BIOECONOMIC ASSESSMENT OF THE RED SPINY LOBSTER FISHERY OF BAJA CALIFORNIA, MEXICO

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ABSTRACT

The red spiny lobster (*Panulirus interruptus*) is the most important fishery of northwestern Mexico, accounting for up to 2,000 t. The trap-based fishery occurs along most of the western coast of the Baja California peninsula. Fishing mortality results indicate that the stock has been overexploited for the last eight years, but is still a profitable activity. A bioeconomic assessment and simulation was made to provide the basis for a sustainable exploitation of the stock. The age structure was reconstructed by linking the biological, economic, and social variables. The maximum stock biomass of >1,600 t was recorded in 1999, followed by declining catch particularly after 2003. Therefore advice is required to ensure a sustainable fishery. Specific recommendations for a gradual decrease in fishing mortality and an increase in the minimum size are given. Their use would result in significant improvement in the volume of the catch and in profits.

INTRODUCTION

The red spiny lobster (*Panulirus interruptus*, Randall 1840) is distributed in waters off California and the western Baja California peninsula. Off the Baja California peninsula there is a well-developed fishery that yields > 80% of the catch of the Mexican Pacific spiny lobster, approaching up to 2,000 t in 2003, with a value > $26 million USD and providing jobs to about 1,160 fishers (fig. 1). The fishery is exploited along the coast of the Baja California peninsula, north of Bahía Magdalena. There are three other species of the spiny lobster off the west coast of Mexico south of Bahía Magdalena: the blue lobster (*P. inflatus*, Bouvier 1895), the green lobster (*P. gracilis*, Streets 1871), and the island spiny lobster (*P. penicillatus*, Olivier 1791). These are found in tropical waters of this coastline, and the catch volume is not significant as compared to that of the red spiny lobster. The fishery data in this paper is for *P. interruptus* only. Up to the present, the scientific research evaluating these stocks and identifying reference points for their sustainable exploitation has not been satisfactory.

Most spiny lobster harvested by the Baja California fishery are imported by Asian countries, mostly as live lobsters. Only about 5% is sold cooked and frozen to the USA and the European countries, with only a small portion sold raw and frozen to the Mexican market.

The increasing demand of new fishermen recruited to this activity and a growing demand by consumers has led to increased fishing intensity. For this reason, the red spiny lobster fishery off Baja California was evaluated. Earlier assessments of this resource have been based on local and sporadic attempts (Ayala et al. 1973; De la Rosa-Pacheco and Ramírez-Rodríguez 1996; Gluyas-Millán 1996; Vega et al. 1996; Vega et al. 2000; Arteaga-Rios et al. 2007), therefore an updated and more comprehensive evaluation was made by us. We identified the most useful bioeconomic-reference points for optimizing the fishery. The goals of the study were to evaluate the status of the red spiny lobster stock in Mexican waters, to evaluate the stock's potential production, to provide advice for a sustainable exploitation of the fishery, and to evaluate the fishing intensity that will maximize yields and profits over the long term.

METHODS

The assessment of the stock was made using catch data for the last fifteen years. The population parameter values were taken from published sources. Changes in abundance over time were determined using the catch data.

The red spiny lobster fishery along the Baja California peninsula is trap-based and is the only authorized means to exploit it. This may allow assessment of the stocks more accurately than for other fisheries where a variety of catch methods are in use. We found that the mean catch per fisher during a fishing season was 1,130 kg and they sell their landed whole lobster for $27.00 USD per kilo.

Trends in the fishing mortality (F) over time and the estimates of the total stock biomass were examined. The criteria for evaluation of fishing scenarios were based on the F and the age of first catch (tc) at the maximum-sustainable-yield level (F_{MSY}), an extreme reference point.

The population parameters plus the catch data were analyzed with the aid of a simulation model, imple-

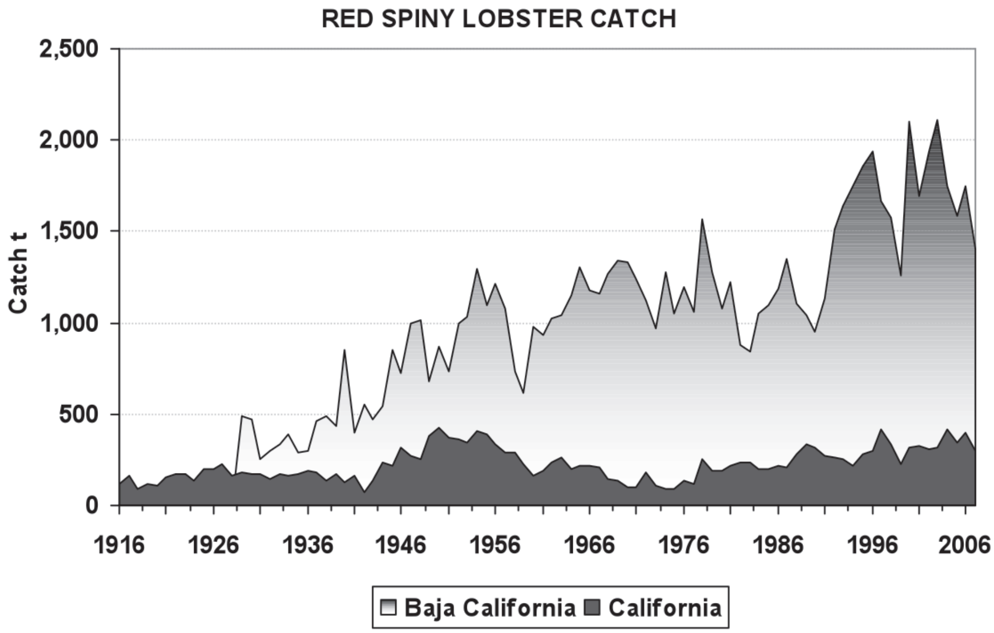

Figure 1. Red spiny lobster catch off California (1916 to 2007) and the Baja California peninsula (1929 to 2007), t.

mented in the semiautomated, age-structured simulation model FISMO (Chávez 2005). The age of first capture was 5 years and was maintained constant in the analysis of the catch records, though this value changes as required in the optimizing process and for designing exploitation policies. The age of first maturity has been estimated to be at about 65-mm carapace length.

Once the catch data and growth rate were known, estimates of the age composition of the catch were made. With these partial results the total mortality (Z_t) could be determined with the exponential decay model as

$$N_{a+1} = N_a \cdot e^{(-Z_t)} \qquad (1)$$

where N_{a+1} is the number of spiny lobsters of age a+1 and N_a is the number of spiny lobsters of age a in reconstructed age-groups. With the numbers per age known, the use of the von Bertalanffy growth equation allowed the determination of their corresponding lengths. These lengths were transformed into their respective weights by using the equation

$$W = 0.0404.L^3$$

where W = Total weight (g) and L = Total length (cm).

The time units are years. The age structures for each year were estimated assuming a constant, natural mortality. For setting the variables of the initial state, the abundance per age-class ($N_{a,y}$) was set using the age-specific abundance $N_a/\Sigma N_a$ obtained from equation (1). In subsequent years, the age structure was defined after the estimation of the number of one-year-old recruits. These values were used to calculate catch-at-age as proposed by Sparre and Venema (1992) and were integrated into the FISMO simulation model (Chávez 2005) as

$$Y_{a,y} = N_{a,y} \cdot W_{a,y} \frac{F_t}{(F_t + M)} \left(1 - e^{(-F_t - M)}\right) \qquad (2)$$

where $Y_{a,y}$ is the catch-at-age a of each year y, $N_{a,y}$ is the number of spiny lobsters at age a in year y, $W_{a,y}$ is the lobster weight equivalent to $N_{a,y}$, F_t is described, and M is the natural mortality. Given the established initial conditions, the values of $Y_{a,y}$ were adjusted by varying the initial number of recruits and linked to the equations described above until the condition of the following equation was fulfilled

$$\sum_{a}^{\lambda} Y_{a,y} = Y_{y(REC)}$$

where $Y_{y(REC)}$ is the yield recorded during the year y, a = 5 years, and $t_\lambda = 3/K$ or longevity, where K is the growth constant of the von Bertalanffy growth equation and $t_\lambda = 25$ years, which is found by assuming that a reasonable life expectancy (L_{max}) is when 95% of the population reaches 95% of $L\infty$, the asymptotic length. Thus by making $L_{max} = 0.95L\infty$ in the von Bertalanffy growth equation and finding the respective value of t the longevity was found. Use of the catch equation was made for each year in the time-series analyzed. For the estimation of the natural mortality (M), the criterion proposed by Jensen (1996, 1997) was adopted, where M = 1.5K = 0.1793 K is further described below. Estimations of the stock biomass and the exploitation rate

TABLE 1
Population parameter values used for the evaluation of the red spiny lobster fishery. To transform carapace length (CL) into total length (Lt), the equation Lt = (CL/0.0275) + 3.2 was used, giving L∞ = 56 cm (Lt), which was the value used as an input in the model. The resulting W_∞ was obtained by using the length - weight equation, W = 0.0404 L^3. To feed the model, five years was arbitrarily chosen as tc, the age of first catch*.

Parameter	Value	Units-Model	Source
K	0.1195	Bertalanffy	Vega et al. (2000)
L∞ (mm, CL)	153	mm, tails-Bertalanffy	Vega et al. (2000)
W∞ (g)	7,135	live weight-Bertalanffy	This paper
to	–0.210	Years-Bertalanffy	Vega et al. (2000)
a	0.0404	Length - weight	This paper
b	3.0	Length - weight	This paper
tc*	7 & 4	♀ and ♂ respectively	Years, Vega (2003)
Maturity age	5	Years	This paper
Longevity	25	Years	As 3/K, this paper
a'	0.25	Beverton & Holt	Estimated after age structure
b'	0.6	Beverton & Holt	Estimated after age structure
M	0.1793	Instantaneous rate	Jensen (1996, 1997)
Max. E (E_{max})	0.4556	$F_{MSY}/(M+F_{MSY})$	Exploitation rate at MSY, this paper
Phi'	2.6	Log K + 2Log L	Growth performance, this paper

E = [F/(M+F)] were made for each age-class in every fishing year analyzed by the model. These values were compared to the E value at the F_{MSY} level. A special case is when E is at the F_{MSY} level corresponding to the maximum exploitation rate that a fishery should attain before the stock is overexploited. A diagnosis of which years of the series the stock was under- or over-exploited was then made, providing an easy way to recommend either a further increase or decrease of F of the fishery.

The annual cohort abundance ($N_{a,y}$) coming from ages older than age-at-maturity (tm = 5 years) were used to estimate the annual abundance of adults (S_y) over the years, whereas the abundance of the one-year-old group was used as the number of recruits (R_y). The stock-recruitment relationship was evaluated by using a slightly modified version of the Beverton and Holt (1957) model in the form

$$R_{y+1} = \frac{a'S_oS_y}{S_y + b'S_o} \tag{3}$$

where R_{y+1} is the number of one-year-old recruits in year y+1, S_y is the number of adults in year y, S_o is the maximum number of adults in the population, and a' and b' are parameters modified from the original model where a' is the maximum number of recruits and b' is the initial slope of the recruitment line, which was constant through the simulation. The values of the parameters used as input are shown in Table 1.

The simulation was used to describe the main ecological processes underlying the stock dynamics. It allowed simulating exploitation scenarios under different combinations of fishing intensities and the age-at-first catch to maximize the biomass, the profits, and the social benefits. For this purpose, analytical procedures adopting the concepts and views of Chávez (1996, 2005) and Grafton et al. (2007) were used. The catch was displayed by the model, where the stock biomass and the fishing mortality for each year of the series were estimated.

The approach to the socioeconomics of the fishery was made through the explicit consideration of the costs of fishing per boat per fishing day, the number of boats, the number of traps, the number of fishermen per boat, and the number of fishing days during the fishing season. All of these variables impose the costs of the activity. The value is the price at the dock of the spiny lobster landed; the difference between the costs and the value is profit and the value (the benefit) divided by the cost is the B/C ratio. In the simulation, the costs of fishing and catch value were assumed constant over time.

The information from the 2008 fishing season allowed us to reconstruct the economic trend of this fishery for the last fifteen years with the aid of the simulation model, using the estimates of fishing mortality over time as a reference and its correspondence to the economic variables.

The changes in the population abundance using the number of survivors in each cohort were estimated. The initial condition is set by assignment of a seed value for F. The graphic display of the potential yield allowed us to find that for the current conditions of this fishery it was F_{MSY} = 0.15, allowing an estimation of an initial recruitment number and then estimations of abundance for each cohort for each year.

To evaluate the maximum number of traps, the Schaefer model (Sparre and Venema 1992), also known as the surplus-yield model, was used on this data series. The high variability of the data is characterized by two peaks of the catch over time, as shown in Figure 1, so we used the data series of 1940 to 2008 for this part of

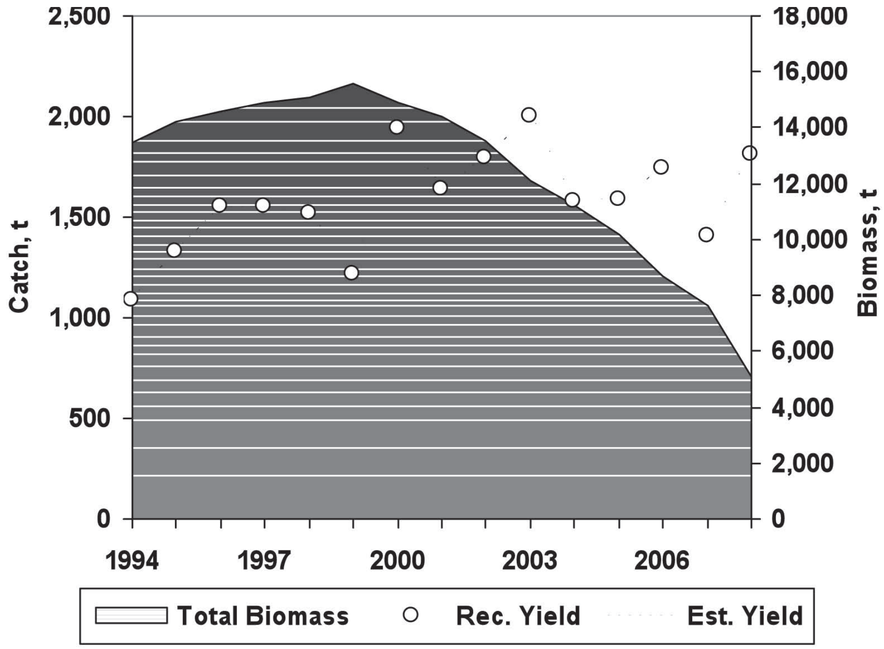

Figure 2. Stock biomass (right) and catch (left) in t by the red spiny lobster fishery off the Baja California peninsula.

the analysis. This model is based on the principle that the population-growth rate is described by a sigmoid curve, whose rate of change can be described by a quadratic equation ($Y = af + bf^2$) where the number of traps is used here as the independent variable and the catch is the dependent variable. The level where the rate of change is zero corresponds to the point where the fishery attains its maximum, equivalent to the MSY. The influence of climate seems to be great and makes the data appear noisy, but the analysis of this effect would be beyond the purpose of this paper.

Model Validation

The model was developed with 15 years of catch data. In the validation process, the 15th year was left out of the direct evaluation and its value was simulated as if it were unknown. Then the model was fitted to the whole series of 15 years. The difference between the recorded and simulated values on this 15th year provided a way to evaluate the uncertainty in the assessment made for 2008, the last year of the catch records analyzed.

Management Options

For comparison of some of the output variables, the condition for the 2008 fishing season was used as the reference. The management options were assessed for the year t + 1, (= 2009), which was used as the target of the fishery. The other three management options are that F_{MSY} is the combination of F and tc producing the highest catch, F_{MEY} is the combination of F and tc producing the highest profits, and F_{Traps} is the condition of the fishery if the number of traps in use were the number suggested by the use of the surplus-yield model.

RESULTS

Some Ecological Processes

We needed to define a parent-recruit relationship to link cohorts over time in the reconstruction of the age structure during the historical catch records and in the simulation process of the fishery. The number of recruits per adult over the fifteen years of data analyzed is 0.48. We saw an interesting variation of this ratio, because up to the year 2000 when the stock biomass was the highest, the value was 0.38, and after 2000, when the biomass was declining, this ratio increased to 0.61. These values could be interpreted as a density-dependence response of the stock biomass with an increase of the recruitment rate when the number of adults was low, and vice versa, but the data-series is not long enough to confirm this as a real pattern.

Condition of the Fishery

Stock biomass. The results show that the stock biomass had an increasing trend until 1999, then a declining trend after 2003. We believe the increasing trend is an artifact of the use of the catch equation, rather than a real one. We interpret the decline as caused by the high exploitation intensity, for if the stock were much larger, the fishing mortality would be negligible. The maximum

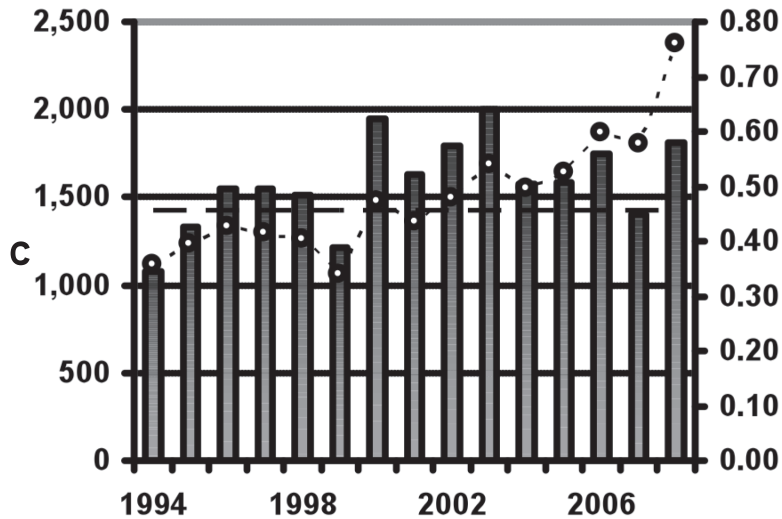

Figure 3. The exploitation rate (E) of the red lobster stock, with the E at the MSY level (0.46, horizontal line). For comparison, the catch (C) is also indicated with bars.

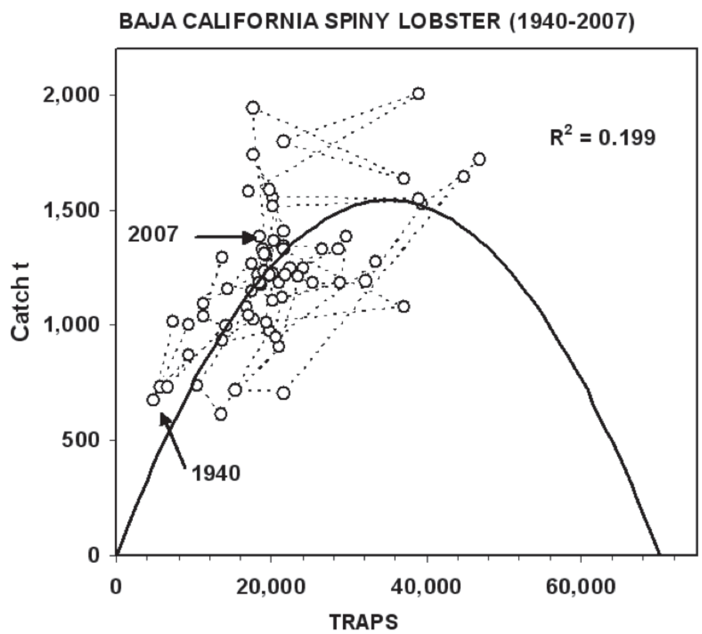

Figure 4. Catch as a function of the number of traps for 1940 to 2007. The parabola fitted to data describes the trend. The upper-catch value of the trend line indicates the maximum catch (1,540 t). According to this, the maximum number of traps/season (35,100, equivalent to 572 fishing boats carrying 38 traps for 85 days per season) is the maximum effort that should be used to avoid overexploiting the stock.

stock biomass of 16,800 t was measured in 1999 (fig. 2). As a consequence, the catch had two maximum values of about 2,000 t, one in 2000 and the other in 2003, declining after that until the last three years when the mean catch was 1,800 t. The difference between direct estimations of catch and those obtained by simulation was between –11% and +22%, with a mean value or mean error of 5%.

The intensity of exploitation indicates that the fishery has been overexploited consistently since 1999 and in particular since 2002, when the values of F increased, about which we need to be concerned. In consequence, the exploitation rate E lay between 0.36 in 1994 and 0.76 in 2008, with E = 0.46 at the MSY level, allowing us to conclude that the stock has been overexploited for the last seven years (fig. 3). A drastic reduction of fishing effort is suggested to keep the fishery healthy.

Further evidence of the overexploitation was examined using the increasing number of traps. The number of traps has increased from 6,000 in 1940 to 21,600 in

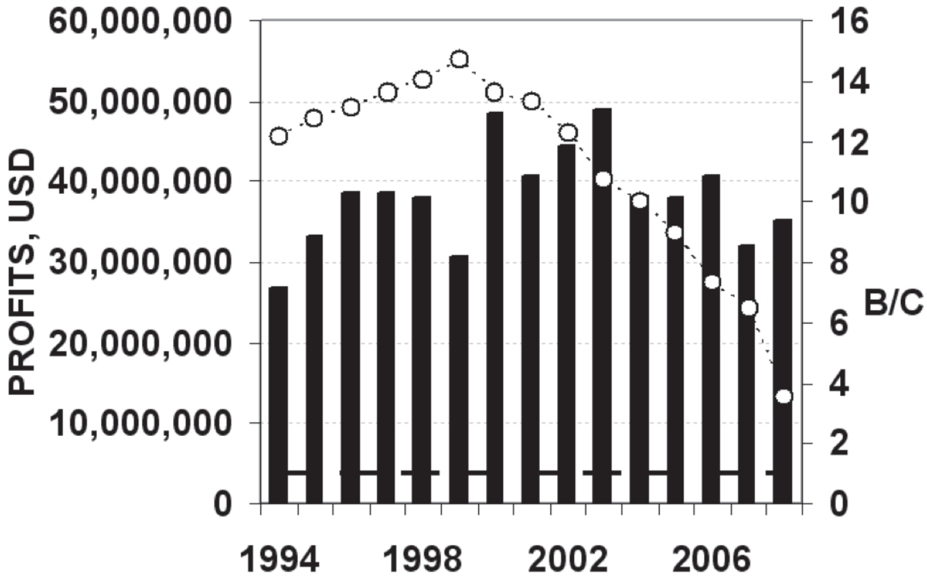

Figure 5. Reconstruction of total profits (bars and left scale) and the benefit/cost ratio over the last fifteen years of the spiny lobster fishery off the Baja California peninsula (dots, right scale), both in Y axis. The horizontal broken line is the B/C at the economic-equilibrium level, when B = C, as a reference to diagnose the economic condition of the fishery.

2007 with peaks of 37,000 and 39,000 in 1994 and 1997. Over 20,000 traps have been in frequent use since 1954 and in particular after 1963.

To determine the maximum number of traps to be used, the parabola was fitted to data as shown in Figure 4. As a result of this, we found that the trends are not as clear as expected. The data do not indicate overexploitation, as the age structure does, which is explained below, though the data of the last group of years suggests the need to enforce a limit for the maximum number of traps.

From the parabola fitted to the data, the quadratic equation ($Y = af + bf^2$) indicates that the maximum number of traps ($fmax = (-0.5{\star}a/b)$) is 35,100, producing a maximum yield ($MSY = (-.25{\star}(a^2/b))$) of 1,540 t. The trend of the last group of years of the series is interpreted as evidence of overfishing (see Sparre and Venema 1992 for further explanation). From this, the reduction of the fishing effort to maintain the condition of relative stability of the fishery is advised. The use of this evaluation of the maximum effort evidently is not suitable, because this underestimates the real effort and overestimates the exploitable biomass. The relative constancy in the number of traps and the lack of a decline in the catch per unit of effort over time also is evidence of excess fishing capacity, explaining why the use of the Schaefer model does not provide the expected results.

Bioeconomic analysis. In 2008, the fishery provided direct employment to 1,164 fishers on 572 boats, each boat working 85 days per fishing season. By examining raw data, we found that the cost of each fishing-day per boat is $112 USD and in 2008 total fishing effort was 122,572 days. The catch obtained was 1,810 t with a value of $48,951,000, producing profits of $35,226,168 with a benefit/cost ratio of 3.6, which is more than three times the cost of fishing operations. The cost of fishing is a variable depending on the stock size and fishing effort. This way, estimates of total profits and the benefit/cost (B/C) ratio were obtained as shown in Figure 5.

The trend shows that the highest profits obtained in 2000 and 2003 were about $50 million USD, but these years are only a short period of maximum profits, declining afterwards to $35.2 million in 2008. The B/C ratio shows a trend similar to the economic efficiency, with a maximum value of B/C = 14.7, recorded in 2000, and evenly declining afterwards, approaching the equilibrium level and a pending socioeconomic crisis, with a B/C = 3.57 in 2008, which is still very profitable. By projecting this trend on Figure 5 it is evident that it will attain the limit in only three or four more years.

To examine the stock response and its socioeconomic condition as a function of the fishing intensity (F), the simulation describes a series of 5 curves; the yield, the profits or economic benefit, the number of boats, the number of fishermen and the B/C ratio (fig. 6). In four of them (yield, profits, boats, and fishermen) the maximum value of F at the MSY is F = 0.15. The B/C ratio then attains its maximum value at the lowest F.

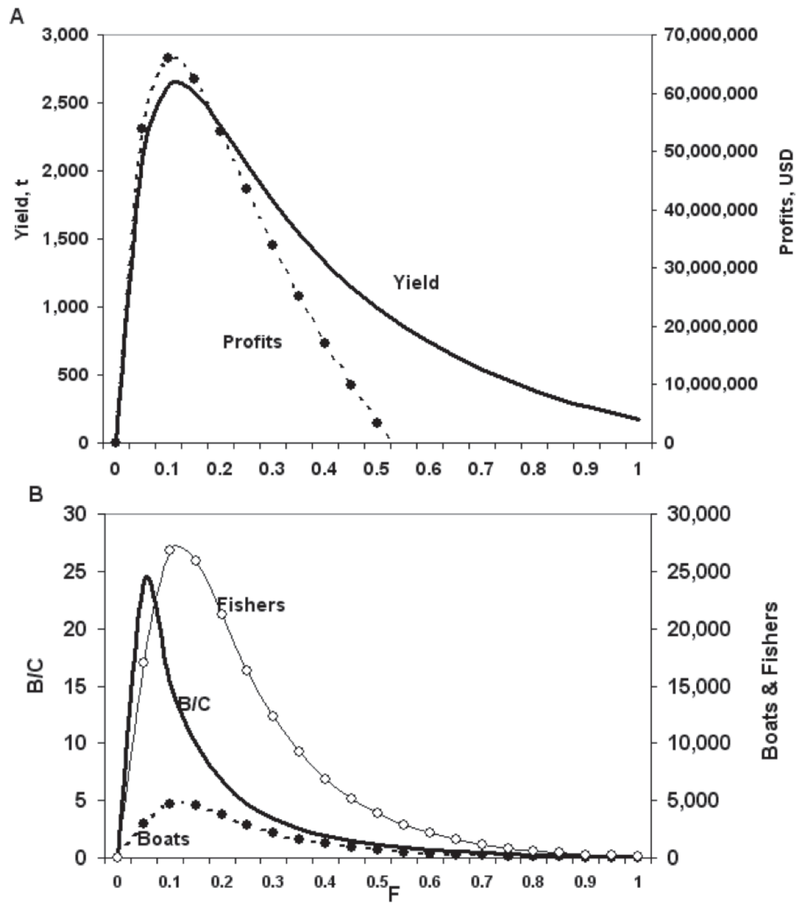

Figure 6. Stock response of the spiny lobster fishery off the Baja California peninsula, showing the trend of the potential yield and potential profits (A) and the number of fishermen, boats, and the B/C ratio (B) as a result of the intensity of fishing mortality. Maximum profits are attained at a lower level of F than the one required for the maximum yield. The number of fishermen and boats reach their maximum at the same value of F as the yield. The maximum B/C ratio is found at the lowest value of F and declines monotonically with a higher fishing intensity.

DISCUSSION

Many papers have documented overexploitation, overcapitalization, and threats to food security (Beddington and Kirkwood 2005). The dynamics of the spiny lobster stocks are strongly influenced by the overexploitation and overfishing as a rather general problem in the fisheries world-wide and though the solution seems straightforward and the benefits are clear, action is often taken after the stock had been driven to low levels (Rosenberg 2003). Unfortunately, most stock assessments use no quantitative information derived from previous experience on other fish stocks (Hilborn and Liermann 1998).

The intensity of recruitment depends to a great extent on the stock size, as part of an ecological mechanism related to density dependence and carrying capacity. By comparing these trends with the historical values of F, we found that the fishery has been overexploited since 2003, with the worst year 2008 when there was a fishing effort nearly two times greater than the one required for the MSY, dramatically leading the fishery to an economic crisis within a few more years. A well-known cause of overexploitation is the fishermen's opposition to a lower catch caused by stock rebuilding, requiring the finding of appropriate incentives to provide security and benefits to them during that process (Grafton et al. 2007).

Assessment

The model was fitted to data from the last fifteen years, from 1994 to 2008, allowing a direct estimation of F for each year. To evaluate the magnitude of uncertainty, the model was fitted again, but this time from data for 1994 until 2007. An estimation of the catch for 2008 was made by simulation and using the same value of F obtained with the previous fit. From this a new estimate of the catch was obtained. Coincidently with this approach, Beddington and Kirkwood (2010) stated that the simple relationships that can be used to estimate potential yield and the maximum sustainable fishing-mortality rate give information about the growth curve and the size at which fishing starts. Current fishery management is working well to achieve the legislated objec-

TABLE 2
Management scenarios for the red spiny lobster fishery off Baja California. The condition for the 2008 fishing season is used as reference. The management options are F_{MSY} = F at the MSY level at a tc = 11 years; F_{MEY} = F at the MEY level at a tc = 11 years; F_{Traps} = the condition of the fishery if the number of traps is 35,100 as suggested in Fig. 4, equivalent to F = 0.48. The days/boat/year are 85 in all cases. Costs and value are in USD.

Indicators	Current 2008	F_{MSY}	F_{MEY}	F_{Traps}
F (/y)	0.283	0.23	0.18	0.476
Age of 1st catch (tc)	5	11	11	5
Yield, t	1,813	3,638	3,562	1,066
Fishing days /y	122,572	3,638	75,300	199,005
Boats	572	449	351	109
Direct jobs	1,164	918	723	929
Catch Value	48,951,000	98,228,900	96,169,000	28,776,300
Costs	13,724,800	10,773,800	8,431,600	22,283,300
B/C	3.6	9.1	11.4	1.9
Profits	35,226,168	87,455,083	87,737,341	6,493,073
Profits/boat	61,580	194,770	249,680	6,990
Traps	21,620	16,970	13,280	35,100

tive of the MSY in some countries but is failing in others (Hilborn 2007).

The exploitation rate E was used as a criterion for the diagnosis of each fishery, where F_{MSY} is the F at the level producing the maximum yield at the apex of the production curve, or the maximum sustainable yield, as it is currently known. This is a useful extreme reference point for the diagnosis of a fishery, because it allows a quick and easy interpretation of the condition of any fishery. It varies under different ages at first catch, as we explained above. The maximum or limit value of E found was E_{max} = 0.46 and it was used as a reference for the diagnosis of the fishery. This criterion was used for the fifteen years of data.

Uncertainty of Assessment

Many fisheries at present are often characterized by an excessive investment in the fishing infrastructure, the profits are close to the economic-equilibrium limit, and new fishermen still have strong expectations of taking part in this activity. Our results show there is an excess number of boats and traps. The catch per unit of effort is not a good indicator of stock density and the large variance in the catch suggests that recruitment is variable, increasing the uncertainty of the estimates. The results of the use of the Schaefer model are evidence of this statement.

Some of the model outputs should be taken as trends rather than hard results. However, the analysis provides a consistent criterion, showing that without any doubt, the fishery is coming to a socioeconomic crisis if the access is not controlled.

Sustainability of the Fishery

Fisheries have rarely been 'sustainable' (Pauly et al. 2002). Ecological extinction caused by overfishing precedes all the other pervasive human disturbances to the coastal ecosystems, but the literature also demonstrates achievable goals for restoration and management (Jackson et al. 2001). There are substantial probabilities of the wrong identification of the condition of the stock being exploited (Punt 2000). Unsuccessful systems have generally involved open access, attempts at top-down control with a poor ability to monitor and implement regulations, or reliance on consensus (Hilborn et al. 2005a). New definitions of sustainability will attempt to incorporate the economic and social aspects of the fisheries (Quinn and Collie 2005), and our work is an example of such an approach. In this fishery, the F_{MSY} has been used as a reference point to evaluate the biological, economic, and social consequences of using the current fishing effort or other possible options, as shown in Table 2, where three different scenarios are compared to the current condition. The driving variables are F and tc and in each case successive changes in tc are tested until either the catch or the profits are chosen as the target to maximize, and reaches its maximum value. The values of all the other variables depend on F and tc so they should be considered as the consequence of any strategy chosen. The maximum social benefit is derived from the number of boats fishing, so their maximum number is multiplied by the number of fishermen per boat. The economic-equilibrium level indicates the value of F is at the limit of fishing intensity beyond which it becomes unprofitable. This is one of the reasons why it is unlikely to force a population to extinction as a sole consequence of the strong fishing pressure. Rights-based management is probably not appropriate for all fisheries (Hilborn et al. 2005b). With recent data on the catch and effort we were able to obtain the corresponding information on costs and profits of the fishing activity such that it allowed us to link this information to the simulation model and to evaluate the optimum bioeconomic-harvesting options.

Here, the so-called stock effect is a nonlinear function of yield and is difficult to estimate with a high level of precision (Hannesson 2007).

The maximum economic yield (MEY) was found by following the costs and benefits of the fishing activity and by depending on the stock biomass and the fishing effort. It usually is where $F_{MEY} \leq F_{MSY}$. In a well-managed fishery it is more convenient to adopt this as the target rather than the F_{MSY} because it implies a lower risk of overexploitation. The tc value producing MSY and MEY may look unreal in this fishery, because the model indicates that tc should be 11 years. Whatever may be the reason for this, it is impractical to wait until the spiny lobster reaches its 11th year to start exploiting this species. The maximum yield obtained currently with tc = 5 years is 3,640 t with a profit of $87 million USD. The use of this fishing strategy implies a significant decrease of 19% in the fishing effort compared to the current situation (tab. 2). Additionally, appropriate control regulations are required to control exploitation to maintain the lobster fishery as sustainable over time and space. In contrast, the option of using the MEY seems to be quite appealing because it provides a profitable economic activity ensuring the sustainability of the exploitation. It has the relative inconvenience that can be attained only with a tc = 11 years, which makes its use impractical. The conversion of scientific advice into policy, through a participatory and transparent process, is at the core of achieving fishery sustainability (Mora et al. 2009) and it is hoped that the results presented here can be used for a sustainable exploitation of the spiny lobster fishery off the Baja California peninsula.

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