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A Multi-Criteria Non-Linear Optimization Model for the Control and Management of a Tropical Fishery

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Abstract *One of the principal problems when dealing with fishery resource management is to estimate strategies that satisfy biological, economic and social objectives simultaneously. As a contribution to solving this problem in the Yucatán Shelf Octopus (Octopus maya) fishery, a multi-criteria non-linear optimization procedure was applied to a dynamic bioeconomic model of the fishery. The procedure coped simultaneously with non linearities and system stochasticity. The min-max optimization, iteratively minimized the difference between the manager's objectives and model output values for the bioeconomic variables in a Pareto-optimal way. Results showed that it was possible to achieve explicit managerial objectives under different scenarios, such as those that simulate the normal 1988 fishing season, the impact of natural phenomena (hurricane Gilbert) and the reaction to such phenomena. Implications of the results are discussed.*

Keywords Fishery management, management objectives, multi-criteria non-linear optimization, tropical fishery, octopus, Yucatán, optimal control.

Introduction

Sound fisheries management should take into account biological, economic and social factors in the decision making process. Fishery biology has always provided important input to management but other types of information are now required to develop sensible policies. Making effective use of additional types of information requires more complex models. Studies by Ervik *et al.* (1981), Hansen (1981) and Allen and McGlade (1986) have begun to explore the possibilities for comprehensive management models. Simulation models have played an important role in understanding the effect of different management strategies on the fishery system components (Grant *et al.*, 1981; Richardson and Gates, 1986; Seijo, 1986; Seijo *et al.*, 1987). Good strategies subjected to realistic constraints can be framed as an optimization problem. When systems are dynamic, with multiple input-outputs, stochasticity or with time delays, the appropriate tool for optimal strategy exploration, formulation and comparison is optimal control theory (Holling, 1978; Hilborn, 1979; Goh, 1979, 1980; Cohen, 1987).

Most of the work developed with the optimization approach has been applied to fisheries in temperate waters, using a single variable as a performance index incorporating a linear cost function or associated functional constraints (Hilborn *et al.*, 1976; Garrod and Shepherd, 1981; Overholtz, 1985; Huppert and Squires, 1986). The assumption that natural phenomena are linear has been criticized by Bojorquez (1982). Shepherd and Garrod (1980) have also pointed out the inherent risks involved in the use of these procedures. Multi-criteria (Drynan and Sandiford, 1985) and/or non-linear optimization models (Agnew, 1979; Shepherd and Garrod, 1980; Kennedy and Watkins, 1986) have seldom been used in fishery management.

The central theme of this paper is to present, as a case study, the estimation of optimal management strategies in a tropical fishery (the Yucatán shelf octopus fishery) that fulfill pre-existing resource-manager preferences for different management scenarios. The approach utilized, combines multi-criteria and non-linear optimization of a comprehensive fishery simulation model in a Pareto-optimal manner. The procedure allowed to work with multiple input-outputs, uncertainties, time delays, non-linear functions and the natural trade-offs during the estimation process. It has been shown to be a useful decision-making aid, when explicit manager objectives are available.

*The Yucatán Shelf Octopus (*Octopus maya*) Fishery*

The fishery for this short-lived species began in 1970 in the Yucatán shelf (Figure 1), following a decrease of the traditional fishable stocks in the Campeche coast. In 1987, it was the second most important fishery in the Yucatán state (after the red grouper) reporting annual catches of 6169 tonnes from 9 ports, selling most of it frozen to the domestic market.

Two types of vessels, artisanal and industrial, exploit the octopus stocks using the line-drift fishing method. The artisanal fleet is composed of wooden and fibreglass crafts with outboard motors. They are of relatively small size (24′ long) carrying one or two small canoes. These vessels undertake their daily fishing trips in the coastal shallow waters where the juvenile component of the stock is to be found.

The industrial fleet began fishing for octopus in 1982. Due to their greater size (40-75′ long, carrying 4 to 8 canoes), their much greater endurance and capacity, enable them to remain in the deeper fishing grounds for one or two weeks.

The fishing season officially starts on the first of August coinciding with the inshore reproductive migration. By mid-August most of the artisanal fleet has entered the fishery. At the end of August and the beginning of September, when the species has achieved a larger and more profitable size, the industrial fleet starts to target on octopus. The season last for 4.5 months ending normally by the 15th of December.

In 1988, hurricane Gilbert hit the Yucatán Peninsula causing severe damage to the fishing fleets and associated facilities (Figure 1).

The Management System

The fishery is a sequential fishery that exhibits common property resource characteristics involving externalities generated among the different resource users

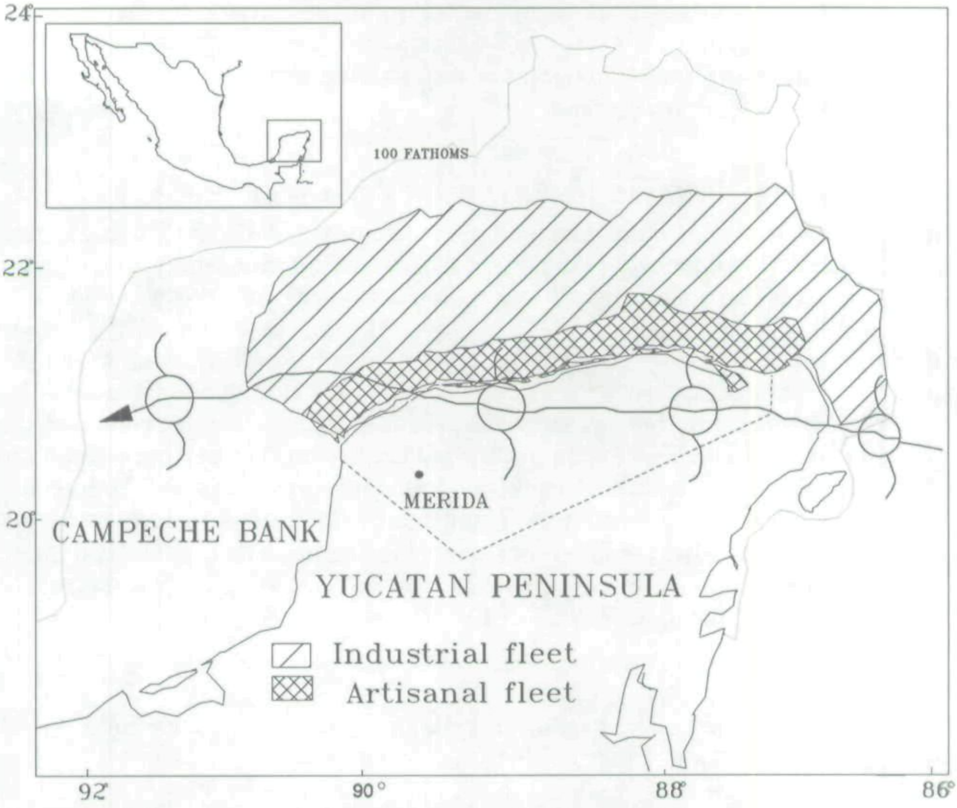

Figure 1. Yucatán major fishing grounds and Hurricane Gilbert trajectory.

(artisanal and industrial fleets). In Yucatán, as in all the Mexican states, fisheries management is a federal matter. In every state the Fisheries Ministry appoints their representative. He/she is the head of the state office and the decision-maker in fishery regulation matters.

In this case, the fishery has been regulated during the last years by means of a static closed season from the 16th of December to the 31st of July of the following year, a minimum size regulation of 110 mm mantle length, and the prohibition of specific fishing methods (commercial diving and any kind of hooks). There is a strong evidence that the minimum size regulation is not adhered to and that the resource is overexploited (Arreguín-Sanchez *et al.* 1987). It has been pointed out that rapidly increasing fishing effort may exhaust this short-lived species and consequently, eliminate its economic rent (Walter 1986).

The Interaction with the Fishery Manager

Several factors made the interaction between the fishery manager and the authors possible: (1) the need to know the impact of a large credit project for fostering labour mobility from agriculture to fisheries, (2) the devastating effect of the hurricane on the regional coastal economy, (3) the existing evidence of resource overexploitation and, (4) the possibility of exploring the impact of optimal policies on key fishery variables leading to the adoption of a dynamic management scheme.

As a result of this interaction, the manager stated explicitly his management objectives for the scenarios derived.

Fishery Scenarios, Management Instruments and Performance Variables

Three fishery scenarios were specified after discussions with the fisheries manager. Scenario (1) assumes a 1988 normal fishing season. Scenario (2) recognizes the existence of hurricane Gilbert and its impact on the fishery. Scenario (3) is almost the same as the latter, but considers a 15 day extension in the fishing season after the hurricane has passed (30th December 1988). In all cases the scenarios were specified under the actual catch composition condition.

Three management controls were selected: the sizes of the artisanal and the industrial fleets and the starting time of the fishing season. The performance of the fishery system was evaluated using the following criteria: standing biomass (tonnes), cumulative total catch (tonnes), catch by fleet (tonnes), cumulative net economic revenue by fleet (millions of pesos), direct employment generated (numbers) and fishery contribution to cumulative coastal food availability (tonnes). All variables were evaluated at the end of the season.

Research Methods

The estimation of optimal management strategies in the octopus (*Octopus maya*) fishery, which fulfill the fishery manager's stated preferences on some bioeconomic variables, can be formulated as an optimal control problem. Its solution was found building a general conceptual model, which is composed of three blocks. The first is the fishery model, the second is the block in which the multicriteria objective function is generated and the third is the optimizing block that deals with the objective function, generating the optimal fishery management strategies (Figure 2).

Fishery Model

The fishery model used was the one developed by Seijo *et al.* (1987). It is a holistic bioeconomic model designed using the system simulation approach. It is a dynamic model representing the spawning, hatching, and recruitment processes and their stochasticity, as well as the fleet entrance to the fishery (both artisanal and industrial) using the distributed delay method. The population structure is modelled using a cohort survivorship model. It includes stochastic production functions for each vessel type. Based on the estimated population structure for the end of the previous season, the model simulates the dynamics of the fishery presenting results every fortnight from the 1st January until the 15th December of the following year. It allows to assess the possible impacts of different management policies on several bioeconomic variables.

Data Collection and Model Updating

The simulation model was updated to take into account the prevailing conditions in 1988. This was done with weekly octopus samples (4770 individuals) of nine

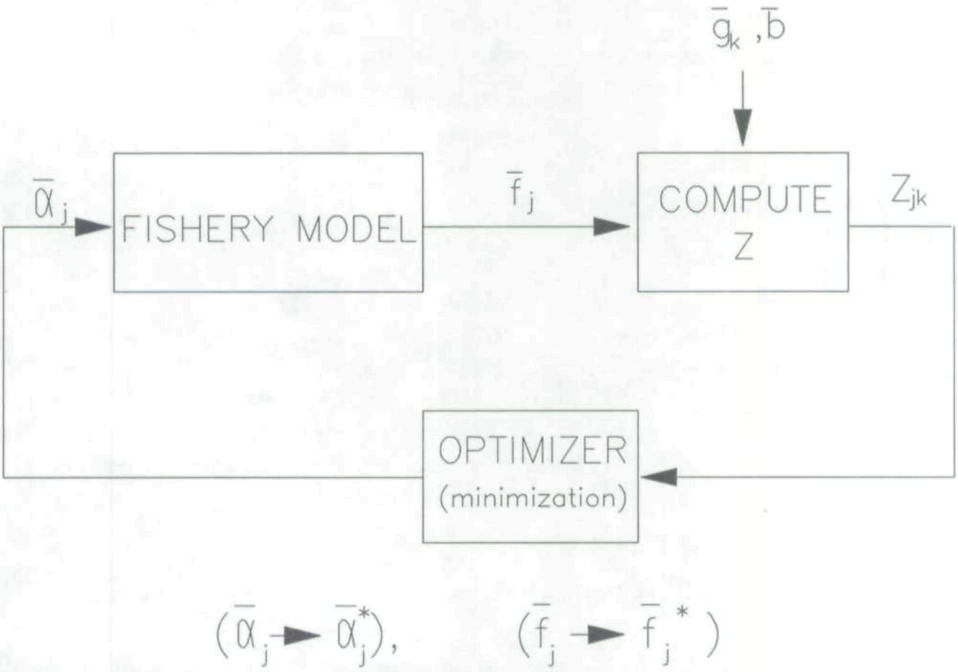

Figure 2. Conceptual model block diagram. (Adapted from Manetsch, 1985.)

ports of the Peninsula of Yucatán during the 1987 season. Catch statistics and fleet information were collected from the Delegación Federal de Pesca de Yucatán. Length cohort analysis (Jones, 1984) was used to estimate abundance and population structure at the end of 1987. The natural and fishing mortality data used were those reported by Solís-Ramírez and Chávez (1986). The fecundity, was the reported by Seijo *et al.* (1987).

At the start of the 1988 octopus fishing season, 2377 fishing boats and ships were registered at the Fisheries office. Of these, 86.2% (2050) belonged to the artisanal fleet and the rest to the industrial fleet.

After Hurricane Gilbert passed (September 15), the artisanal and the industrial fleets were reduced by 37% and 27% respectively.

It was estimated that 1587 artisanal boats and 225 industrial ships were available to start fishing for octopus before the hurricane. Afterwards (21st September), 1002 boats and 163 ships remained. With the above information, the optimization scenarios, management strategies, and associated restriction were identified (Table 1). After updating, adapting and running the model to simulate the selected scenarios, the base-run values were presented to the fishery manager. Based on these runs, the resource manager defined his objectives for each of the scenarios.

The Objective Function and its Treatment

Since more than one relevant criteria is necessary to evaluate the performance of the fishery, the optimization process is inherently complex. Added to this, the fishery manager needs to deal with trade-offs between conflicting and competitive

Table 1
Scenarios, Management Strategies and Associated Functional Constraints

Management Strategy	Scenario 1 Normal Season	Scenario 2 After Hurricane	Scenario 3 Extended Season
Size of Artisanal Fleet (No)			
*Base	1587	1002	1002
*Lower bound	1270	802	802
*Upper bound	1904	1202	1202
Size of Industrial Fleet (No)			
*Base	225	163	163
*Lower bound	180	130	130
*Upper bound	270	196	196
Start of the season (Month)[1]			
*Base	7	8.7	8.7
*Lower bound	6	8.7	8.7
*Upper bound	9	10	10

[1] Month 7 correspond to 31st of July.

criteria (biomass, yield, revenues, employment, *etc*) producing contradictions between the system performance and the costs of keeping it at any desired levels.

In this situation, Pareto-optimal solutions are helpful in finding the best possible trade-offs for the multi-criteria decision problem. The Pareto-optimal concept has been utilized by Hanesson (1978) and Mendelssohn (1979) in fisheries and Randall (1981) in resource economics. Since the "min-max" optimization strategy (Osyczka, 1984) converges to Pareto-optimal solutions, it was selected for this application.

Manetsch (1985) states that if a model M of a system exists, such that:

$$\bar{f}_j\,(T) = M\,(\bar{\alpha}_j, T) \tag{1}$$

where $\bar{f}_j\,(T) \in E^m$ is the vector of criterion-function values corresponding to the j-th strategy option (evaluated over the time horizon (0,T), $\bar{\alpha}_j\,(T) \in E^n$ is the decision or control parameter vector related to the j-th strategy ($j = 1,2 \ldots, J$), and (0,T) is the decision time horizon of interest.

It is possible to couple the "min-max" optimization strategy, to the latter model where:

$$Z_{jk} = \mathrm{MIN}[\mathrm{MAX}_i(Z_{ijk})] \tag{2}$$

such that

$$Z_{ijk} = \frac{(g_{ik} - f_{ij})}{|b_i|\ \mathrm{sgn}\ (g_{ik} - b_i)} \tag{3}$$

where:

g_{ik} is the goal for the i-th criterion for the k-th goal set.

f_{ij} is the i-th criterion value for the j-th strategy.

b_i is the base run value of the i-th criterion variable.

The problem consists of estimating $\overline{\alpha}_j^*$, which is an optimal control parameter vector that results when finding the "min-max" optimum Z_{jk}^* and $\bar{f}_j^*$. The variable Z_{ijk} is the normalized deviate of the i-th model criterion value from the i-th goal for strategy j and goal set k. The sgn () function changes the sign of Z_{ijk} for those goals which are less than the "base" values. This is how Z_{ijk} values related to different variables, different strategies and different goal sets can be compared.

The iterative procedure finds the largest deviation and minimizes it, operating on all criteria until no significant improvement can be made in the one with the largest goal deviation. The result is an optimal parameter vector. For this reason the "min-max" method tends to find Pareto-optimal solutions to the multi-criteria optimization problem.

The problem with the approach is the possibility of obtaining multiple solutions, some Pareto inferior to others. To cope with this, it was necessary to use a search procedure in an attempt to find a global optimal solution. This was achieved using the "Complex" method.

The Complex and the Search for Optimal Solutions

This method was developed by Box (1965) and applied in an enhanced manner to multi-criteria problems by Manetsch (1985, 1986). Its purpose is to find the maximum or minimum of a non-linear multivariate function subject to non-linear inequality constraints.

$$\text{Max } F(X_1, X_2, X_3, \ldots, X_n) \tag{4}$$

subject to

$$G_i \leq X_i \leq H_i \quad \text{for } i = 1,2, \ldots n \ldots, k. \tag{5}$$

The implicit variables $X_{n+1}, \ldots, X_k$ are dependent functions of the independent explicit variables $X_1, X_2, \ldots, X_n$, and the superior and inferior restrictions H_i and G_i could be either constants or independent variable functions.

The method is a sequential search technique that attempts to find global optimal solutions (minima or maxima) since the initial set of points are randomly scattered within the feasible region. Each of these sets of values corresponds to a vertex of a geometrical figure or "complex" generated in the n-dimension searching space.

Associated with each vertex is a function value (calculated from the simulation model). The procedure converges towards the global optima, shrinking the search around that point (Manetsch 1985).

The problem was solved using the M-OPTSIM system (Manetsch 1986) run on a personal computer. The solution was reached in the optimization module, calling the simulation model and the "min-max" strategy as subroutines.

Results

Objectives and Preferences of the Fishery Manager

This study allowed to obtain explicit management objectives from the Yucatán fisheries manager (Table 2). In the first scenario (1988 normal fishing season), the target was to increase the biomass escapement from 2298 to 4000 tonnes. The resource manager accepted a proportional reduction in most of the remaining variables. After hurricane Gilbert (second scenario), due to the effects on the fleets and yields, the decision-maker wanted to increase the yield and the rest of the variable values, diminishing the biomass escapement if necessary (from 5626 to 5200 tonnes). In the third scenario, the resource manager wanted to explore the possibility of extending the fishing season to compensate fisherman for their delayed entry to the fishery.

Optimization Results

Scenario 1: 1988 Normal Fishing Season

The optimal management strategies that direct the fishery towards the desired targets are achieved by decreasing the size of fleets and allowing entry to the fishery after the first week of August (Table 3). Optimization results are near target values in 6 of the 8 bioeconomic variables. The two where this is not the case are industrial fleet catch and artisanal net revenues (Table 4).

Table 2

Resource Management Objectives for Different Management Scenarios

Variable[1]	Base[2] Run	Scenario 1	Scenario 2	Scenario 3
Biomass (tonnes)	2998	4000	5200	4200
Total yield (tonnes)	8787	8000	3500	4500
Yield of artisanal fleet (tonnes)	4866	4000	1700	2250
Yield of industrial fleet (tonnes)	3921	4000	1800	2250
Profits: Artisanal fleet ($ 10^6 pesos)	288	200	80	40
Profits: industrial fleet ($ 10^6 pesos)	369	200	230	310
Direct employment (No.)	6331	5500	4300	4500
Food for domestic market (tonnes)	699	500	300	350

[1] All the variable values are at the end of the fishing season.

[2] Base run values for a normal fishing season.

Table 3

Optimal Management Strategies for Different Fishery Scenarios

Management Strategy	Scenario 1	Scenario 2	Scenario 3
Size of artisanal fleet (No)	1495	1129	1202
Size of industrial fleet (No)	217	187	196
Start of season (Month)	7.14	8.7	8.7

The Optimal Trajectories of the Bioeconomic Variables

Octopus biomass. The biomass curve has at T = 0 (end of December 1987) a value of 5945 tonnes, decreasing towards T = 2 (end of February 1988). The base run and the optimization values at this point are 5158 and 5202 tonnes respectively. Afterwards, coinciding with the spawning and the hatching processes maxima, it increases towards T = 7.5 (mid August 1988) where it takes values of 11089 and 11697 tonnes for the base run and the multi-criteria optimization. At this point, the fishery begins, contributing to biomass decline towards the end of the season (Figure 3, A).

Total fishery yield. At the beginning of the fishing season, the base run yields 110.8 tonnes with an increasing trend until the end of the season where it declines due to the dominating effect of a diminished resource biomass (Figure 3, B). The

Table 4

Bioeconomic impacts of optimal management strategies for different fishery scenarios

	Scenario 1		Scenario 2		Scenario 3	
Variable	Target	Optimal	Target	Optimal	Target	Optimal
Biomass (tonnes)	4000	3759	5200	5271	4200	4438
Total yield (tonnes)	8000	7775	3500	3930	4500	5186
Yield of artisanal fleet (tonnes)	4000	4530	1700	1816	2250	2540
Yield of industrial fleet (tonnes)	4000	3245	1800	2114	2250	2645
Profits: Artisanal fleet ($ 10^6 pesos)	200	305	80	134	40	189
Profits: industrial fleet ($ 10^6 pesos)	200	176	230	242	310	290
Direct employment (No.)	5500	5996	4300	4691	4500	4977
Food for domestic market (tonnes)	500	642	300	249	350	348

optimized solution show an increase in yield until it reaches a maximum of 1318 tonnes at the end of November. Throughout the season, the optimal strategy's values are smaller than the base run value until the last month when the opposite situation results.

Artisanal fleet yield. The yield of base run shows an increasing trend with a maximum value located on the 17th fortnight (843 tonnes). At the end of the season the fleet yield is 360 tonnes (Figure 3, C). This decline is attributed to a biomass decrease in the coastal zone due to natural and fishing mortality and migration to deeper waters. When the fleet is reduced as a result of the optimal strategy, the optimization trajectory shows an increase in yield from the start, ending the season with 562 tonnes, a substantially higher yield than the one generated by the base run.

Industrial fleet yield. The industrial fleet performs the fishing operations in deeper waters delaying the shift from the red grouper fishery until the recruitment levels and expected individual octopus weight, increases their possibilities of fishing success. Because of this, an increasing yield is shown in the base run curve and in the optimization towards the end of the season (Figure 3, D).

Artisanal fleet cumulative net revenue. The artisanal fleet overcapacity and a decreasing biomass make the existence of negative net revenues toward the end of the season possible, when cumulative net revenue declines as shown by the base run value curve (Figure 3, E). The optimal strategy avoid this problem.

Industrial fleet cumulative net revenue. The base run as well as the optimized solution, show an increase in net revenues from the beginning to the end of the fishing season (Figure 3, F). It indicates that the fleet operates at lower effort levels than bioeconomic equilibrium.

Employment. The direct employment generated by both fleets, always increase towards the mid of the season, with values in the base run and the optimized solution of 6155 and 5778 fishermen respectively. Throughout the fishing season, the former generates more employment than the latter (Figure 3, G), because it starts sooner with bigger fleets than the optimal strategy.

Octopus availability for coastal consumption. Because this variable is determined by the amount harvested by the artisanal fleet, throughout the fishing season the base run values are always higher than the optimal values (Figure 3, H).

Scenario 2: Hurricane Gilbert Impact on the Fishery

The optimal management strategies that drive the system and optimize it are 1129 artisanal boats (which means an increase of 13% from the base value), 187 industrial ships (additional 14.7%) starting the fishing season immediately after the hurricane passed, the 21st September 1988 (Table 3). The optimal trajectories of the bioeconomic variables are presented in Figure 4.

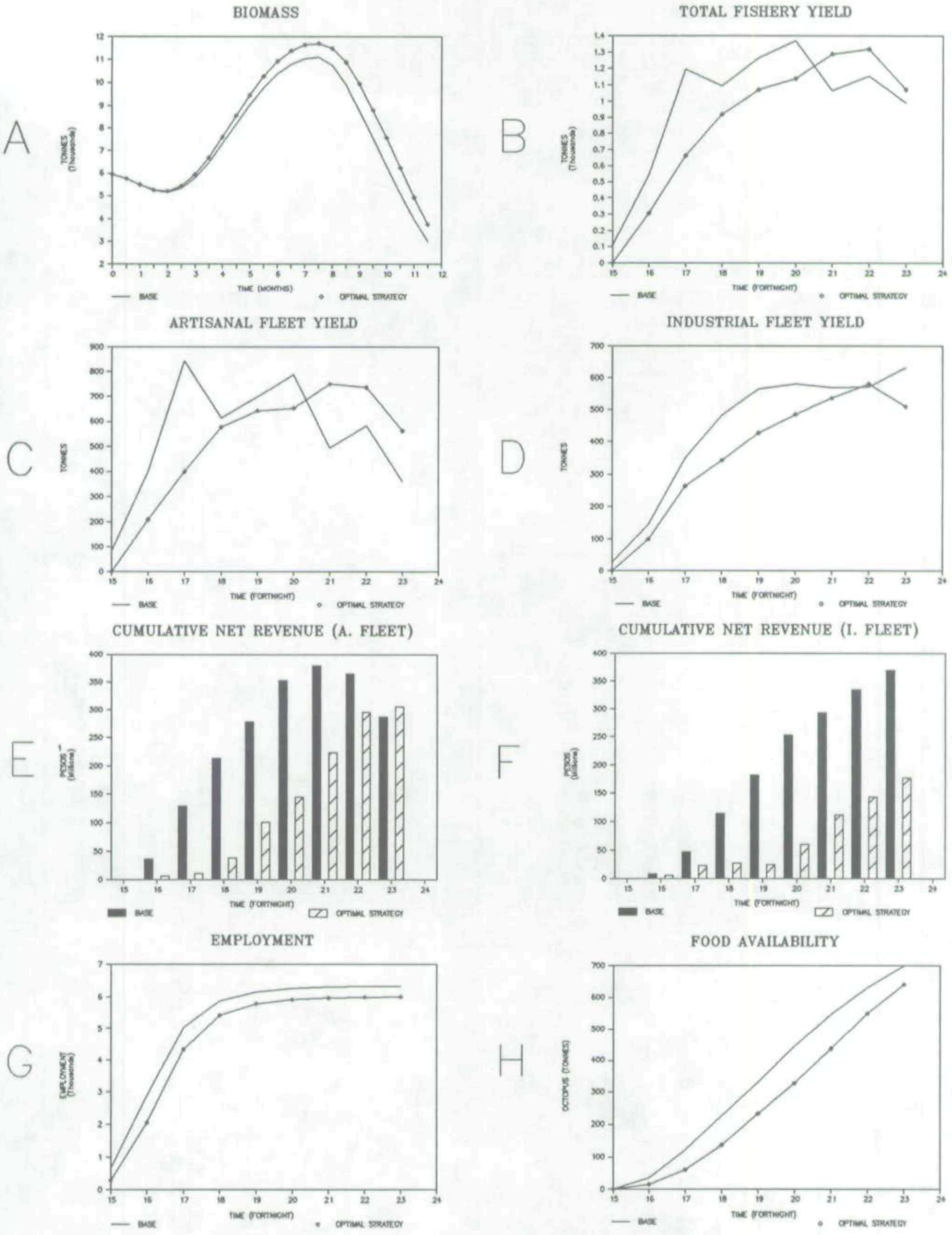

Figure 3. The optimal strategy dynamic impact on bioeconomic variables. Scenario 1: 1988 normal fishing season.

Movements towards the desired targets are present in all the bioeconomic variables, exceeding the targets in six of the variables (Table 4).

Scenario 3: Extended Fishing Season after Hurricane Gilbert

To achieve the manager's objectives in this scenario, the optimal management strategy demands an expansion of both fleets to its upper bound limit (+20% in

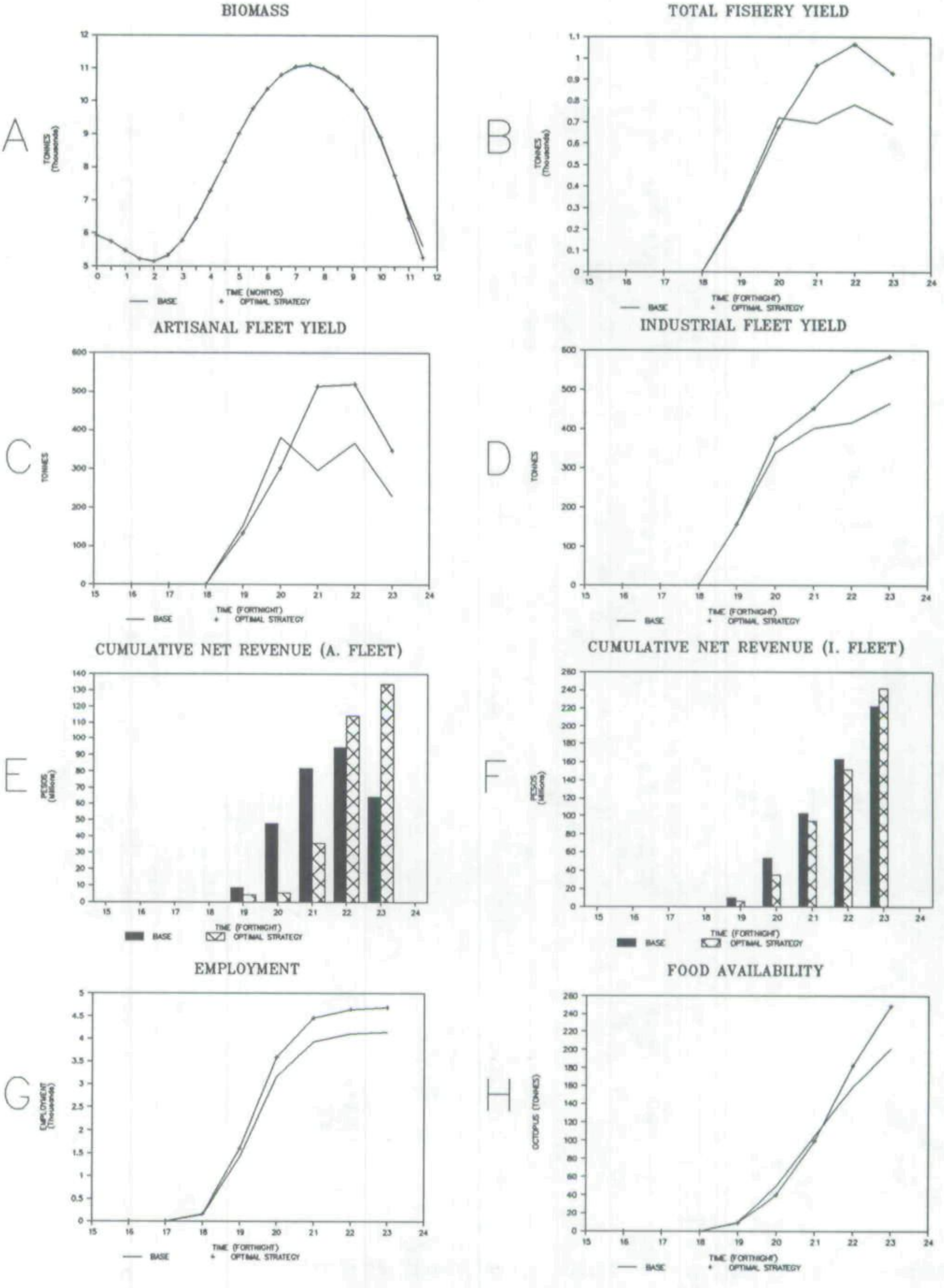

Figure 4. The optimal strategy dynamic impact on bioeconomic variables. Scenario 2: hurricane Gilbert's impact on the fishery.

both fleets) and the starting of the fishing operations immediately after the hurricane has passed on the 21st September, 1988 (Table 3). The optimal trajectories of the bioeconomic variables are presented in Figure 5.

The optimization process shows a pattern towards the desired targets in all the bioeconomic variables, exceeding the target values in 5 of them (Table 4).

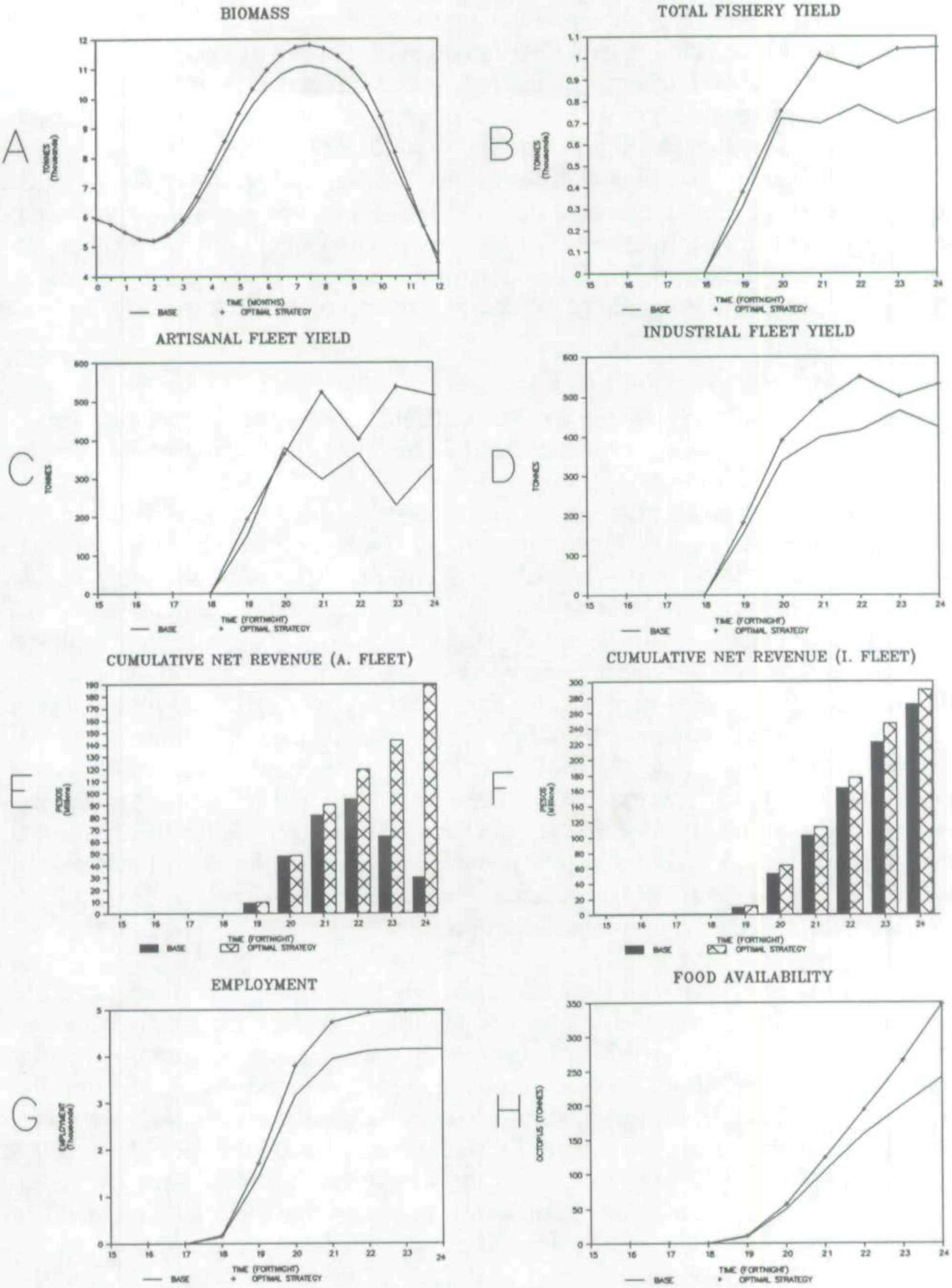

Figure 5. The optimal strategy dynamic impact on bioeconomic variables. Scenario 3: extended fishing season after hurricane Gilbert.

Discussion

In this modelling effort, the optimal number of vessels of the artisanal and industrial fleets, and the optimal starting season were estimated. The former can regulate the catch size and can lead to property rights allocation (Rothschild, 1983).

The latter and the effect of size limit control can regulate the octopus catch composition. These management instruments were chosen as system control variables due to their ease of implementation. It is well known that the success of a management program depends on the possibility of moving away from the prevailing conditions (Shepherd and Garrod, 1980; Pringle, 1985).

The criteria for choosing the performance bioeconomic variables were the representation of the biological, extractive, economic and social components of the fishery and their attractiveness to the fishery manager. The number of artisanal boats and industrial ships, the start of the fishing season and its associated restrictions reflected the state of affairs, before and after the hurricane.

Model Updating and Base Run Trials

Model updating was a relatively easy task. In the case of the control variables, it received as inputs the correct values for the artisanal fleet, the industrial fleet and the season starting time.

In scenarios 2 and 3, the values of the distributed delay model parameters relative to the fleets entry to the fishery had the same value because after the hurricane passed both fleets were willing to enter the fishery as soon as possible.

When a minimum size limit was the issue to represent, the elements of the size composition vector containing the desired sizes were changed to zero. Simulations illustrated that the impact was marginal in the three scenarios augmenting the biomass escapement in all cases. The effect on total yield and its associated benefits was a small increase in the first scenario and a decrease in the other two.

The model represented the fishery and the management scenarios in an adequate manner. Trade-offs existed between total yield and its associated benefits and resource biomass. As observed in the first scenario higher yields (due to higher effort levels) resulted in low resource biomass at the end of the season. When the sizes of fleets were reduced as a result of the hurricane (scenarios 2 and 3), the yield and associated benefits diminished and the resource biomass was higher at the end of the season.

A limitation of scenarios 2 and 3 is that they were modeled taking the 21st September as the start of the fishing season. This is slightly unrealistic because a small part of the fleet was fishing before the hurricane's arrival, and this was not taken into account. Other limitations of the model included the assumption that octopus growth can be represented by a Von Bertallanfy growth curve, which has been criticized by several authors (Van Heukelem, 1976, 1977; Forsythe and Van Heukelem, 1987) and, that there are constant natural mortality rates within age classes. Nevertheless, the simulation model has been satisfactorily validated (Seijo *et al.*, 1987). An integration time interval of 0.1 which gives stability and reduces numerical integration error, was used in the original model.

When the fishery model was coupled with the optimization model it became unstable due to negative feedbacks and additional mathematical computations. To solve this problem, the time increment was further reduced to 0.01, increasing not only the precision levels but also the computing time.

Objectives and Preferences of the Fishery Manager

Explicit quantitative objectives in fishery management are difficult to obtain. It is more complex to design a management program if objectives are not made explicit beforehand (Drynan and Sandiford, 1985). It has been pointed out that whether these are explicit or implicit in policy making discussions, normally there are many diverse and conflicting objectives which require much attention in their trade-offs (Beddington and Rettig, 1984). Nevertheless, for the purpose of this study, in the Yucatán state the fishery manager defined his management objectives for the 1988 octopus fishing season. This definition gave the authors the opportunity to explore resource conservation issues, economic performance of the fishery, and the feasibility of implementing alternative resource management strategies.

In the first scenario, before hurricane Gilbert, the resource manager was more concerned with sustaining the yield of the fishery over time, than increasing harvesting rates in the short-run. This is reflected in the explicit target of increasing estimated biomass at the end of the fishing season, even at the cost of decreasing current harvest rate. In the second scenario, because of hurricane Gilbert, which damaged the fleets and delayed starting of the season, the estimated biomass was higher than before the natural disaster. Hence, the resource manager suggested higher yields and more direct employment targets. In the third scenario, the extending of the fishing season was considered by the resource manager in order to compensate for the delayed fleet entry to the fishery. Using the results of the above mentioned optimization experiments as input to decision-making, a dynamic management scheme was adopted by the resource manager.

Scenario Optimization

The model has been capable of obtaining optimal solutions in the three scenarios. In the first scenario, both strategies approached the desired objectives in most of the variables, reducing yields in favour of increases in resource biomass. Because total yield is an additive result of fleet yield, the seeking of a minimum deviation of total yield related to its management objective had the same effect to that of introducing an additional constraint to fleet yields. On the other hand, due to the fact that the fleet's revenue is a direct function of yield and its price and of fishing effort and its cost, again the fleets sizes and their catches define the quantity of accumulated revenues.

Hurricane Gilbert's impact on the fishing fleet drove the fishery manager's objectives towards increasing yield and its benefits, sacrificing biomass to levels that could not endanger the population. The satisfaction of his objectives was reached increasing the size of both fleets and starting the fishing operations just after the hurricane passed the 21st September of 1988. The fact that the total yield have exceeded the target total yield, caused variables associated to catch and effort to surpass, in all cases, their specified targets. The principal trade-offs again were between total yield and associated variables (ie. artisanal and industrial fleets yields and revenues) and the resource biomass. In the third scenario (extended fishing season), the fishery manager wanted an increase in yield without endangering the population.

This study has shown that it was the optimal number of vessels and its relative entrance to the fishery more than the optimal starting date, the key variables that determined the optimal solutions. The optimized management strategies for the three scenarios were Pareto-optimal. With this approach, new Pareto-optimal strategies can be obtained through intensive searching of improvements in one or several bioeconomic variables, having at the end of the day a set of strategies according to different management objectives and preferences. An interesting approach would be the use of other optimality criteria.

This multi-criteria optimization approach can be extended to other fisheries. Nevertheless, it requires an interface that permits the user to become familiar with the optimization process. Further research and modelling efforts are needed to incorporate in this type of models the interdependencies and trade-offs present in multispecies fisheries.

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