

BIOECONOMICS OF THE PACIFIC SARDINE (*SARDINOPS SAGAX*) FISHERY IN THE GULF OF CALIFORNIA, MEXICO

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ABSTRACT

A bioeconomic model integrating biological and economic factors is developed for the Pacific sardine fishery in the Gulf of California. The model factors in the dynamics of the population structure and applies the basic concepts of the cohort-survival method. Seasonal recruitment was modeled with the distributed-delay method. The dynamics of the fleet were modeled by Smith's function with distributed delays to represent time lags in entry-exit processes. Performance variables such as biomass, fishery yield, effort, and net returns offered robust valuations of the behavior over time, showing a resource overexploited and a fishery fleet overcapitalized. The maximum economic yield and bioeconomic equilibrium of the fishery were also obtained. Of the alternative management strategies considered, minimum size of capture was most successful, offering important increases in the bioeconomic variables.

INTRODUCTION

The small pelagic fishery in the Gulf of California is one of the most important in terms of amount harvested and income generated. This fishery is based on a variety of different taxonomic groups, which include the Pacific sardine (*Sardinops sagax*, Jenyns, 1842; Parrish et al. 1989); the thread herring, including three species (*Opisthonema libertate*, *O. medirastre*, and *O. bulleri*); mackerel (*Scomber japonicus*); round herring (*Etrumeus teres*); "bocona" (*Cetengraulis mysticetus*); and northern anchovy (*Engraulis mordax*). Of these, the Pacific sardine catch is the largest. Its main landing port is Guaymas, Sonora, where Mexico's most important fish-processing plants are found. Fish meal constitutes 85% of the processing plants' production (Cisneros et al. 1988). Fish processing, as well as the fishery itself, is of major importance for the Mexican economy, as it provides work for a considerable number of people. In addition, the industry produces inexpensive food for large sections of the population.

The marine fisheries generally are characterized by overexploitation of the resource and an overcapitalization of the fishing industry. The management policy, known as open access, is characterized by (1) unrestricted

access to the resource for all who have an interest in its use, and (2) adverse interactions among the users of the ecosystem. Overexploitation of a resource and the overcapitalization of the industry can cause important economic losses, especially in highly productive fisheries.

Regulating a fishery by considering only the maximum sustainable yield can be inadequate because it uses only biological criteria. To represent effort dynamics, one must consider additional criteria, such as the cost of fishing and the corresponding fleet benefits. It is appropriate to consider how different management strategies may affect capture, biomass, incomes of artisanal and industrial fishers, direct employment, and foreign exchange earnings. Dynamic bioeconomic modeling is a robust approximation for exploring a large number of management strategies of renewable marine resources (Sejo 1986; Sejo et al. 1997).

Until now, studies of the Pacific sardine have concentrated on biological factors, with no consideration of the economic aspects that determine its exploitation level over time. The purpose of this study is to analyze the Pacific sardine fishery with a dynamic stochastic and nonlinear model that integrates biological and economic factors. In addition, the bioeconomic effects of alternative management strategies are discussed.

METHODS

Bioeconomic Data Set

The biological, statistical, and behavioral data of the fishery were obtained from logbooks of the sardine fishing vessels, and from samples taken during off-loading in port. The required data were catch composition, fishing effort, and seasonal length-frequency distribution, all derived from commercial harvest for the period from 1972 to 1990. The information on costs and benefits of the fishing fleet was obtained by direct interview with fishermen and vessel owners.

The parameters used in the von Bertalanffy growth equation are those of natural fishing and fishing mortality, the population structure, the catchability coefficient, and the function that describes recruitment of individuals to the Pacific sardine population. Environmental variability effects on recruitment were incorporated by

using functions reported by De Anda et al. (1994). In addition, an analysis was made to estimate costs and benefits for the fishing fleet. All this information was incorporated into the simulation model.

Mathematical Model

The dynamics of the population structure of the Pacific sardine were modeled by applying basic concepts of the method of survival of cohorts (Gulland 1965; Pope 1972). This model is based on the dynamic accounting of the input and output of individuals to each cohort of the population. For a set of initial conditions $[N_K(0)]$, the structure of the population is estimated in a dynamic form by the expression

$$N_K(t + DT) = N_K(t) + \int_t^{t+DT} [S_{K-1}(t) \cdot N_{K-1}(t) - N_K(t)] dt \quad (1)$$

given N_K at time 0 and where

- $N_K(t)$ = number of individuals of age K at time t ;
- $S_{K-1}(t) = 1 - \{1 - \exp - [FM_K(t) + M]\}$; i.e., the survival rate of individuals of age $K-1$ in time t ;
- $FM_K(t)$ = mortality by fishing of age K at time t ;
- M = natural mortality coefficient;
- DT = time increment.

Integrating equation 1 by the Euler method yields

$$N_K(t + DT) = N_K(t) + DT \cdot [S_{K-1}(t) \cdot N_{K-1}(t) - N_K(t)] \quad (2)$$

Subsequently, to obtain the biomass for age group B_K , the number of individuals of each age group (N_K) was multiplied by the average weight (W_K) of an individual of age K

$$B_K(t) = N_K(t) \cdot W_K$$

To estimate total biomass $[BT(t)]$ all ages were added up, resulting in

$$BT(t) = \sum_{K=1}^{MAGE} B_K(t)$$

where $MAGE$ = maximum age of species.

The number of individuals of the adult population (NA) is obtained from the expression

$$NA(t) = \sum_{K=s}^{MAGE} N_K(t)$$

where s = age at first maturity.

The feedback of expression 2 is given by $N_1(t) = R(t)$, where $R(t)$ is the recruitment estimated by the environmentally driven stock-recruitment function. The function incorporates biotic and abiotic factors that affect the recruitment of the Pacific sardine over time as follows:

$$R(t) = \{b_1 P(t) \cdot \exp^{-b_2 P(t)} \cdot \exp^{-b_3 [VA(t)]}\} + X_1$$

Where $P(t)$ = spawning stock at time t ;

b_1 = density-independent coefficient;

b_2 = density-dependent coefficient;

b_3 = coefficient that reflects the effects of environmental changes;

$VA(t)$ = environmental variable (upwelling index) over time;

X_1 = random variable with normal distribution, generated from the average and standard deviation observed for recruitment.

The incorporation of the above estimated number of recruits over time was modeled by using the distributed delay method (Manetsch 1976; Seijo 1986; Díaz de León and Seijo 1992; Seijo et al. 1997). The model is based on gamma probability density function, which is described as follows:

$$dr_1/dt = m/DEL(R(t) - r_1(t))$$

$$dr_2/dt = m/DEL(r_1(t) - r_2(t))$$

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$$dr_m/dt = m/DEL(r_{m-1}(t) - r_m(t))$$

where $R(t)$ = input to the delay process;

$r_m(t)$ = output from the delay process;

DEL = expected value of the transit time of an individual entity through the process;

m = order of the process of delay;

$r_1(t), r_2(t), \dots, r_{m-1}(t)$ are the intermediate rates of the delay process.

The parameter m specifies the member (distribution) of the gamma family of probability density function, which describes the transit time of entities through the recruitment process of delay.

In addition, we used a table look-up function known as TABLIM to numerically interpolate the values of the upwelling indexes.

The effort applied to the fishery was also modeled with the method of distributed delay to represent the gradual entry of vessels during the fishing season. The expression that represents the accumulated effort by type of vessel is

$$f_V(t + DT) = f_V(t) + \int_t^{t+DT} [VESS_V(t) \cdot TRIPS] dt \quad (3)$$

where $f_V(t)$ = the effort in number of vessels by category V ;

$VESS_V(t)$ = the number of vessels in each category over time;

$TRIPS$ = fishing trips;

V = harvesting (storage) capacity where
 $V_1 < 120$ metric tons; $V_2 = 121-140$ t;
 and $V_3 > 141$ t.

The dynamics of the fishing fleet were modeled with the Smith function (1969), which assumes that the effort changes in proportion to profits; that is,

$$\frac{dVESS_V(t)}{dt} = k_V \pi_V(t)$$

where k_V = fleet dynamics parameter, a positive constant ($K_V > 0$), and $\pi_V(t)$ = profits in time t by vessel V .

The accumulated yield by type of vessel [$YIELD_V(t + DT)$] is calculated from the equation

$$YIELD_V(t + DT) = YIELD_V(t) + \int_t^{t+DT} [q_V(t) \cdot f_V(t) \cdot BT(t)] dt$$

where $q_V(t)$ = dynamic catchability coefficient of vessel type V , and $f_V(t)$ = number of vessels type V in time t .

By using the function of catchability (q) proposed by MacCall (1976) for pelagic species, which is

$$q_V = \alpha_V \cdot NA(t)^{-\beta_V},$$

in the interval $0.000124 < q_V < 0.0000476$ (Martínez-Aguilar et al. 1997), we estimate the $CPUE(t)$ according to type of vessel by applying the expression

$$CPUE_V(t) = \sum_{K=1}^{MACIE} W_K(t) \cdot N_K(t) \cdot q_V(t)$$

The accumulated net returns by type of vessel are obtained by the expression:

$$PROFIT_V(t + DT) = PROFIT_V(t) + \int_t^{t+DT} (((CPUE_V(t) \cdot PRICE_1) + (CATCHIN(t) \cdot PRICE_2) - COST_V) \cdot f_V(t)) dt$$

where $PROFIT_V(t)$ = net returns by type of vessel in time t ;

$PRICE_1$ = price of target species (US\$/kg, constant);

$CATCHIN(t)$ = incidental harvest of species in time t ;

$PRICE_2$ = price of the incidental species (US\$/kg, constant);

$COST_V$ = unit cost of effort (US\$/trip, constant) by type of vessel V .

A discount rate of 0% is assumed (i.e., net benefits should be given equal weight over time). The unit price was calculated as a weighted average of the packaged and processed prices, with the weights being the respective proportions of the harvest going to packaging and processing.

Finally, the trip costs by type of vessel are obtained from

$$TC_V(t) = FC_V(t) + OVC_V(t) + [OMEG(t) \cdot CPUE_V(t) \cdot PRICE_1 + CATCHIN(t) \cdot PRICE_2]$$

where $TC_V(t)$ = vessel's total costs (including fixed and variable costs) over time t ;

$FC_V(t)$ = fixed costs (US\$) by type of boat over time t ;

$OVC_V(t)$ = other variable costs (US\$/fishing trips) by type of vessel over time t ;

$OMEG(t)$ = pay to fisherman as a percentage of the value of harvest (21%).

Stability Analysis

An appropriate value of the time increment (DT) was determined for stable numerical solutions of the differential equations in the distributed delays. The necessary condition of stability requires that DT be within the interval $2 \text{ MIN } [Dn] > DT > 0$, where $Dn = DEL/m$ and $[Dn]$ is the smallest delay constant of the model (Manetsch 1982 cited in Seijo 1986). In this case, the values were $DEL = 2$ and $m = 3$. Therefore, the upper limit for DT in this model is 1.33.

Given that the model contains feedback processes in estimating the population structure for stable simulations, one should be sure that $1/C > DT > 0$, where $C = 1/Dn$.

Thus the value of DT in this model must be within the interval given by $0.66 > DT > 0$. We used the value 0.05, because this value satisfies the conditions of stability, and errors of numeric integration are <5%.

Model Validation

The real values observed were compared with those generated by the model for the two important variables of the system: effort and capture by season. The Kolmogorov-Smirnov nonparametric test was used to validate the model.

Sensitivity Analysis

Natural mortality coefficient (M), the curvature parameter of the von Bertalanffy growth equation, age at first maturity, and unit cost of effort and price of species were varied. Each of these parameters was independently varied with increases and decreases of 10% and 20% of the initial conditions to observe changes in performance variables. The model was run in deterministic

mode to prevent random variables from influencing the observed changes.

Simulation of Fishery Management Strategies

Different management strategies were simulated to determine the effect on relevant variables, recruits, biomass, effort, yield, and profits. These variables were compared with the value reached at the end of the simulation, run in deterministic mode with respect to the base run. The strategies were:

1. Restricting the entry of new vessels to the fishery (i.e., a license quota of 76 boats).
2. Instituting a minimum legal capture size of 150 mm standard length.
3. Increasing the fishing season from 10 to 12 months.
4. Reducing the fishing season from 10 to 9 months by starting the season in November.
5. Combining a minimum capture size with 12 months of fishing.

Each of these strategies was implemented for a time $t > 10$ (i.e., starting from the 1991–92 season and for a period of 40 years).

RESULTS

Model Validation

The historic data of effort, catch, and CPUE were compared with those generated by the models for a period of 10 years beginning with the 1981–82 season. In figure 1, the general performance of the model exhibits robust estimates of the output variables, showing—in the three cases (effort, catch, and CPUE)—congruent patterns with small deviations of the same sign.

We used the Kolmogorov-Smirnov nonparametric test to determine if the observed and modeled catch and effort distribution over time were equivalent. The effort variable had a significance of 99%; catch and CPUE were 76% significant.

The consistency of the model output with accepted theory is shown in figure 1c. At the beginning of the period, there are increases in effort, and subsequently increases in CPUE. Starting with the 1987–88 season, CPUE decreases even though effort continues to increase.

Sensitivity Analysis

In general, the model indicated moderate alterations, with nonlinear changes in the direction and magnitude theoretically expected from the cause-effect relations represented in the mathematical model.

Biomass and Recruitment

The results of modeling biomass and individuals age 1 and 3, over time (120 months, or 10 years, beginning

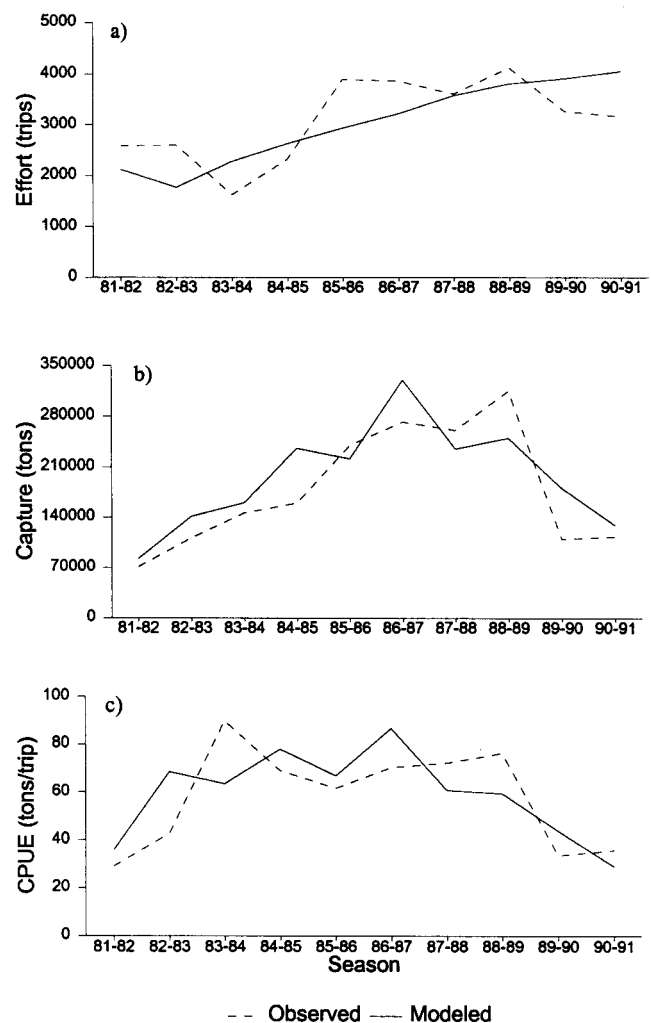


Figure 1. Validation of the model, comparing a, effort; b, captures; and c, CPUE for fishing seasons 1981–82 through 1990–91.

in 1981–82) are presented in figure 2. Biomass shows two important periods, the first characterized by growth until the record season of 944,000 metric tons in 1986–87 (months 61–72). The second period was characterized by a decrease in biomass, possibly because of overexploitation of the resource. The levels of effort grew until the 1988–89 season (months 85–96), which began with a biomass of 526,000 t, when a record 4,133 trips were made. At the beginning of 1990–91 season (month 109), the biomass dropped to 326,000 t (fig. 2a).

For the number of individuals of ages 1 and 3, alternating periods of good and moderately low levels of recruitment were observed. In the later years, the numbers decreased (fig. 2b, c).

Effort

The effort in number of modeled trips by category of vessel (V_1 , V_2 , and V_3 in equation 3) over time is illustrated in figure 3a. A positive trend is seen to a max-

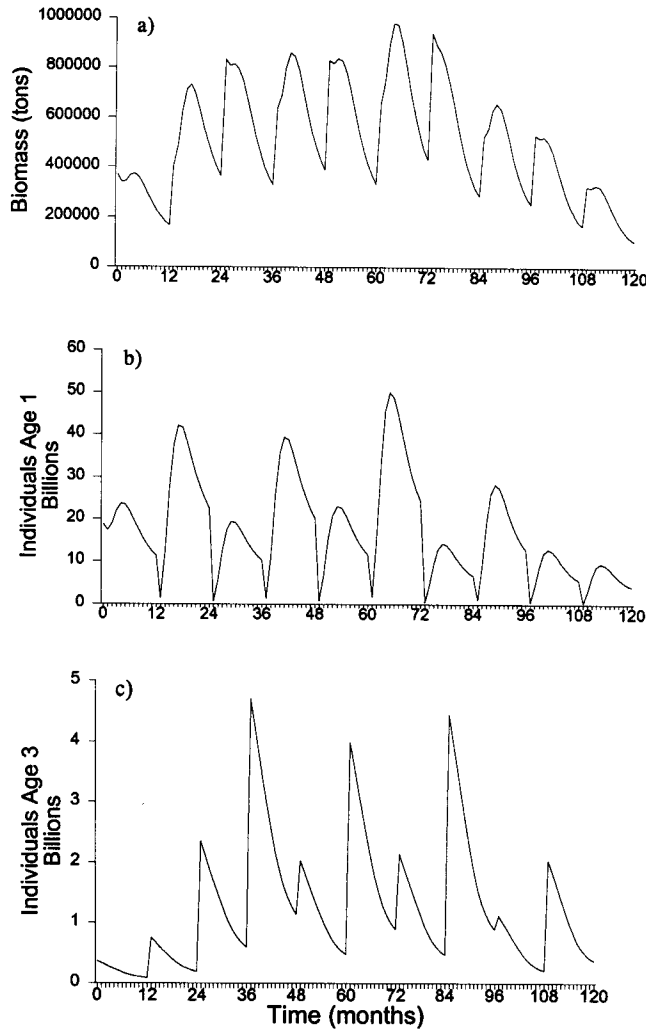


Figure 2. Model of dynamic behavior of the population of Pacific sardine over 120 months (10 years), beginning with the 1981–82 season: a, biomass; b, individuals age 1; and c, individuals age 3. Time (months) 1 = October 1981; 120 = September 1991.

imum of 4,065 model fishing trips. Category 1 always shows a lower number of trips. This is reasonable, because when the season begins and the resource is farther away from the base port, smaller vessels take longer to reach the fishery. The same effect occurs at the end of the season, when the resource is again farther away. Category 1 vessels are the first to stop fishing because their cruising range is so limited.

At the end of each season, there are fewer trips, and fewer vessels in each category. Vessels in categories 2 and 3 show similar changes in distribution and number of trips per season.

Eight new vessels were added to the fleet from 1981–82 to 1991 (fig. 3b). Category 1 remains nearly constant during the 10 seasons, gaining only one new vessel. The total number of boats modeled for categories 2 (28) and 3 (29) correspond to the number in the real fishery.

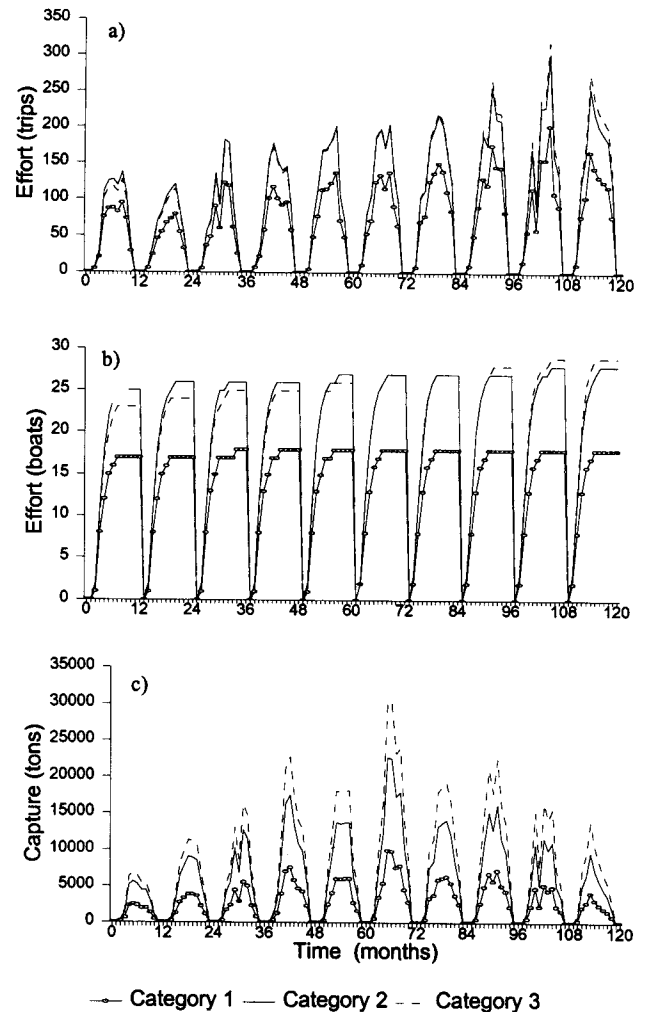


Figure 3. Model of dynamics of the short-term and long-term fishing effort by category of vessel in the Pacific sardine fishery, beginning with the 1981–82 season: a, effort in number of trips; b, effort in number of boats; and c, metric tons captured. Category 1, <120 t; category 2, 121–140 t; category 3, >141 t. Time 1 = October 1981; 120 = September 1991.

Category 3 added five new boats; category 2 added two. These results coincide with the net returns obtained for the three categories in the period modeled. The highest returns were from category 3 vessels, motivating the deployment of new vessels into the fishery.

Yield

The yield modeled by category of vessel is illustrated in figure 3c. Two important, well-defined periods were observed. The first increased until the 1986–87 season (months 61–72), with a maximum harvest of 340,000 t. The second period showed a decreasing harvest from the 1987–88 season (months 73–84) until the 1990–91 season (months 109–120); only 130,000 metric tons were captured. Category 3 and category 1 always had the highest and lowest captures. Because of this decrease during the second period, in spite of the increasing fishing ef-

fort, the CPUE by category of vessel remained the same (fig. 4a). The decrease produced a series of substantial economic losses for the fishing fleet.

Costs and Returns

The net returns by category of vessel modeled over time are illustrated in figure 4b. At first, in the 1980–81 season, small losses were observed for category 1. In this case, the total costs were more than the total returns. Later, the net returns for the three categories increased, the highest in category 3, until the record season of 1986–87 (61–72 months). After that, the net returns decreased, and the 1990–91 (109–120 months) season showed losses for category 1 and category 2. The average value of the CPUE for this season of losses was 18.6 and 28.6 metric tons for the first and second categories. At this level of CPUE, the average costs are higher than the average returns, causing vessels to leave the fishery or reduce the number of trips. The maximum economic yield is at $t = 6$ years (61–72 months; fig. 4b). Finally, the model predicted losses for the next two seasons for all three categories of the fishing fleet because of the low harvest.

Fishery Management Strategies

The effects of biomass, recruitment, effort in number of trips by category of vessel, and catch of the Pacific sardine, over time and under the different management strategies, are shown in table 1.

For biomass, the best results were produced with strategies 2 and 5. For recruits, strategies 2 and 5 yielded the best results. Strategy 2 (setting a legal minimum size) offered the best means of increasing biomass and recruits. This strategy is so important that even increasing the season to 12 months yields results similar to a 10-month season (closed in the summer).

Strategies 2 and 5 can sustain higher effort levels for category 1. These strategies' effects on category 2 were

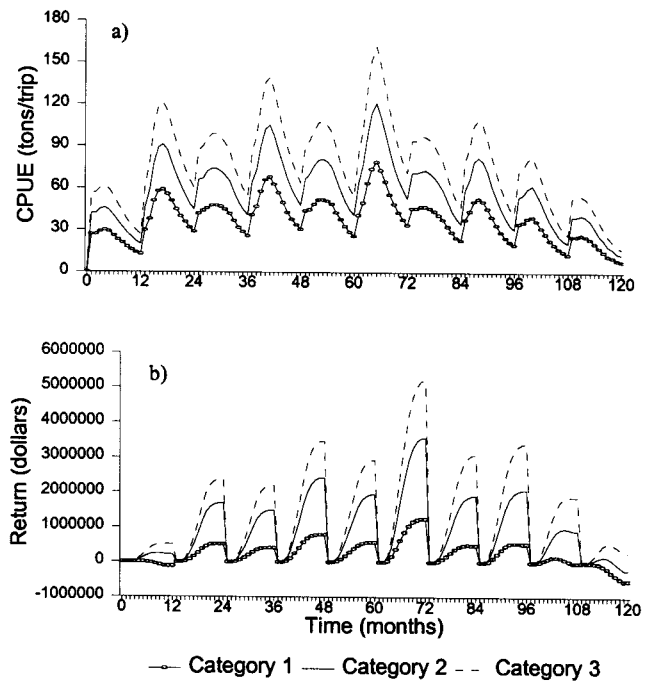


Figure 4. Model of dynamic behavior of CPUE (a) and the net returns (b) by category of vessel in the Pacific sardine fishery, beginning with the 1981–82 season. Category 1, <120 t; category 2, 121–140 t; category 3, >140 t. Time 1 = October 1981; 120 = September 1991.

not as great, but still important. For category 3, strategy 1 caused a decrease of 47%, and strategy 5 an increase of only 16%. Strategy 3 had the least effect on the level of effort.

All strategies except strategy 1 reduced the yield. Strategies 2 and 5 caused the catch to drop the most. Strategy 1 limits the entry of new vessels into the fishery, resulting in a 15% increase in catch, or 234,000 metric tons. This is about the same as the catch in the 1985–86 season, as well as in the two subsequent sea-

TABLE 1
 Effects of Management Strategies,
 Expressed as Absolute Values in Thousands, and as Percentages (in Parentheses)* of Baseline

Variables	Baseline	Management strategies									
		1		2		3		4		5	
Biomass (metric tons)	201	305	(52)	793	(295)	208	(4)	207	(3)	790	(294)
Recruits (number)	620,412	789,468	(27)	865,122	(39)	635,312	(2)	633,573	(2)	866,178	(40)
Yield (metric tons)	204	234	(15)	128	(-37)	200	(-2)	197	(-4)	129	(-37)
Effort (number of trips)											
Category 1	0.21	0.56	(169)	2.13	(912)	0.21	(0)	0.26	(23)	2.33	(1,008)
Category 2	1.27	2.37	(87)	3.40	(169)	1.28	(1)	1.51	(19)	3.73	(195)
Category 3	4.60	2.45	(-47)	4.82	(5)	4.43	(-4)	4.08	(-11)	5.32	(16)
Net returns (dollars)											
Category 1	-552	-161	(71)	11,988	(2,273)	-483	(12)	-564	(-2)	11,541	(2,192)
Category 2	-811	6,538	(907)	41,617	(5,234)	-245	(70)	-452	(44)	40,358	(5,079)
Category 3	4,917	13,917	(383)	88,166	(1,893)	6,410	(230)	5,042	(203)	86,139	(1,852)

*For instance, the biomass value (52) for strategy 1 means that biomass would be 52% higher than it would be for the baseline.

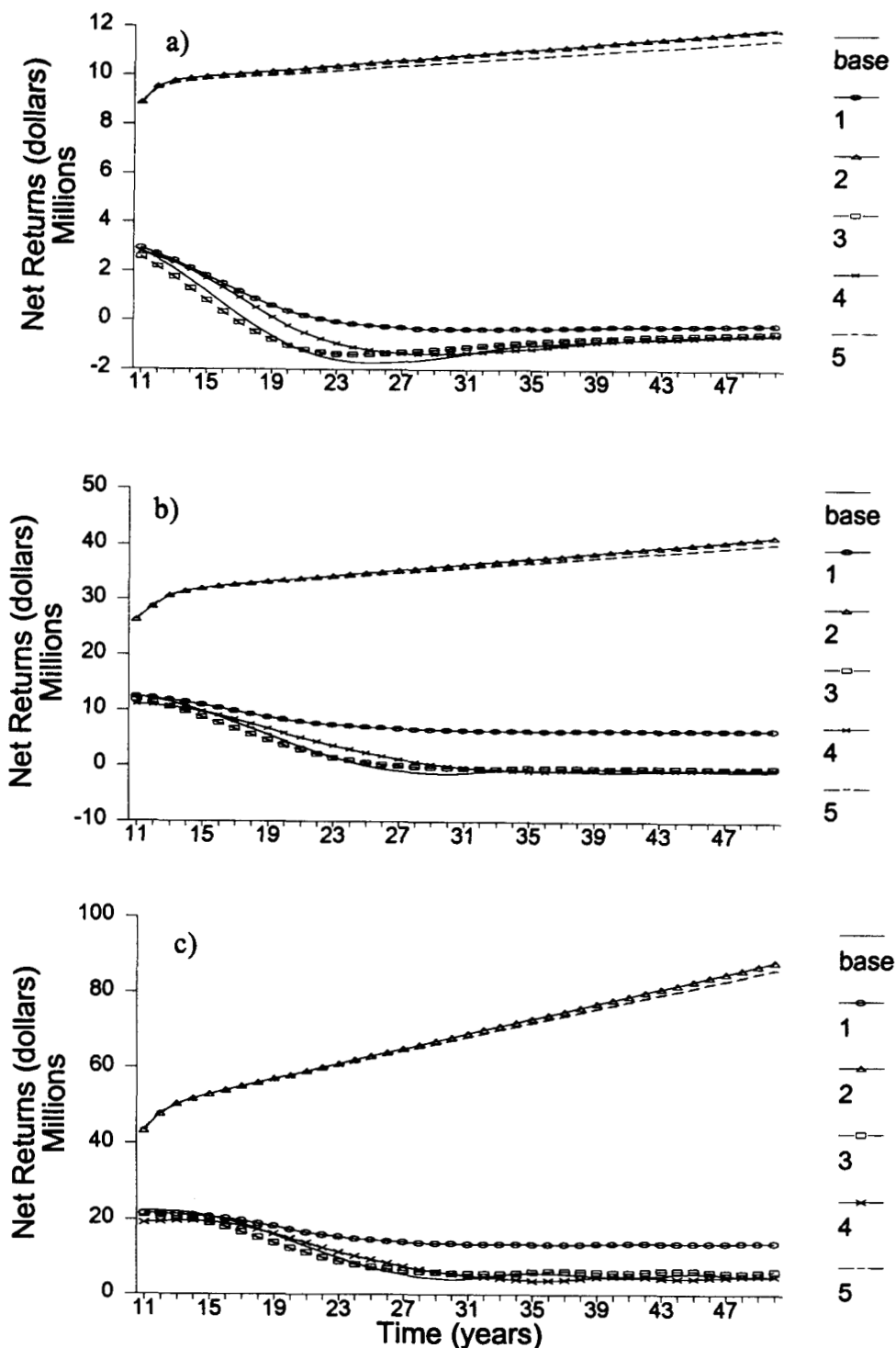


Figure 5. Effect on net returns by category of vessel with different modeled management strategies, deterministic manner: a, category 1 (<120 t); b, category 2 (121–140 t); and c, category 3 (>140 t). Time (years): 11 = 1991–92 season.

sons. Obviously, the decreasing catch, especially with strategies 2 and 5, affects the levels of recruitment and biomass in general, yielding substantial increases in biomass (fig. 1).

The changes in the net returns by category of vessel over time are illustrated in figure 5. For vessel category

1 (fig. 5a), the behavior of the base, run together with strategies 1, 3, and 4, shows a point of bioeconomic equilibrium at approximately 19 years. Later a negative economic yield is observed for category 1. The point of equilibrium for category 2 comes at approximately 25 years (fig. 5b) and for category 3 at about 29 years (fig.

5c). At these points, the average returns equal the average costs and consequently cause a lack of stimuli for entry into or exit from the fishery. Strategies 2 and 5 produce the best effects, with more economic yield for each of the three categories.

Of the five strategies analyzed, a minimum size at capture was the most important, offering considerable benefits from a biological and economic point of view.

DISCUSSION

Simulation Model

The bioeconomic model proposed for the fishery of the Pacific sardine in the Gulf of California satisfactorily represented the real system, considering the principal phenomena of the fishery. Holling (1978) mentions that a model is efficient if it leaves out everything except the essential part of the phenomenon.

The CPUE shows a behavior consistent with that accepted in the literature: after reaching a maximum, additional units of effort reduce the CPUE (Anderson 1977). This phenomenon has repercussions for total cost and total return. As the CPUE decreases, the cost increases and the return becomes smaller, until total cost surpasses the total return.

Possibly the most important parameters from the point of view of the sensitivity analysis were the natural mortality (M) and the curvature of the growth equation, which are difficult to estimate. An error in these parameters would affect all the performance variables used for the adequate management of the resource. Nevertheless, the results presented in this study, generated by systems simulation methodology, have produced a robust estimate, thus validating the model.

Modeling the principal variables in the system has produced a drastic decrease in the levels of biomass, recruitment, capture, and CPUE in the later seasons. The model simulates the overexploitation syndrome common to developed open access fisheries of the world. As a consequence of these low resource levels, the economic yield decreases until losses are observed in the 1990–91 season. These yields can be considered a measure of economic inefficiency caused by managing the resources with an open access regime.

The high catches of the 1987–88 and 1988–89 seasons and the coinciding high net returns did not result from an increased biomass of the Pacific sardine, but rather from high levels of effort in number of trips. Therefore, state intervention is imperative for preventing or mitigating the exhaustion of the Pacific sardine population in the Gulf of California. Clark (1976, 1985) and Anderson (1977) mention that the dynamics of a resource under open access exploitation will eventually lead to bioeconomic disaster for the fishery.

Simulation of Management Strategies

Of the five strategies analyzed, 2 and 5 offer highly desirable results for the main bioeconomic variables of the fishery, demonstrating the importance of restrictions on the minimum-capture size. Not capturing juveniles yields abundant biological and economic benefits, including—under strategy 5—a fishing regimen of 12 months.

In addition, we have shown how inefficient strategies 3 and 4 could be. From the biological point of view, the changes in biomass, recruitment, and yield would be nearly the same as the base run. But the poor performance of strategies 3 and 4 may result from the fact that they affect fishing activity only at end of the season and not during peak periods. Nevertheless, in the seasons when there was fishing in the summer, large numbers of Pacific sardine were captured, even in off-peak periods. Finally, strategy 1 offers positive and interesting results and an increase in all the biological and economic variables.

Establishing and enforcing a minimum size restriction is not an easy assignment for a fishery in which large volumes are captured with purse seines. But other mechanisms can help to prevent the capture of juveniles, such as establishing a closed season in the summer near Isla Angel de la Guarda on the west coast, where the juveniles are located, and where there have been sporadic closed seasons in the last decades. The closure would have to be permanent to substantially reduce the capture of juveniles.

Harvest quotas—another type of restriction that can be effective in purse-seine fisheries—were not considered in this study. As mentioned above, only strategies that we believe could be implemented and enforced were included in the simulation experiments for the Gulf of California Pacific sardine fishery. We did not include harvest quotas because of high enforcement costs and expected low levels of compliance.

Even if it were feasible to implement quotas, by themselves they would only maintain biomass at a desired level, forcing economic rent to be eliminated with the corresponding overcapitalization of the fishery. Catch quotas, to be bioeconomically efficient, require license quotas and other restrictions such as minimum size to enhance the resource over time. All management measures must be viable from an administrative, political, and practical point of view.

Although this type of holistic simulation model requires the estimation of more parameters than other, traditional fishery biology models, the dynamic structure of the model has allowed us to explore a large number of resource-management alternatives.

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