Bio-economic Modelling Applied to a Spiny Lobster Fishery of the Northwestern Caribbean

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ABSTRACT

The spiny lobster *Panulirus argus* (Latreille, 1804) is the most important fishery for the Caribbean coast of Mexico and represents the highest lobster catch for this species in the country with over 900 t caught yearly. The Chinchorro Bank Biosphere Reserve is one of the most productive zones in the area and provides 98 direct jobs for three fisher cooperatives. Results from the model in the present study suggests that fishing pressure on the spiny lobster is over exploiting the stock, and although some non-explained changes could also be determined by climate change effects on recruitment, migration or other specific population parameters, simulation results indicate that relative high fishing mortality has occurred over time. Although this fishery has remained as a profitable activity as observed in the yearly catch stability, advice is given to enhance recruitment and restore stock biomass to its initial values. The models results suggest that maximum yield may be achieved by a reduction of current fishing mortality (F) by 29%; however, the risk of a socio-economic crisis requires a gradual reduction of fishing effort, which could be attained by reducing (F) by 0.025 per cent each year; which means a one week reduction on the first fishing season, until the goal is achieved. The models projection shows that after the first few years of applying this F reduction, catch decrease would be minimal, and the stock could be restored to levels obtained 30 years ago, where yields were twice the current ones. Simulations also suggest that if this management strategy is adopted, the number of fishers and profits produced would reach more than twice the current levels.

KEY WORDS: Fisheries, bio-economic simulation, Caribbean spiny lobster, harvesting strategies

Evaluación Bio-económica de una Pesquería de Langosta del Caribe Noroccidental

La langosta del Caribe *Panulirus argus* (Latreille, 1804) constituye la pesquería mas importante del Caribe de México donde se capturan los volúmenes mas altos de langosta en el país. La pesquería de langosta de la Reserva de la Biosfera Banco Chinchorro fue evaluada; la explotan 98 pescadores y constituye una de las zonas pesqueras más productivas de la región. Los resultados sugieren que la presión de pesca ha sobre explotado el recurso en años recientes, a pesar de que se detectaron ciertos cambios no explicados pero poco significativos en la biomasa que pueden haber sido inducidos por el cambio climático. Sin embargo, esta pesquería aún es redituable. Se proponen medidas para mejorar el reclutamiento y para restaurar la biomasa del recurso; para evitar el riesgo de una crisis socio económica se requiere de una reducción gradual del esfuerzo de pesca mediante una reducción de las temporada de captura en una semana, hasta que la captura anual muestre una tendencia creciente por arriba de las 30 t anuales. La simulación sugiere que si se adopta esta estrategia de manejo, la biomasa de la población podría recuperarse a niveles mayores que el doble de los actuales, lo cual implicaría la posibilidad de duplicar el número de pescadores y las utilidades en el marco de la conservación.

PALABRAS CLAVES: Pesquerías, langosta espinosa, simulación bio-económica, estrategias de pesca, Caribe

L'évaluation Dioeconomique d'une Pêcherie de Langouste des Caraïbe du Nord-ouest

La langouste *Panulirus argus* (Latreille, 1804) est la pêcherie la plus importante pour la côte antillaise du Mexique et représente la prise la plus élevée de langouste pour cette espèce dans le pays. La pêcherie a été évaluée à la Chinchorro Bank Biosphere Reserve, une des zones les plus productives dans la région, en fournissant 98 emplois directs aux pêcheurs. Les résultats suggèrent que la pression de pêche sur la langouste ait été sur le fait de surexploiter le stock ces dernières années, en dépit de quelques changements non-expliqués, mais non-significatifs dans la biomasse de stock ont été observés qui ont pu avoir été causé par le changement climatique. Cependant, cette pêcherie est encore une activité profitable. Il es conseillé d'améliorer le recrutement et de restituer la biomasse de stock; le risque d'une crise socio-économique exige une réduction graduelle d'effort de pêche en raccourcissant la saison de pêche d'une semaine chaque année, jusqu'à ce que la prise commence à montrer une tendance à augmenter régulièrement au-dessus de 30 tonnes métriques / l'année. Les simulations suggèrent que si cette stratégie de direction est adoptée, la biomasse de stock pourrait être restituée aux niveaux deux fois supérieurs aux valeurs actuelles, en impliquant la possibilité de doubler le nombre actuel de pêcheurs et de profits dans le cadre de conservation.

MOTS CLÉS: Pêcheries, langouste, simulation bio-économique, stratégies de récolte, caribéen,

INTRODUCTION

Scientific surveys and records of the commercial fisheries are the main source of data available to determine stage-specific, spatial and temporal distributions of exploited stocks in the Caribbean. Since 1967, fishing activity at the Mexican Caribbean developed new techniques and a series of regulations aimed to improve the management of marine stocks. Minimum tail length was fixed to 14.5 cm, capture of females egg carriers was prohibited and the season was limited from July 15th to March16th. Although in 1979 minimum legal tail size was reduced to 13.5 cm (Lozano Alvarez 1994) and the artisanal fishermen acquired larger motorized boats later on; scuba diving has been prohibited as a means of fishing, and only skin diving is allowed which limits the fishery to the 15 - 20 m surface depths within the Banco Chinchorro`s Biosphere Reserve. Management goals of the local authorities consider the rational exploitation of stocks in order to obtain the maximum possible benefits over the long run.

Commercial lobster fishery represents 40.8% of the coastal communities fishing industry income in the Region of the Caribbean coast of Mexico, and 71.6% of the total fishing income for Chinchorro Bank (CB), our case study area. In the Caribbean, general catch has declined for crustaceans, conch, and fish since the late sixties, which could be attributed primarily to over-exploitation, whilst lobster catch at the Bank is currently fluctuating at a relatively stable rate of 25 metric t (t).

The present study was carried out with the purpose of finding trends and possible answers to the following questions:

i) What is the status of the spiny lobster stock at CB, Mexico?
ii) Given the recent decline in catch, how can stock be restored?
iii) What size at first catch will maximize benefits (biomass, profits and social)?
iv) Are optimum exploitation options compatible?
v) What are the optimum biological and economic fishing intensities for the fishery?

In order to answer these questions, the goal of this is study was to assess the stock, to diagnose the spiny lobster fishery of CB in the north western Caribbean, and to suggest optimal biological, economic and social strategies which will provide informed advice to fishers and authorities in order to achieve a sustainable exploitation.

METHODS

A combination of several procedures and methods for stock assessment were used. Using catch data as a reference, changes in abundance, costs and benefits of fishing activities were determined over time, as well as observing trends in fishing mortality and estimates of total stock biomass. Criteria for evaluation of fishing scenarios were based on biological reference points, such as specific fishing mortality levels (F) that represent particular stages of the population, such as the F required for the Maximum Sustainable Yield $_{\text{(FMSY),}}$ the fishing intensity producing the Maximum Economic Yield $_{\text{(FMEY),}}$ the levels of employment under these two scenarios in contrast with the optimum, and the fishing mortality (F) at the economic equilibrium yield level (EEY), when Benefits = Costs or B/C = 1 (F$_{\text{EEY}}$).

Population parameter values plus catch data were analyzed with the aid of a simulation model. A time data series of the catch data reported in the Caribbean for the spiny lobster between 1982 - 1983 and 2004 - 2005 and population parameters obtained for that species were used in the analysis implemented in the semi-automated, age-structured simulation model FISMO (Chávez 2005). Population parameter values, age of first capture catch data, catch value, costs of fishing, fleet size, number of fishermen, and sources of information are shown in Table 1. The age of first maturity considered (2.6-3 years), has been estimated around 90-96 mm of carapace length, obtained from population dynamics studies of the species (Davis 1975, Lozano-Alvarez *et al*. 1993).

Table 1. Input data required by FISMO: fifteen years of catch data; population parameters include growth parameters (L∞, W∞ K and t_0), "a" and "b" values of the length-weight power regression, age of first capture. (tc), and age of first maturity. Bold values indicate the highest and the lowest catch recorded.

Catch data records for spiny lobster fishing of Chinchorro Bank, Mexico

Fishing season	Recorded catch (Kg)	Year	Recorded catch (Kg)
1982/83	67,021	1996/97	17,511
1983/84	**67,448**	1997/98	**14,221**
1984/85	41,222	1998/99	16,732
1985/86	32,926	1999/00	22,882
1986/87	30,051	2000/01	23,721
1987/88	24,713	2001/02	18,845
1988/89	22,673	2002/03	19,474
1989/90	23,243	2003/04	24,542
1990/91	23,099	2004/05	30,915
1991/92	17,576	2005/06	26,300
1992/93	18,232	2006/07	30,940
1993/94	16,528	2007/08	32,230
1994/95	16,504	2008/09	32,200
1995/96	19,756		

Population parameters (* = estimated by the model)

L∞ L∞(cm)	31	Age of 1st. Catch, tc (years)	3
W∞ (g)	1,619	Age of 1st. maturity, tm(years)	3
K (/year)	0.24	Phi*	2.4
t_0	-0.16	Est Longevity (as 3/K, years)*	13
a	0.038	M (/year)*	0.36

Growth and Age Structure

Once growth rate was known, data was referred to total catch, so estimates of age composition of catch were made. With these partial results 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 lobster of age a in samples. Time units are years.

Preliminary age structures for each year were estimated assuming constant proportional abundance between age classes and constant natural mortality. For each year, initial abundance per age class $(N_{a,y})$ was set according to age specific proportional abundance $n_a/_{\Sigma}n_a$ obtained from Equation (1). These values were used to calculate catch-at-age as proposed by Sparre and Venema (1995) and were integrated into the FISMO simulation model (Chávez 2005)

$$C_{a,y} = N_{a,y} \bullet W_{a,y} \frac{F_t}{(F_t + M)} (1 - e^{(-F_t - M)}) \qquad (2)$$

Where, $C_{a,y}$ is the number of spiny lobsters at age a in the catch of each year y; $N_{a,y}$ is the abundance number of spiny lobster at age a in year y, $W_{a,y}$ is the lobster tail weight equivalent to $N_{a,y}$ and F_t and M are as described before. Given the established initial conditions, $C_{a,y}$ values were adjusted varying the value of $N_{a,y}$ until the fulfilment of the condition.

$$\sum_{a}^{k} C_{a,y} = Y_{y(OBS)}$$

Where, $Y_{y(OBS)}$ is the yield recorded during the year y. These equations were evaluated for each year in the time series analysed.

For the estimation of Natural Mortality (M) the criterion by Jensen (1996, 1997) was adopted, where M = 1.5K, here K is the growth rate parameter of the von Bertalanffy growth equation. Estimation of stock biomass was made for the fifteen fishing seasons analysed by the model and the exploitation rate E = (F/(M+F)). These values were compared to the E value at the F_{MSY} level and this way a diagnosis on which years of the series the stock was under or over exploited, providing an easy way to recommend further increase or reduction of F.

Recruitment

Annual cohort abundance $(N_{a,y})$ calculated from ages older than age-at-maturity (originally two years, but currently considered as three years) were used to estimate the annual abundance of adults (S_y) over the years, whereas abundance of one year-old group were used as the number of recruits (R_y). The stock-recruitment relationship was evaluated through a slightly modified version of the Beverton and Holt model (1957) in the form:

$$R_{y+1} = \frac{a'S_o S_y}{S_y + b'S_o} \qquad (3)$$

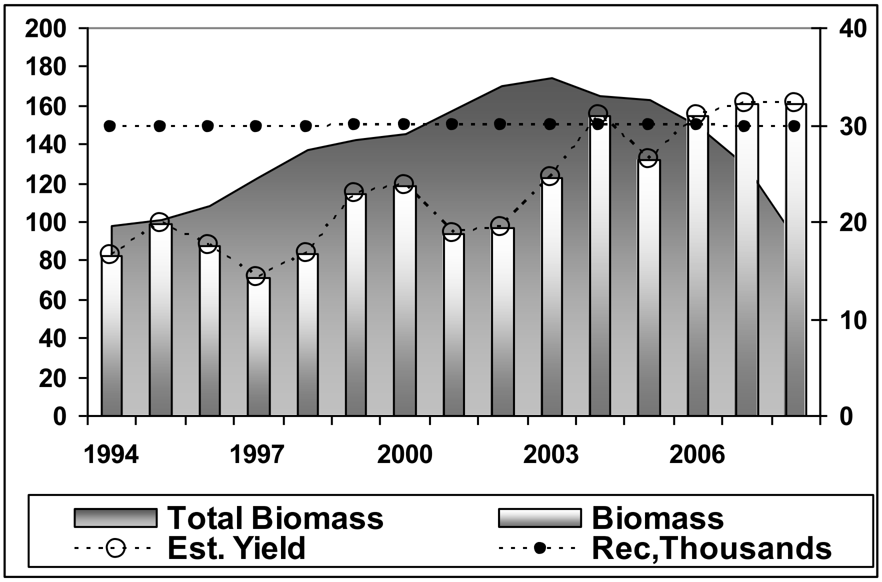


Figure 1. Relationship between stock biomass, recorded and simulated catch of spiny lobster captured by trawling fleet at the Chinchorro Bank fishery, t. Grey area = Stock biomass, left scale; Lines with filled circles, Number of recruits (thousands), left scale;

where $_{Ry+1}$ 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; a' and b' are parameters modified from original model that satisfy a = a'S_o, and b = b'S_o. In the original model, a is the maximum number of recruits, and b is the number of adults to obtain a/2; its value was fitted to the catch recorded the last fishing season and the number assigned was b = 1.5338 and it was maintained constant through the simulation. Therefore, a' = a/S_o, i.e. the minimum recruitment rate $_{(amin)}$ when density of the spiny lobster stock is high. The proportion a/b represents the initial slope or maximum recruitment rate $_{(amax)}$ when density population is low (Hilborn and Walters 1992); in this case its value was kept constant and equal to 0.25, however, it can be modified by the user. One of the characteristics of the recruitment model as adapted to the simulation and constraining its general application to intensively exploited stocks, is that once the highest yield is identified, the number of recruits estimated is kept constant, this characteristic leads to an over estimation of the stock biomass and under estimation of fishing mortality in subsequent years when the stock size is declining; for this reason, recruit numbers for each year was estimated directly over the historical period and the stock-recruitment equation was applied only for the simulation of exploitation scenarios.

Bio-economic Analysis

Updated information on costs of fishing activities and value of landings at the fishery provided the information necessary for a basic bio economic analysis, just enough to define some criteria useful for management purposes. Data was obtained directly from the largest of the three fisheries cooperatives, accounting for the 51.97% of total lobster fishing activity at the Bank in 2004. Total revenues from catch value at the dock were considered as benefits and total costs of fishing trips per fleet size, multiplied by the total number of trips were considered as costs. Detailed information on the costs and revenues for the fishing season 2004 - 2005 is provided in Table 2.

Fishing Capacity and Number of Fishermen

Data on the fleet size, number of fishers, and approximate number of days of fishing trips were obtained. Here, the number of boats fishing at the Bank is 33 and the number of fishers working per season is 98. In addition to the number of boats, there are three nurse 45-foot long boats, where the daily catch is landed and stored for several days until their storage capacity is full. Then, the catch is taken to Mahahual, nearly three hours away, from where it is landed, and sold to companies, who take it to Merida, Cancun and Chetumal, where it is sorted by size and generally sold in Cancun. An estimation of the fishing capacity or number of 22 foot-long boats, called pangas in Mexico, or Â and the number of fishers at any fishing season were made by developing the following model:

TABLE 2. Economical and social indicators of the spiny lobster fishery. Data from the 1994-2008 fishing season referred to the number of fishers and additional staff depending on the spiny lobster exploited at the same fishing ground. Values are expressed in USD. Costs and benefits transformed from Mexican pesos to USD at a rate of $13.5 pesos per one dollar. Bold names indicate the main values of socio-economic variables and values of the attributes being compared.

Item	**Per boat**	**Total**
Food	1313.60	—
Fuel	258.00	—
Ice	2.71	—
Management costs/kg	5.08	—
Catch/fisher/day (kg)	3.78	—
Catch/boat (kg/day)	9.45	—
Catch/fisher/season (kg)	—	315.3
Total catch 2004 (kg)	—	30,900
Number of 23 foot-long boats	—	**33**
Number of daily fishing trips per month	—	10.2
Fishing effort per month, daily trips	—	336
Fishing effort, daily trips per eight-month season	—	**2,691**
Number of fishers	—	98
TOTAL CATCH VALUE ($25.42/kg)	—	**858,334**
TOTAL COSTS (50% of value)	—	**88,803**
Administration costs (20% of each kg)	—	71,667
(Remaining costs, retirement fund, accountant payments, fuel, ice, and repairing (30%)	—	257,500
Food, USD/day	14.82	39,865
PROFITS (Catch value-Costs)	—	**769,531**
BENEFIT/COST	—	**9.7**

$$B = C \bullet F \bullet B/C \bullet \partial$$

where C, F and B/C are the catch, Fishing mortality and the Benefit/Cost of the year respectively, and ä is a coefficient fitted to the 2004 fishing season, where the other variables were known or estimated previously. In this case ä = 2.78, such that at the fishing season 2004 - 2005, B = 33 and multiplying this number by 2.7 plus nine others working on the three nurse boats, this way the number of fishers (N_f) obtained is 98. The equation developed for the estimation of the number of boats depend on the catch in such way that its maximum number (36) is linked to the catch at the MSY level, a value given by the model; its minimum size (23) is determined by a high F = 0.32, such that the B/C = 1; with higher F values the fishery is no longer profitable. Likewise, the number of fishers is obtained just by multiplying the number of pangas by 2.7 plus 9 crew members aboard the three nurse boats.

Simulation

This technique was used to describe the main ecological and economic processes underlying in the stock dynamics. It allowed simulating exploitation scenarios under different combinations of fishing intensities offshore to maximize the benefits (in biomass or profits and fleet carrying capacity and their social values as dependent variables). For this purpose, analytical procedures adopted the concepts and views from Chávez and Arreguín-Sánchez (1993), Arreguín-Sánchez (1995), and Chávez (1996).

With population parameters, growth curves in length and weight were obtained. The catch was displayed by the model, where stock biomass and the fishing mortality for each year of the series were estimated. Initial age structure of the stock and its size was defined.

The model allows estimate changes in population abundance through the number of survivors in each cohort. Initial condition is set by assignment of seed values for F, which allows preliminary estimations of abundance for each cohort at each year. Adjustment of each annual F value was done by calculation of catch as proposed by Sparre and Venema (1995). Varying the annual value of F attained the condition that simulated catch equals to recorded catch. By adding into the model the pertinent information on costs of fishing, benefits and social value of current fishing activities, it was possible to obtain further information on the economic and social value of this fishery under a wide variety of exploitation scenarios.

Exploitation Scenarios

This analysis allowed determination of the F values required for defining two reference points, the F_{MSY} and the F_{MEY}. Other reference points, like the F required to attain the maximum fleet size and the maximum number of jobs can also be defined. In addition to F, the age of first catch is important, because catch level also depends upon this variable, which affects the catch and socio-economic variables. Estimations of profits, the B/C ratio, number of boats, and number of fishers are other outputs in each scenario. A series of simulations were made to determine the level of uncertainty in stock and yield estimates. Model outputs analyze yield, profits, stock biomass, and harvest rates. Results were compared to reference points, with respect to F and tc (the age of first catch). This allowed testing a wide number of scenarios providing several feasible options for use as management targets.

RESULTS

Data

Input required by FISMO including the population parameters and fifteen years of catch data records of *P. argus* at Chinchorro Bank are shown in Table 1. Catch data since the 1982 - 1983 fishing season are included, but reconstruction of the stock comprise only the last fifteen fishing seasons (1990 - 1991 through 2004 - 2005).

Model Fitting

The relationship of stock biomass, exploited stock, and the number of one year old recruits reconstructed with the simulation, model is displayed in Figure 1, showing changes occurring over time, caused by random (presumably climatic) events as well as by changes in fishing effort. Catch fluctuates around 20 t over the last fifteen fishing seasons, with a slight increase from 19 to 31 t caught through the last four seasons. The model fitting was developed by assuming initially that the fishery was exploited to its maximum capacity, to an exploitation rate of 0.29 constant every year (F_{MSY} = 0.15/year); F values > 0.15 produced lower yields, so the next step to fit the model for each year was the estimating the recruit number, and then final fitting was made changing F. The number of recruits displays a contrast with the stock biomass, being high during years when the biomass was low and vice versa.

Exploitable biomass and catch display a high variability due to possible changes in catchability over time, or could also be caused by fluctuations associated to environmental factors. This is one of the most valuable fishery stocks of the Caribbean; the highest spiny lobster catch at CB since the 1982/1983 fishing season was 67.4 t recorded in 1983/84, with 67.5 t and the lowest in 1997/98 with 14.2 t. However, yields recorded at the early eighties could be a target to pursue by the CB fishery.

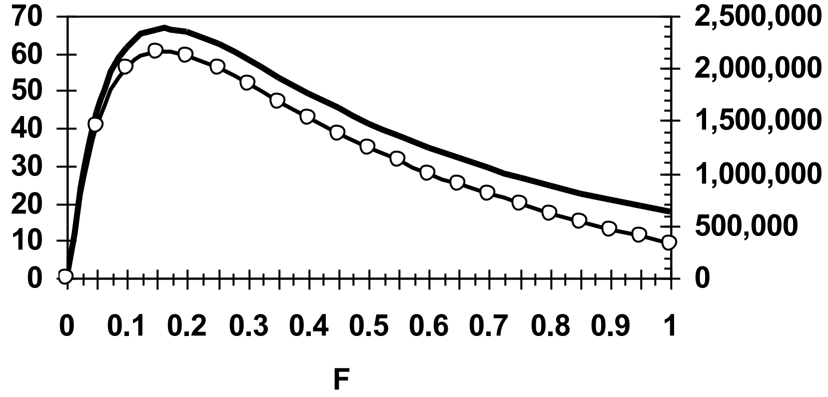
Stock-Recruitment

The parent-recruit analysis of spiny lobster of the Caribbean shows that the number of age one recruits ranged around 25,000 in the first few years of the series, but during the last half of this period this number often exceeded 220,000 (Figure 1). The number of recruits displays a contrast with the stock biomass, being high during years when the biomass was low and vice versa. The catch may decrease if spiny lobster size in the recruited cohort is reduced as a result of overfishing; however, this is unlikely to occur if the minimum tail size (135 mm) is maintained and enforced by the constrains in size imposed by the US government to lobster tail imports.

Potential Yield

While reconstructing the fisheries history, it was found that in 1999 the fishers may have had no profits (B/C = 0.97), and the fishery could have faced some difficulties because there was no catch recorded in December that year. Evidence supporting that situation is provided by the exploitation rate (E), observing that in that season biomass was low and E was the highest (45%) of the series of years examined. The relationship between potential yield and potential economic benefits as well as socio-economic indicators like fleet size, the B/C ratio and the number of fishers was obtained for a wide combination of F and tc values (Figure 2 a, b), in order to estimate the optimum yield. The output helped to diagnose the status of the fishery, where potential yield, potential profits and their corresponding social values (fleet size and number of fishers) could be compared to current values, these outputs allowed to reorient and optimise fishing strategies (Chávez 2005). Considering that the ages of first capture producing the highest yield were tc = 2 and 3 years and that tc = 3 was chosen for applying precautionary principles to stock management, the maximum yield MSY = 32.1 t can be obtained at an F = 0.15 (Figure 2a); however, this is an extreme reference point or threshold of overfishing and it should not be adopted as management target. Simulations over a wide series of F and tc values suggest that current biomass tends to produce maximum yield values with F < 0.15 and tc = 2 and 3, declining at a high rate when increasing F and tc values (Figure 3). An additional option was found by applying a gradual reduction of fishing effort at an annual rate of 0.0225, which would mean that the fishing season could be one week shorter the first year and continue a reduction for shorter periods in the subsequent years; this way and according to results of simulation, the stock recovery could be spectacular and after 30 years of simulation the catch would attain 69.2 t. In this case the social and economic benefits

A. Pot. Catch (t), left &
Profits (USD) right



B. Boats, Fishers and Benefit/Cost ratio

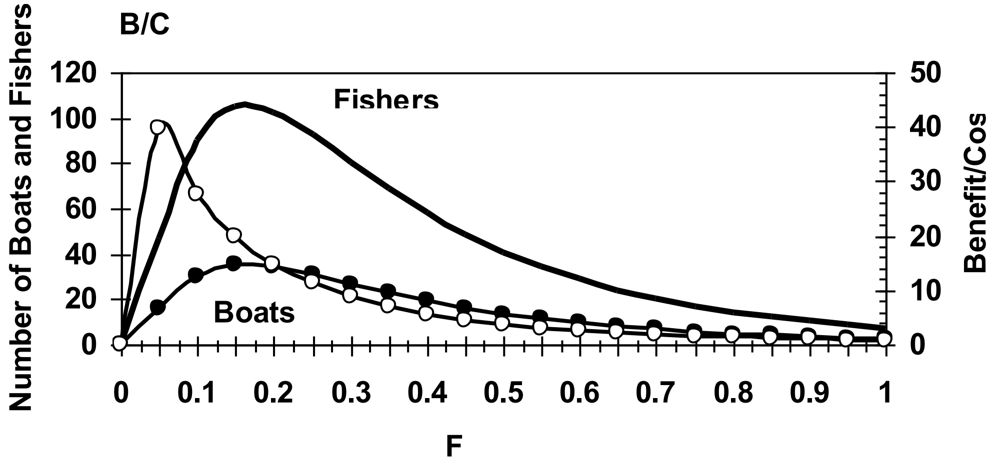


Figure 2. A. Potential maximum biological yield $_{(YMSY)}$, as a function of the age of first catch and the fishing mortality. According to the last fifteen years of simulation, the Maximum Yield (33.8 t) can be obtained at a fishing pressure of F = 0.15 and tc = 3 years old. This scenario would provide profits in a maximum of $602,791.00. However, the MEY would be obtained by reducing F at F_{MEY} = 0.1 with $647,051.00; here, the yield would be Y_{MEY} = 31.3 t. B. Potential maximum economic indicators (B/C, number of fishers and number of boats) as a function of the age of first catch (tc = 3 years old) and the fishing mortality, which is different for each variable.

would also be significantly higher without having a considerable decrease in effort in the immediate years after applying this regulation, as is has been described in the following paragraphs.

Potential Economic Yield

Economic factors of the fishery examined were based on data regarding shore landing catch value, and the main costs of fishing operations per small boat, details are shown in Table 2; the cost of fishing depends upon the estimations of F values for each year. By exploring the stock response under a range of tc and F values, its is evident that catches over 30 t can be obtained under the low range of these variables, this is, tc = 3 years and F < 0.21 (Figure 3). Estimated values indicate that according to the stock response shown in Figure 2a the fishery is quite profitable nowadays, producing 769,000 USD per year. Maximum economic potential yield MEY = 798,333 USD can achieved with $F_{MEY} = 0.1$, this is, 30% less effort than the F_{MSY} and 52% less than the current one; for this reason, F_{MEY} seems to be a good prospect as management target, because it leaves a good safety range to cope with undesirable bad years when recruitment levels are low and the chances of over exploiting the stock increase significantly. One consideration would be to find the way to apply this with small annual reductions to avoid an undesired social and economic crisis, as an immediate consequence after the regulation has been applied. Other indicators show that at the F_{MEY} level, B/C = 20.8 can be attained with 32 pangas and 88 fishers, which implies an effort reduction.

When the response of the fishery and its economic performance was explored under a wide variety of F and tc values, the output shows that it is profitable under a relatively narrow range of the control variables (F < 0.15 and tc 2 - 3) with the maximum of $838,709.00 at F = 0.1 and tc = 3 (Figure 4a). Likewise, the B/C ratio at the lowest F it is at its highest. However, the target adopted for the fishery will not be attained immediately, it will be achieved after the stock is recovered and this may take several years after the regulations addressed in the right direction are adopted.

The Fleet Size

The number of boats in this fishery was obtained from the fisher cooperative with the largest number of members (Langosteros del Caribe) as a data for calibration of the model before simulations were made; this information accounts to 55% of the total. Data show that the fishing season lasts for 8 months, from July to March the year after. The information obtained from the fishers (Table 2) states that the fleet is composed by 33 pangas and three nurse boats; each panga makes 10.2 - 17 daily trips per month, which results in a 2,691 total number of trips made by the 3 cooperatives after an 8-month season. After each fishing day, lobster tails are previously cleaned and pre-processed, and the catch is stored in one of the nurse ships for approximately 10 days before taken to the mainland cannery where tails are sorted by size and commercialized. The current fishing intensity and tc to fulfill this condition are F = 0.21 and tc = 3, as displayed in Figure 5. In order to keep > 30 boats in the activity, it is required that mortality is 0.1 < F > 0.21 and age of first capture tc < 0.3.

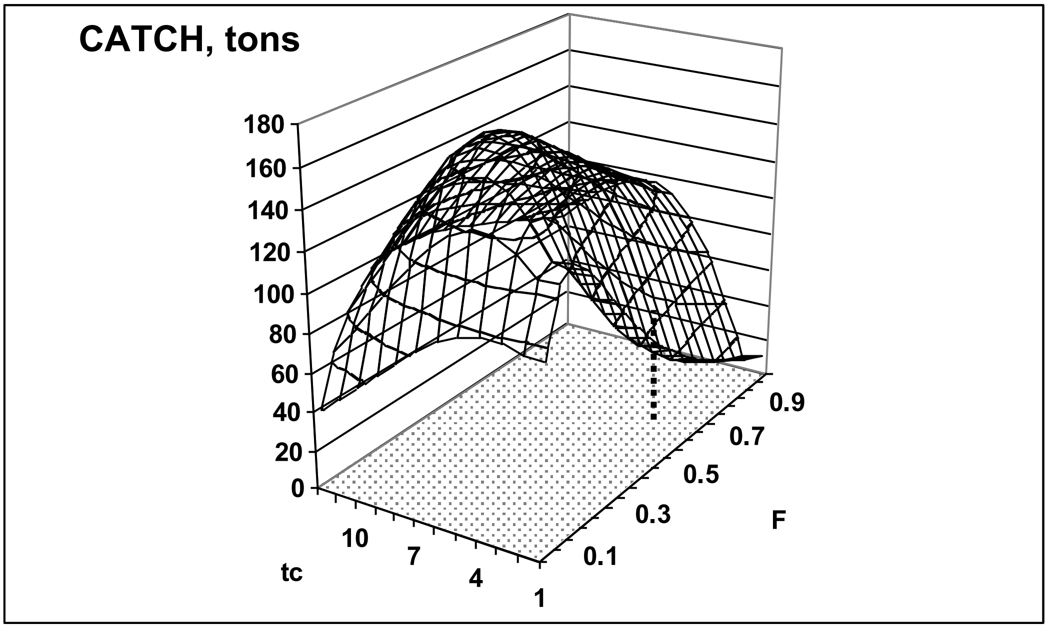


Figure 3. Potential yield as a function of the age of first catch and the fishing mortality. The highest yields (Y >30 t) can obtained with 1> tc <3 and 0.05 < F < 0.3.

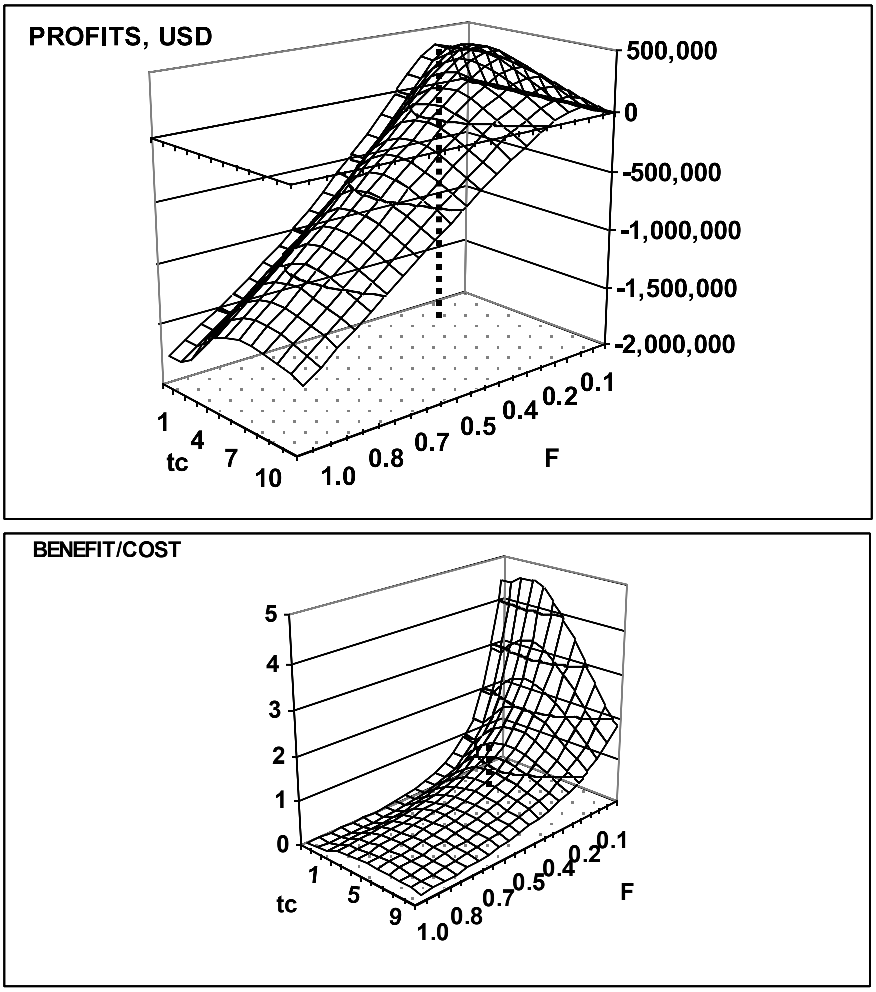


Figure 4. A. Profits, Economic variables B. The Benefit/Cost ratio, as response of the spiny lobster fishery in function of F and tc.

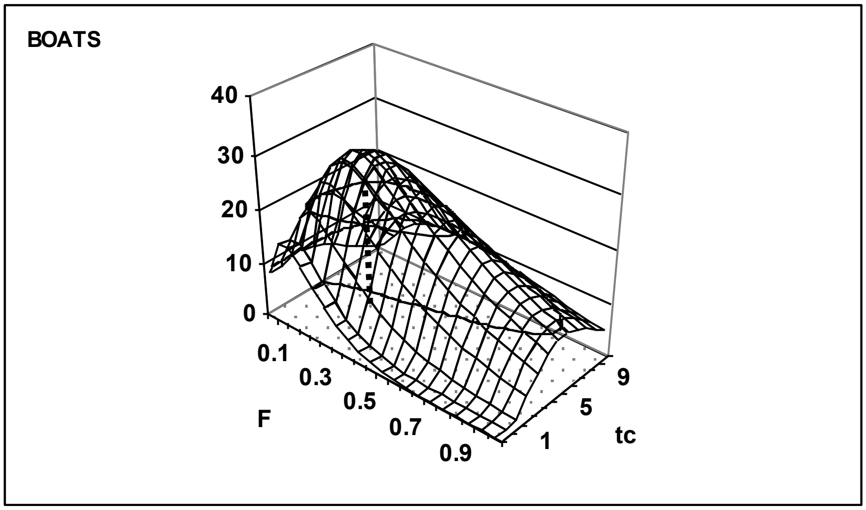


Figure 5. Effect of fishing intensity and age of first catch, on the fleet size (the number of boats). The maximum number of boats that the fishery can withstand with a profitable activity is 39 boats with F = 0.15 and tc = 1 and 2 years old.

Social Benefits

The current number of employees was fitted by multiplying the number of boats by 2.7 and adding 12 others which account for administrative fishers and occasional non registered helpers, giving a figure of 98 direct employees (Figure 2b). By considering the range F and tc values providing high level of employments to keep > 95 and up to 114 fishers in the activity, the model suggests (Figure 6) that $0.1 < F > 0.21$ and $tc < 3$ should be applied. The trend in which the number of fishers and employees affect the yield, behaves identically to the fishing intensity and the age of first catch. In the same way as the potential yield and fleet are treated, the maximum social benefits, (number of direct employees -102 fishers) is fitted to $F = 0.15$ with $tc = 3$ year-old spiny lobster; this is, at the $_{FMSY}$ level. However, the best option is also achieved with a gradual reduction of F at a rate of 0.025 per year, attaining up to 202 employees at the 30th year after the application of this regulation.

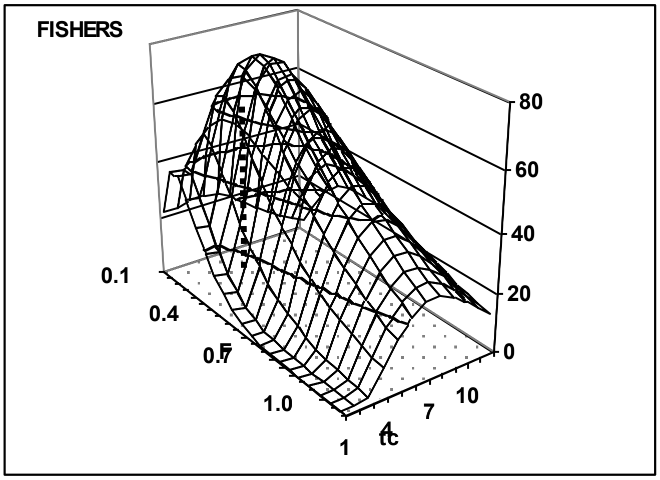


Figure 6. Effect of fishing intensity and age of first catch, on the number of fishers. The maximum number of fishers that the fishery can withstand with a profitable activity is 113 and 114 fishermen with F = 0.15 and tc = 2 and 1 years old, respectively.

DISCUSSION

The possibility of finding a decreasing stock biomass resulting from the increase of fishing effort after the main reproductive peaks was explored, based on the strong evidence for seasonality of spiny lobster stocks. The fishery at CB has shown a strong characteristic monthly trend throughout the years, which has evidenced some depletion towards the end of each fishing season.

Uncertainly associated to management of exploited stocks imposes the need to apply the precautionary principles in order to avoid the risks of stock depletion and collapsed fisheries if the $_{FMSY}$ reference point is adopted as target. Harvesting strategies were examined with the purpose of giving advice to the fishing cooperatives and the decision-making agencies in charge of the exploitation of spiny lobster stock at Chinchorro Bank. Dynamic biomass models provide estimates of a number of reference points; maximum sustainable yield (MSY) and related points; fishing mortality to attain the MSY $_{(FMSY),}$ fishing effort at MSY, biomass at MSY, as well as the biomass of the unexploited stock. These may be useful in assessing the condition of stocks and on framing management rules, but are sensitive to model choice. The assumption of a constant catchability (i.e. that biomass is proportional to the index of abundance) may be modified using relationships such as a power model with catchability dependent on population size (Arreguín-Sánchez 1996; Martínez-Aguilar *et al*. 1997), or stochastic catchability, modelled as a random walk to account for random variability or uncertainty presumably induced by climate. However, Punt and Hilborn (1996) warn of caution in shaping the relationship between catch rate and biomass. Nevertheless, the assumption of a constant catchability value is often violated over time, which is a common problem with many fishery assessments, that is also caused by spatial and behavioural characteristics commonly exhibited by crustaceans. Poorly estimated catchability coefficients may result in spurious estimates of absolute stock size or fishing mortality (Smith and Addison 2003).

Diagnosis of the Fishery

The process of reconstruction of the fishery: the stock biomass, its age structure and its socio-economic indicators over the historic period, allowed to diagnose its condition over the last fifteen fishing seasons. A procedure adopted to examine the status of the stock over time was by identifying the limit reference point for each year as the E at the $_{FMSY}$ level fixed $[F_{MSY}/(M+ F_{MSY})]$, and then estimating E of each fishing season by using the F value found for each year; this was a good way to diagnose the condition of the stock over time, as shown in Figure 7, where the catch is also represented each year with bars. This figure evidences that the stock was underexploited only from the 1990 - 1991 to 1990 - 1994 fishing seasons and being slightly overexploited afterwards; particularly it is remarkable to see that in the season 1999 - 2000 E reached its highest value (0.45). In the season 2000 - 2001 E was at the limit of overfishing increasing its values again in the last two years it. A conclusion of this diagnosis is that fishing effort should be reduced in order to restore the fishery, especially if the goal is to achieve yields like those obtained at the beginning of the eighties, and assuming that potential larvae recruitment from elsewhere remains unaffected. By examining the catch trends in the figure, it is evident that despite the fact that the model shows the fishery could has been overexploited for nearly fifteen years, some sort of recovery has occurred since 1997; a feasible reason that explains this is that Chinchorro Bank was declared as a Biosphere Reserve (Protected Area) since 1996 with stricter norms, management plans and regulations, where vigilance on poaching has increased therefore leading to a reduction in fishing mortality caused by this problem.

In addition to the biological condition of the fishery, the performance of economic indicators for the last fifteen years of the series is shown in Figure 8, where the profits, the Benefit/Cost ratio every year, and the B/C = 1 this is, the economic equilibrium level, are displayed. The profits describe a growing trendendency for most years, with profits approaching 1 M USD. Likewise, the B/C shows that evidently this is a quite profitable activity, explaining why fishermen, like any other fishery in similar conditions, are prone to over exploit the resource; here, this variable shows a growing tendency during the first nine years and then a decline for the rest of the series, dropping from B/C = 16 to > 6 in 2008. This tendency explains why the fishermen recently expressed their concern respecting to an economic crisis they already approaching through the fishing season, mainly in September October and November, where the catch per unit of effort is much lower than in July and August, fishing near the economic equilibrium level. Lack of control in the capture, and illegal fishing surely have contributed to this condition. Lack of control in the capture sizes, poaching, and illegal fishing which would translate as a free accessed fishery could derive in another chapter of the tragedy of the commons (Hardin 1968).

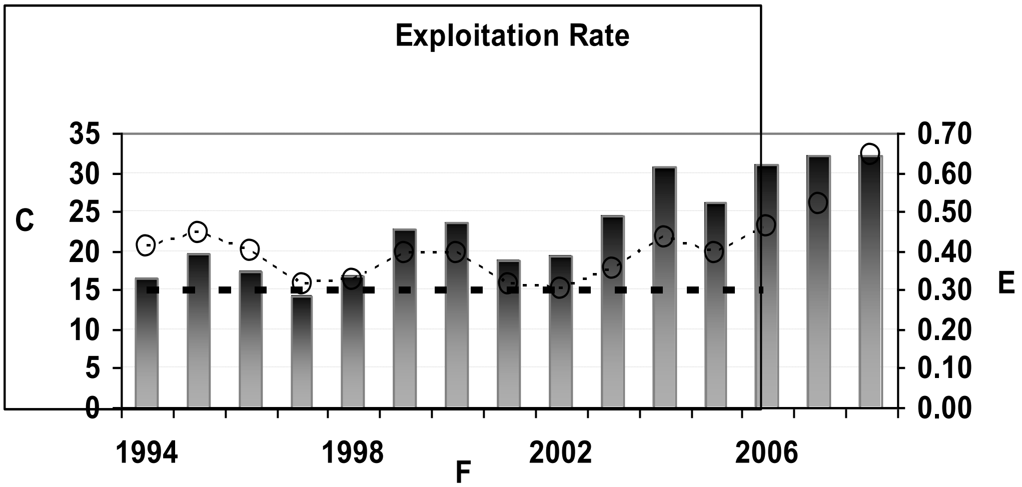


Figure 7. Historic diagnosis of the fishery. Bars represent the catch and the dotted line indicates the exploitation rate; by comparison, the exploitation rate at the MSY level or extreme reference point is shown as a horizontal dotted line.

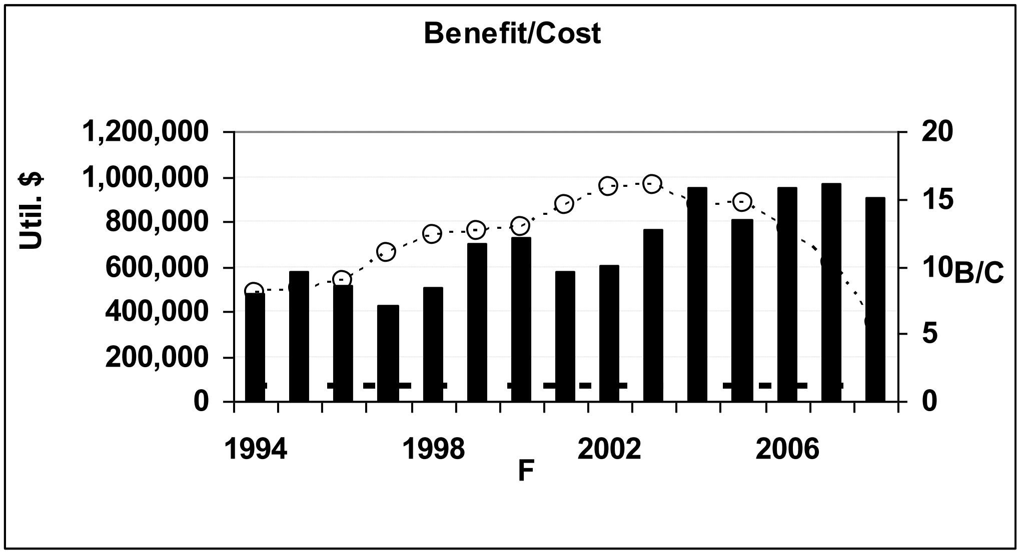


Figure 8. Historical economic diagnosis of the fishery. Black bars represent the profits (left scale) and the dotted line indicates the Benefit/Cost ratio for the years 1994-2008; by comparison, the B/C = 1, or economic equilibrium level, is shown as a horizontal dotted line.

Scenarios for Management

Simulations were done by seeking the performance of socio-economic indicators which are important for the management of the fishery, based on the feasibility of their application; these were the fishing intensity (F), and the age of first catch, which can effectively be controlled through accurate regulation and close inspection of landings. Current permformance indicators of the fishery were compared to those obtained at the levels F_{MSY}, F_{MEY}, B_{MAX} (the maximum number of boats), N_{fmax} (the maximum number of fishers), and by reducing F in 0.025% per year, which means a reduction of F from the current level (0.21) to 0.058 at the 30th simulation year, or in practical words, a shortening of the fishing season of one week the first year and a little less than that in subsequent fishing seasons.

Other reference points, such as $F_{0.1}$, F_{MAX}, $F_{25\%}$ and $F_{40\%}$, have often been used to develop fishery management strategies. Several authors have proposed $F_{0.1\%}$ or $F_{40\%}$ as target reference points and $F_{25\%}$ as a threshold reference point in order to obtain near optimal yields while ensuring against stock collapse (Gulland and Boerema 1973, Deriso 1987, Sissenwine and Shepherd 1987, Quinn *et al*. 1990; Hildden 1993, Leaman 1993, Rivard and Maguire 1993, Thompson 1993, Mace 1994, Kirchner 2001).

The fishery currently exploits spiny lobsters as young as two years, but three years is the age when it is fully recruited to the fishery, so it was fixed at 3 in the simulations. Numeric results are displayed in Table 3. The values represent the mean of the last 5 years of the 30-year simulation period; since undesirable differences sometimes observed in the output regarding the last data of the historical period were ignored; it is expected that any management disposition derived from this simulation could be applied for the following year only, as a step in the process of adaptive management.

The management option shown in the right side column of Table 3 implies an annual reduction of 0.025 in F for each simulated year, and it seems to be the most convenient one, considering that it allows a stock recovery to the catch levels recorded 22 and 23 years beforehand (69 t) with a considerable improvement in socio-economic variables; however, if it is adopted as management target, the reduction in F (from 0.21 to 0.06) should be applied as advised here, which is gradually, in order to avoid a socio-economic crisis amongst the fishers in initial years after its application. Reduction of F can be accomplished by extending the closed season, which in the first year it would mean to shorten one week the length of the current fishing season; in subsequent years the reduction would be shorter than a week. Keeping this strategy as a fishery policy after the first year of its application should carefully be assessed, after an accurate evaluation of its performance has been done, under the principles of an adaptive management advice. If the stock responds accordingly to simulation predictions, then other factors potentially affecting the stock response such as density-dependent factors, food availability, larval recruitment and predation should always be bared in mind in order to explain part of the expected variability.

TABLE 3. Comparison of biologic, economic, and social indicators of the fishery. Several harvesting scenarios are indicated, all departing from the current conditions of the 1994-2008 fishing season, which are used as a baseline. Economic values are given in USD. Other scenarios tested were the maximum number of boats and the maximum number of fishers, but it was found that the outputs of both options are the same as the F_{MSY}. The age of first catch is 3 years in all cases. Numbers in bold indicate the optimum values of the attributes being compared. The targets would be attained after the stock is recovered.

	MANAGEMENT SCENARIOS			
INDICATORS	**Current (2004-05)**	**F_{MSY}**	**F_{MEY}**	**F = (0.975F)/yr**
F (per year)	0.21	0.15	0.1	**0.06**
Yield/ton	30.9	32.1	30.2	**69.2**
Fishing days/yr	2,691	1,922	1,281	**807**
Days/boat/yr	81.5	53.9	40.7	**5.1**
Boats	33	36	32	**158**
Direct jobs	98	102	88	**202**
Catch value	858,334	892,336	838,709	**1,857,874**
Costs	88,803	68,554	40375	**127,343**
B/C	9.7	13.0	**20.8**	14.1
Profits	769,531	823,772	798,333	**1,739,531**
Profits/boat	9,437	15,285	19,630	**338,131**

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LITERATURE CITED

Arreguín-Sánchez, F. 1996. Catchability: a key parameter for fish stock assessment. *Reviews in Fisheries and Biology of Fish* **6**:221-242.

Beverton, R.J.H. and S.J. Holt. 1957. On the dynamics of exploited fish populations. *Fishery Investigations, London, Series 2* **19**:533p.

Chávez, E.A. 1996. Simulating fisheries for the assessment of optimum harvesting strategies. *Naga* **2:**33-35.

Chávez, EA. 2005. FISMO: A generalized fisheries simulation model. Assessment and management of new developed fisheries in data-limited situations. 21st Wakefield Fisheries Symposium. University of Alaska. 659-681 pp.

Chávez, E.A. and F. Arreguín-Sánchez. 1993. Simulation Modelling for conch fishery management. Pages 125-136 in: R. Appeldorn (Ed.) *International Symposium on Queen Conch Biology, Fisheries and Mariculture*. Caracas, Venezuela.

Davis, E. 1975. Minimum size of mature spiny lobsters, *Panulirus argus*, at Dry Tortugas, Florida. *Transactions of the American Fishery Society* **4**: 675.

Deriso, R.B. 1987. Optimal *F*0.1 criteria and their relationship to maximum sustainable yield. *Canadian Journal of Fisheries and Aquatic Sciences* **44**:339–348.

Gulland, J.A. and L.K. Boerema. 1973. Scientific advice on catch levels. *Fishery Bulletin* **71**:325–335.

Garcia, S.M. and K.L. Cochrane. 2005. Ecosystem approach to fisheries: a review of implementation guidelines. *International Center for the Exploration of the Seas Journal of Marine Science* **62**:311-318.

Hardin, G. 1968. The Tragedy of the Commons. *Science* **162**:1243-1248.

Hildden, M. 1993. Reference points for fisheries management: the ICES experience. *Canadian Special Publication on Fisheries and Aquatic Science* **120**:59–66.

Hilborn, R. 1997. Lobster stock assessment: report from a workshop, II. *Marine and Freshwater Research* **48**:945–947.

Leaman, B.M. 1993. Reference points for fisheries management: the western Canadian experience. *Canadian Special Publication on Fisheries and Aquatic Science* **120**:15–30.

Lozano-Alvarez, E. 1994. Análisis del Estado de la Pesquería de la Laangosta *Panulirus argus* en el Caribe Mexicano. Paginas 243-255 en: A. Yáñez-Arancibia (Ed.*) Recursos Faunísticos del Litoral de la Península de Yucatán*. EPOMEX, Universidad Autónoma de Campeche, México.

Lozano-Alvarez, E. P. Briones-Fourzan, and F. Negrete-Soto. 1993. Ocurrence and Seasonal Variations of Spiny Lobsters, *Panulirus argus,* (Latreille) on the shelf outside Bahía de la Ascención, México. *Fishery Bulletin US* **91:**808-815.

Mace, P.M. 1994. Relationships between common biological reference points used as thresholds and target of fisheries management strategies. *Canadian Journal of Fisheries and Aquatic Sciences* **51**:110–122.

Martínez-Aguilar, S, L.A. De Anda-Montañez, y F. Arreguín-Sánchez. 1997. Densidad y "capturabilidad" de la sardina monterrey, *Sardinops sagax* (Pisces Clupeidae) del Golfo de California, México. *Revista de Biología Tropical* **4(**3)/45(1):527-535.

Nikolsky, G.V. 1968. *The Ecology of Fishes.* Academic Press, London, NewYork.

Kirchner, C.H. 2001. Fisheries regulations based on yield-per-recruit analysis for the linefish silver kob *Argyrosomus inodorus* in Namibian waters. *Fisheries Research* **52**:155–167.

Quinn Ii, T.J., R. Fagen, and J. Zheng. 1990 Threshold management policies for exploited population. *Canadian Journal of Fisheries and Aquatic Sciences* **47**:2016–2029.

Rivard, D. and J.J. Maguire. 1993. Reference points for fisheries management: the eastern Canadian experience. *Canadian Special Publication on Fisheries and Aquatic Sciences* **120**:31–58.

Sissenwine, M.P. and J.G. Shepherd. 1987. An alternative perspective on recruitment overfishing and biological reference points. *Canadian Journal of Fisheries and Aquatic Sciences* **44**:913–918.

Smith, T.M. and J.T. Addison. 2003. Methods for stock assessment of crustacean fisheries. *Fisheries Research* **65**:231-256.

Sparre, P,. and S. Venema. 1992. Introduction to Tropical fFsh sSock Assessment., Part 1 Manual. *FAO Fisheries Technical Paper 306/1* Rome, Italy. 376 pp.

Thompson, G. G. 1993. A proposal for a threshold stock size and maximum fishing mortality rate. *Canadian Special Publication on Fisheries and Aquatic Sciences* **120**:303–320.