factors appears to play an important role causing an environmental stress on shrimp stock but despite this situation management based on fleet control appears to support the recovery for the shrimp stock.

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