

THE SARDINE FISHERY OF THE GULF OF CALIFORNIA

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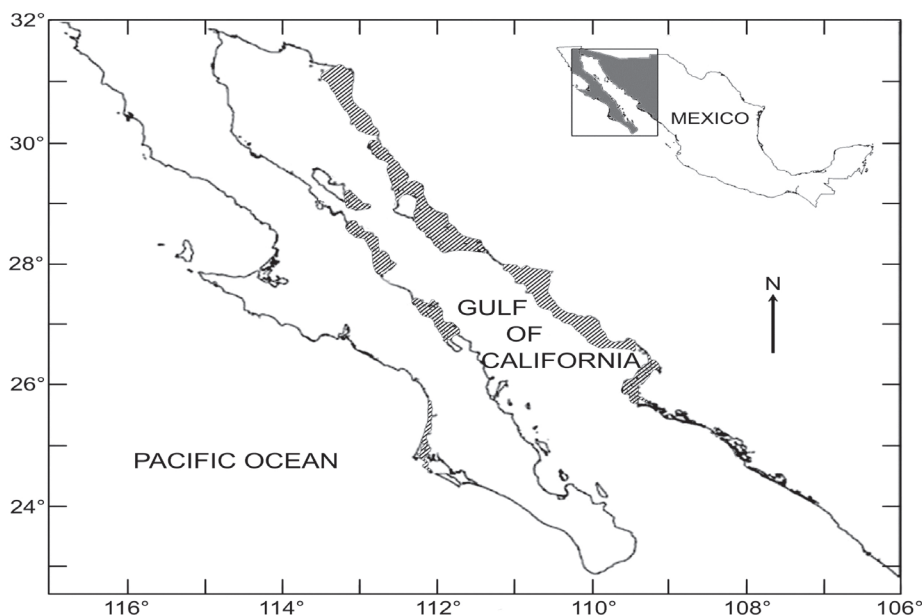


Figure 1. The Gulf of California, showing the areas where the sardine stock is exploited. (Modified after Lanz et al. 2008).

ABSTRACT

In the sardine fishery of the Gulf of California (1969–2012), the annual catch declined to ~400,000 mt in 2010–12 (average: 129,000 mt), after three years of high harvest (average $>532,000 \text{ mt} \cdot \text{yr}^{-1}$). The fishing intensity was relatively stable up to 1997, fishing 5,000 days per season, increasing in 2008 and 2009 to 15,000 and 28,700 days, respectively. Fishing trips increased steadily from 40 to 80 trips per vessel in the last five years. Total profits follow the same trend as the catch, ranging between \$1–12 million in most seasons, with four peaks. In 12 years, the fishery produced more than 15 times the cost of fishing operations. Oceanographic conditions determine abundance levels, and significant correlations exist between population estimates and the Pacific Decadal Oscillation Index. Climate and fishing intensity are the main responsible forces; to ensure a stable fishing activity, we recommend that fishing effort should range between 4,000 and 6,000 fishing days per season.

INTRODUCTION

Depletion of the sardine fishery of the West Coast of North America has stimulated numerous studies trying to understand causes, such as climate change, overfishing, schooling behavior, or interaction with other pelagic species, particularly anchovy (Murphy 1966; Sokolov 1973; Sokolov and Wong 1973; MacCall 1979; Cisneros-Mata et al. 1995). In the Gulf of California (fig. 1), a large quantity of sardine was found in the late 1960s; its exploitation began in 1969 (fig. 2). The peak yield was reached in 2009, with a catch of over 580,000 metric tons (mt). This was followed by an abrupt decline, with a catch of about 88,000 mt in 2012. About 85% of the annual catch is used to produce fish meal, mostly for animal feeds (<http://www.msc.org/track-a-fishery/fisheries-in-the-program/certified/pacific/gulf-of-california-mexico-sardine>; Feb. 2013). External forces affecting the sardine fishery are related to the demand for fish meal, where the aquaculture sector consumed

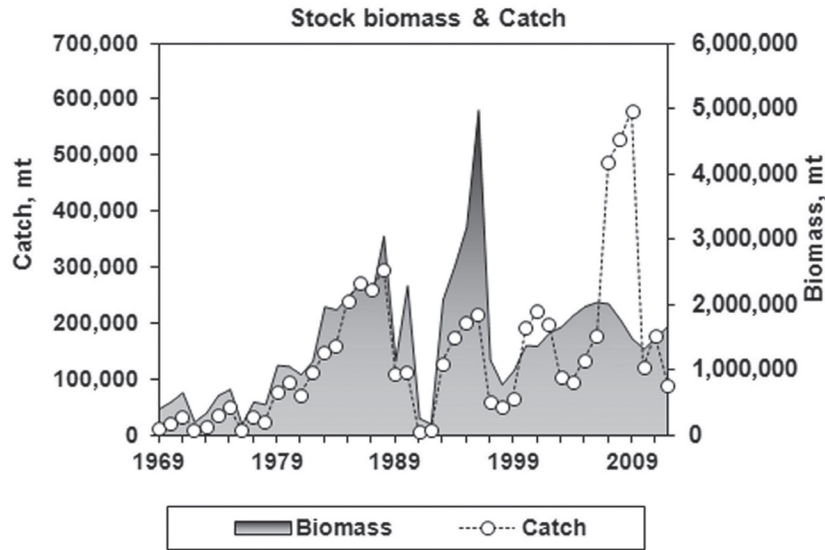


Figure 2. Sardine catch and stock biomass (mt) in the Gulf of California since 1969.

20–25 million mt, from which 23% is used in aquaculture (Tacon et al. 2006). In northwestern Mexico, shrimp cultivation has had an exponential increase in the last few decades, currently producing >60,000 mt, which in turn, imposes a strong demand for fish meal. This leads to a perception that the fish meal supply is limited and the demand is increasing. This increases the fishing pressure on the sardine, greatly increasing the risk of overfishing (Herrick et al. 2006, 2009). Six other species and an undetermined mix of other stocks are part of the catch. The biomass of the bycatch exceeds 100,000 mt and is also used as fish meal (SAGARPA 2012).

The highest sardine catch of the Gulf of California was almost comparable to the highest catch recorded off the California coast, amounting to 664,000 mt in 1936 and a biomass peak of 3.6 million mt in 1934 (Murphy 1966; MacCall 1979). This story seemed to be repeated one more time, now in the Gulf of California. For this reason, an updated assessment of the gulf sardine fishery was carried out, with the aim of examining the catch trend, since the origin of this fishery and other bioeconomic activities and climatic variables are possible factors responsible for variability and decline. Finally, some recommendations for sustainable exploitation are proposed.

METHODS

Catch and effort

Data for the Gulf of California sardine fishery was available for the 1969–2008 fishing seasons (Nevárez et al. 2010). Data for 2006–12 was obtained from the statistical records available for the landing sites in the State of Sonora. An estimate of the expected total catch in the Gulf of California for the years when no other data

were available was calculated as the mean proportion of the years 2006–08. This provided a catch data series through 2012. The number of vessels and nominal effort were available from the report by Nevárez et al. 2010 and similar data were estimated for 2009–12 by applying the same procedure for missing data. According to the Marine Stewardship Council (MSC 2013), each fishing trip lasts 1 to 2 days, so each fishing trip was multiplied by 1.5 to get an estimate of the number of fishing days in the fishing season (fig. 3). According to the MSC, each vessel has a crew of eight fishers, such that the number of vessels (25 m long) per year provided the total number of workers.

With 15 years of catch data and the growth parameter values K , L , t_0 of the von Bertalanffy growth model, length–weight parameter values (a , b), age of first catch (t_c), and age of first maturity (t_m) as biological variables, plus the sardine value at the dock, the fishing cost per boat-day, number of boats, and length (in days) of the fishing season (table 1), it was possible to determine other variables useful for a bio-economic assessment and diagnosis of the fishery with the FISMO simulation model (Chavez 2005): total number of days per fishing season, total profits, profits per boat and per worker, as well as the benefit/cost ratio. Estimates of the catchability coefficient q were based on the relationship $F = qf$, where F is the fishing mortality and f is the fishing effort in days. Most fisheries are now at the stage of full exploitation or overexploitation of the stocks, with fishing fleet capacity in excess (Gréboval 2003; Munro and Clark 2003; Kirkley and Squires 2003). Under these conditions, fishing effort (f) is no longer proportional to the stock size. For this reason, the estimation of F was deliberately made to avoid the use of f , as advised by the traditional meth-

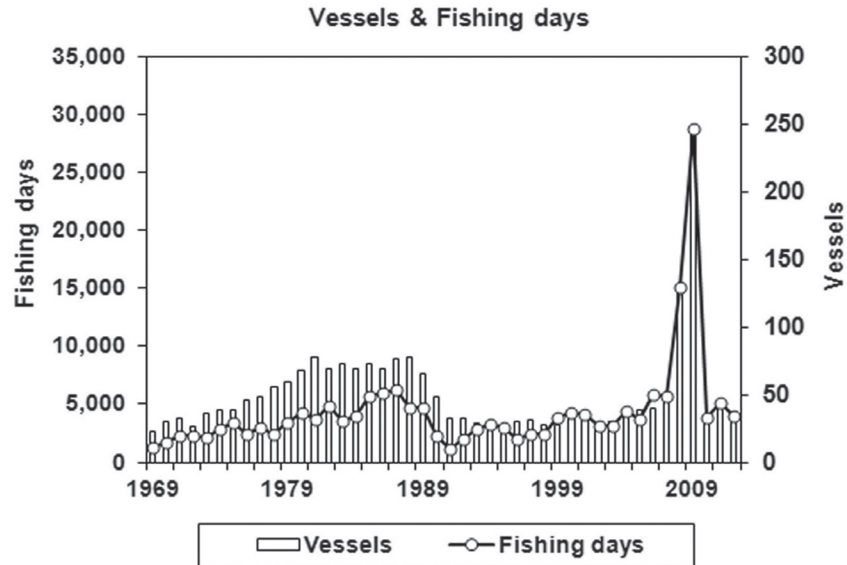


Figure 3. Trends of the fleet size and fishing effort of the sardine fishery.

TABLE 1

Population parameters, social and economical values of the sardine fishery in the Gulf of California used as input for use with the fisheries simulation model. *K*, *L*, *W*, and *t₀* are from the von Bertalanffy growth model; *a*, *b* are from the length–weight relationship; age units are years. *M* is the natural mortality; *Phi'* is growth performance; Coef. Fitting fleet in arbitrary units; Catch value, costs of fishing, and profits are in \$US and correspond to the 2012 fishing season, as well as the B/C ratio.

Variable	Value	Source or units
<i>K</i>	0.45	Hill et al. 2009
<i>L</i>	31	cm, Hill et al. 2009
<i>W</i>	206	g, from the length–weight equation
<i>-t₀</i>	0.17	Hill et al. 2009
<i>a</i>	0.00637	Froese & Pauly 2011
<i>b</i>	3.07	Froese & Pauly 2011
<i>M</i>	0.6750	As 3/ <i>K</i> , after Jensen 1997
<i>Phi'</i>	2.6	Estimated by the model
Value/kg	0.07	Cisneros unpublished
Cost/day	253	\$US
Longevity	7	Years, as 3/ <i>K</i>
Age of first catch	1	Marine Stewardship Council 2013
Maturity age	1	Hill et al. 2009
Coef. fitting fleet	0.0005	Estimated by the model
Num. of Boats	47	Nevárez-Martínez et al. 2010
Days/boat/season	85	Nevárez-Martínez et al. 2010
Num. of trips	3,995	Nevárez-Martínez et al. 2010
Profits	14,012,438	Estimated by the model
Benefit/Cost	14.9	Estimated by the model
Fishers/Boat	8	Marine Stewardship Council 2013

ods applied in fisheries biology. Here, *F* was estimated for the last 15 years of catch data, using the catch equation in the simulation model (described in the following paragraph); the model estimates of *F* for each year were directly calculated from the catch equation by performing an approximation of successive values until observed and simulated catch were equal. The *f* is known for the

whole data series from 1969 to 2012 and was used as a variable linked to the economic forces implicit in the fishery. Hence, a mean *q* value was obtained for the last 15 years and this mean was applied year by year to the *F* equation just described for estimates of *F* of the earlier catch data (before the years analyzed by the model). With this procedure, an analysis of the data series since the beginning of the fishery can be made. Other authors have found a relationship between catchability as a function of the stock biomass (Arreguín-Sánchez and Pitcher 1999; De Anda-Montañez et al. 1999; Martínez-Aguilar et al. 2009). For this reason, a function was used, but in the years where a *q* value was estimated, a pattern between stock size and *q* was not found ($R^2 = 0.019$, $p = 0.89048$).

The age and growth rate of exploited stocks is a condition imposed by the need for estimating growth rates of all of the exploited populations. Fortunately, many studies focus on sardine stocks; it is now possible to determine growth rate without the need to start the assessment with a sampling program. The power regression used to transform length into weight is $W = a \cdot L^b$.

The initial assessment of the stock was made with catch data for the last 15 years and then it was reconstructed for the 43-year period of the fishery. Changes in abundance over time were determined by using the catch data as a reference for estimating population size. Growth parameters were taken from Hill et al. 2009. Estimates of the age composition of the catch were made, and further analysis, including scenarios of feasible harvesting strategies, were calculated with the FISMO simulation model (Chávez 2005), which transforms catch data into age structure of the population. The age structure of the stock in each year was estimated by assuming a con-

stant natural mortality (M), adding the fishing mortality (F) estimates that were different for each age class, and the total mortality was determined, using $Z = M + F$ in each year. The age structure was determined after the estimation of the number of one-year-old recruits and then used to calculate catch-at-age, as proposed by Sparre and Venema 1992. This was integrated into the simulation model, as:

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

where $Y_{a,y}$ is the catch-at-age a of each year y , $N_{a,y}$ is the number of sardines at age a in year y , $W_{a,y}$ is the sardine weight equivalent to $N_{a,y}$, F_t and M are as described earlier. The values of $Y_{a,y}$ were adjusted by varying the initial number of recruits and linked to the equations until the condition of the catch recorded and simulated catch were equal by varying F for each year. The catch equation was applied for each year in the time series.

For estimating natural mortality (M), the criterion of Jensen (1996, 1997) was followed, using $M = 1.5 K$. The stock biomass and the exploitation rate $E = F / (M + F)$, were estimated for each age class in every fishing year analysed by the model after transforming the numbers per age into their corresponding weights. With estimates provided by the simulation model, a mean value of the catchability coefficient was obtained, and with this value, it was possible to estimate F and other variables for the whole series of catch records. A diagnosis of the status of the fishery was made, and recommendations of the most convenient fishing intensity to maintain sustainability were made. The stock-recruitment relationship was applied by using the equation by Beverton and Holt 1957. Intensity of recruitment depends to a great extent on stock size.

Model simulation

The simulation model reconstructs the age structure over time and different exploitation scenarios (fishing intensities and the age-at-first catch) to maximize biomass, profits, and social benefits, as well as the number of fishermen and maximum profit per fisherman, adopting the ideas of Chávez (1996, 2005) and Grafton et al. 2007.

The approach to the socioeconomics of the fishery concerns only fishing activities and was made through consideration of the costs of fishing per boat per fishing day (\$253), number of boats (47 in the 2012 fishing season), number of fishermen per boat (8), and the number of fishing days during the initial fishing season (85). The catch value per kg (\$0.07) is the price at the dock before added value. The difference between the costs of fishing (C) and the catch value (the benefit, B) is known, so the value divided by the cost is the B/C ratio (table 1). In the simulation, the costs of fishing per

boat-day and catch value were assumed to be constant over time. The information of the 2012 fishing season allowed us to reconstruct the biological and economic trend of the fishery for the last 15 years and was estimated for the data series, as well as the 30 years of simulation. This used the estimates of fishing mortality over time as a reference and its correspondence to the economic variables.

Bioeconomic analysis

This part of the description is based on the so-called stock effect (Hannesson 2007), which are the costs and benefits occurring only during fishing activities; therefore, costs and benefits after catches were landed were not considered. Therefore, the approach is quite simplistic because the market forces are left out of the analysis. Hence, costs are linked to fishing effort and economic benefits or profits, and the catch value (catch times its value per kg) from which costs (costs per daily trip multiplied by the number of trips) are subtracted. By this approach, a detailed diagnosis of how profitable the fishing can be is provided and it is easy to perceive why, in many fisheries, stock declines at some point resulting from excessive fishing pressure; at that point, the fishery reduces its fishing effort and the activity becomes an economic crisis because there are no profits.

RESULTS

Stock biomass and catch

The stock biomass describes a clear pattern of oscillation, possibly induced by climatic variability rather than fishing intensity (fig. 2). The fishery was simulated by Nevárez-Martínez et al. 1999 and the analysis presented here is an update with additional information. We found that in the first five years, the stock size was ~500,000 mt and the catch was below 33,000 mt. Then there was a decrease of biomass to 167,000 mt that was followed by a major increase that reached 3 million mt in 1988, followed by a sudden decline with a catch of just 7,500 mt in 1992 (fig. 2). The highest biomass was recorded in 1996 with an abrupt increase that reached almost 5 million mt. After 1996, the biomass was maintained, but the catch suddenly increased to almost 600,000 mt in 2009, leading to a low catch of only 89,000 mt in 2012.

Fishing effort

Examining the fishing activity by the number of boats and fishing days (fig. 3), a relationship between these two variables and stock biomass is not very clear, except in 1990 when there was a large decrease of biomass that affected the fishing effort. In 2007–09, there was an abrupt increase in catch that was not related to high

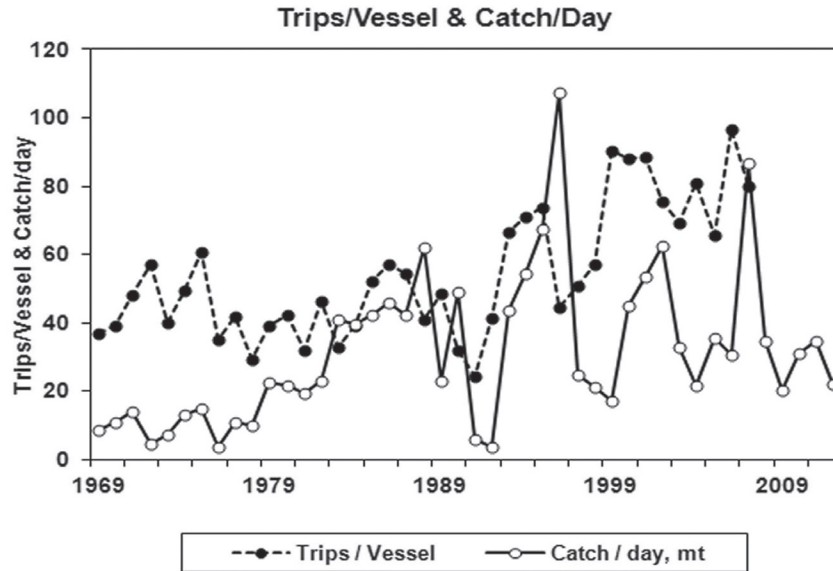


Figure 4. Number of trips of each fishing season per vessel, and catch per unit of effort ($\text{mt} \cdot \text{day}^{-1}$) of the sardine fishery in the Gulf of California.

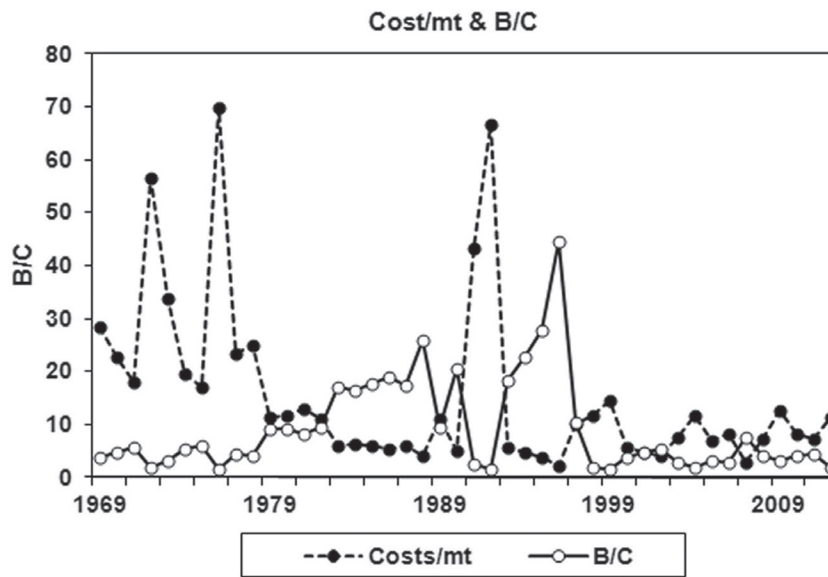


Figure 5. Benefit/cost ratio and Costs per mt of the sardine fishery of the Gulf of California.

biomass (fig. 2). Instead, there was an increase in fishing capacity created by a huge increase to 242 vessels and nearly 28,000 fishing days. This may have resulted from high catchability not shown in the q values. A detailed examination of fishing intensity was made by looking into fleet behavior; it is evident that there was a change in the attitude of fleet owners, which since 1993 decided to increase the number of trips per fishing season from a mean of 47 before that year to about 85 in 2009 (fig. 4). By contrast, the catch per unit of effort was dramatically variable, with a decreasing trend in the last four years of the series, when catches were below 40 mt/day , lower than yields in the 1980s.

Bioeconomic analysis

The benefit/cost trend shows that this fishery is very productive and can remain productive for a long time if it is carefully managed, since 13 fishing seasons yielded profits that were >15 times the cost of fishing operations (fig. 5); however, the increase in fishing intensity after 1993 caused a reduction in the benefits to about half the income of the 1980s. Simulation indicates that the maximum potential economic yield is $F = 0.3$, which may generate \$11 million.

The costs of fishing were variable and usually high in the early years of the fishery (\$18–60/ mt), decreasing for some years to less than \$7/ mt and then increas-

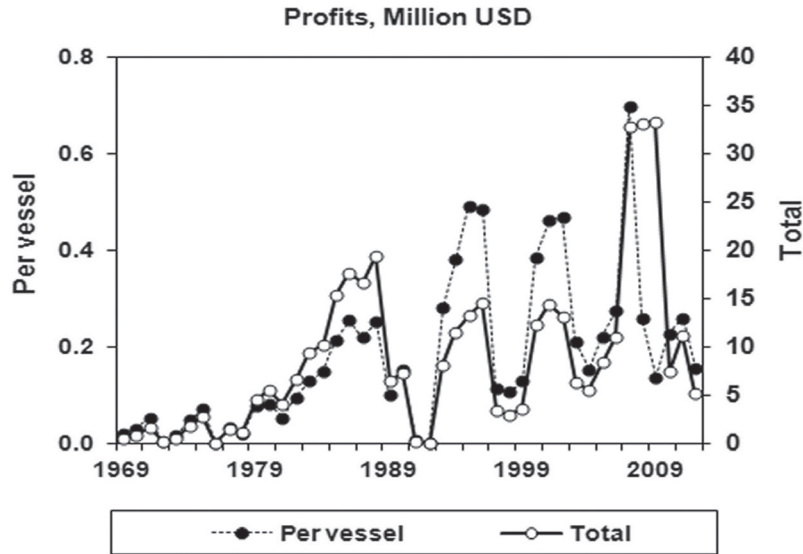


Figure 6. Total profits and profits per vessel of the Gulf of California sardine fishery.

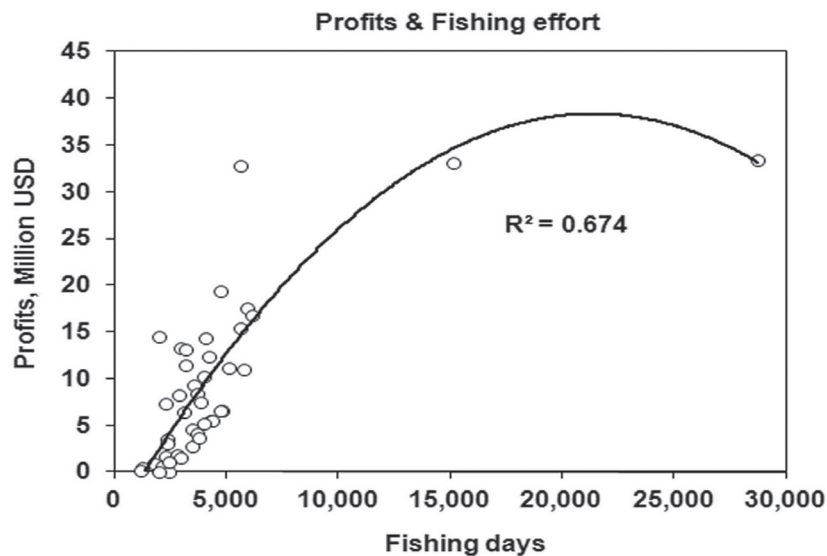


Figure 7. Total profits as a function of fishing effort in the Gulf of California sardine fishery.

ing again to \$65/mt in 1992, when the lowest catch was recorded. Afterwards, the costs ranged from \$3–14/mt (fig. 5). The profits of the sardine fishery indicate that with a few exceptions, each vessel produced \$4–28 million since the mid-1980s. In 1991 and 1992, when the catch was below 8,000 mt, profits decreased to \$0.02 million. In 2007, when the catch increased to 490,000 mt with only 47 vessels, each vessel produced its largest profits, \$0.7 million. This exceptional profit led to an increase in 2008 and 2009 of 127 and 242 vessels, respectively. This reduced each vessel's profits to \$0.14 million (fig. 6). Other years with high profits, nearly \$0.5 million per vessel, were 1995–96 and 2001–02, which resulted from high yields, with less than 32 vessels (fig.

6). Total fishery profits were highly variable, but with a tendency to increase. Historical records suggest that the fishery has been profitable, producing up to \$33 million per season, with low risk of overexploitation when the fishing effort was between 4,000 and 6,000 days (fig. 7).

Social benefits

Based on a constant number of fishermen per vessel, the number of direct jobs in the fishery ranged from 185 workers in the first year to 1,935 workers in 2009. The trend increased, except for the last three seasons, with only 261–344 workers (fig. 8). Assuming an equitable distribution of income per vessel, there was an upward trend in profits, reaching a maximum of the mean trend

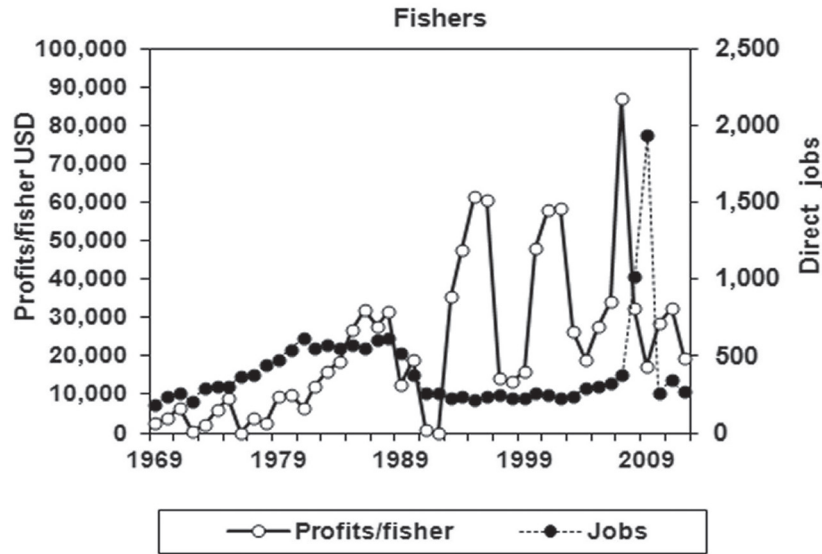


Figure 8. Social impact of the Gulf of California sardine fishery, expressed as the number of direct jobs, the fishermen, and the economic benefit per fisherman, assuming an equitable distribution of the income.

in 2011, \$32,000/worker in 2010–11; however, in 1976, 1991, and 1992, the profits per worker were critically low, ranging from \$4,700 to \$6,975/worker. In contrast, high profits occurred in 1996 and 1997 (up to \$61,000/worker), and the highest in 2007 (\$ 534,000/fisher). The maximum sustainable yield is the maximum yield that is attained at a certain F value (F_{MSY}). The fishery at $F_{MSY} = 0.35$ would produce 2,073 direct jobs. The F at the maximum economic yield, that is, producing the maximum economic return, is $F_{MEY} = 0.3$, which would produce 2,131 direct jobs. Under current conditions, the fishery provides 381 jobs, but in five fishing seasons with peak yields, it provided more than 1,500 jobs (fig. 8).

To find a concurrent cause of the recent decline in the stock biomass and the catch, the possible effect of climate variability was explored. Historical data series of six climate indices (SOI, anomalies of SOI, LOD, NAOI, ACI, and AFI) were compared with the stock biomass since 1969, when catch data records began. Significant correlation was found only between the stock biomass and PDOI, when compared to the rising catch periods, in 1969–96 ($r^2 = 0.5124$, $p = 0.0004342$), and 1997–2012 ($r^2 = 0.7499$, $p = 0.00002185$), as shown in Figs. 9A and 9B. The comparison with other indices was lower; however, the figures suggest that climate variability may play an important role in drastic changes in the stock biomass of this fishery, as occurs along the coast of California (Murphy 1966; MacCall 1979; Lluch-Belda et al. 1986, 1991).

DISCUSSION

The sardine fishery is a typical resource population with a short life cycle that responds rapidly to pulses of high productivity, but at the same time, is exposed to

dramatic decreases when exposed to extreme increases in fishing effort (Cisneros-Mata et al. 1995; Barange et al. 2009; MacCall 2009; Martínez-Aguilar et al. 2009). This is particularly true in fisheries where management practices are inaccurate or insufficient, leading to major impact on the stock biomass, overall profits, and available jobs. This situation suggests that monitoring stock assessment provides opportunistic advice to fisheries before economic crises arise. The industry can take action to maintain the stock biomass at constant, sustainable levels.

For estimating mortality rate (M), several authors explored the problem (Chávez 1995; Jensen 1996; Cubillos 2003; Charnov et al. 2012). Chávez 1995 made a comparison of six methods to estimate M , based on data of 75 fish stocks, where M was used as a dependent variable and longevity was an independent variable. One year later, Jensen 1996 found a more convincing approach, stating that M and two other invariants are an expression of fundamental ecological functions, not just statistical relations. Cubillos 2003 agrees with Jensen and proposes a variation to estimate M . Likewise, Charnov et al. 2012 examine the relationship between M and the von Bertalanffy growth equation, reaching a solution similar to that of Jensen.

Apart from 2008 and 2009, the fishing effort may be considered roughly constant. By examining the trends of fishing effort and profits, it is evident that they describe the same variability; therefore, the peaks are caused mainly by the catch-per-day and secondly by the whole catch. The peaks in stock biomass available for exploitation stimulated the increase in fishing effort that produced high profits for one or two fishing seasons, followed by large decreases in biomass, fishing effort, and profits.

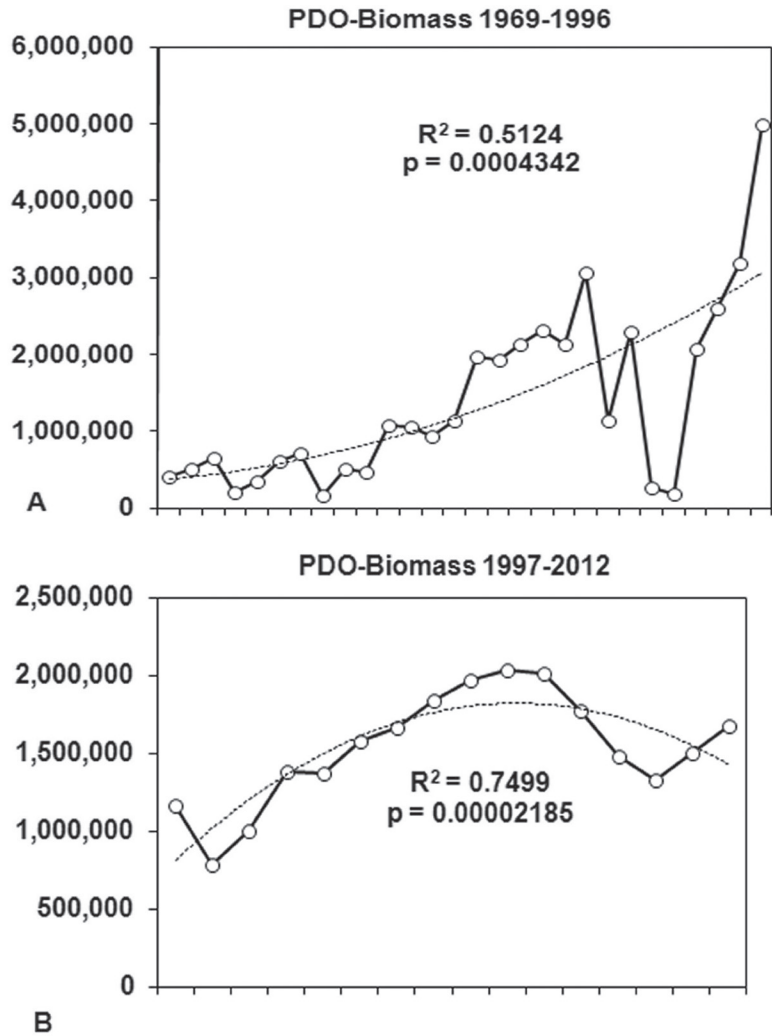


Figure 9. Trend of the sardine stock biomass in the Gulf of California as a dependent variable and the Pacific Decadal Oscillation Index (PDOI) as an independent variable since the beginning of the fishery. (A) 1969 to 1996. (B) 1997 to 2012. Significant correlations were found in the period of catch increase (A), and in the period of stock decline (B).

With the formulas that we used, once the catch data were transformed into their corresponding numbers and biomass-per-age class, then the catch equation was applied. The economic data are the costs linked to the fishing days and the profits to the value of the catch minus the costs of fishing, such that all results are affected by the stock size, that is, they are closely linked to the dynamics of the population being analyzed. When a fishery has been underexploited, there is surplus production of biomass and this may reach a very large quantity, but when it has been exploited near or more than its maximum capacity, the spawning stock biomass is gradually reduced.

In recent years, climate variability induced a favorable change in the stock biomass that allowed catch increases in the coastal California stock (Hill et al. 2005, 2007, 2009), as well as the Gulf of California stock. In the gulf,

this significant increase led to the sardine fishery being certified as sustainable in July 2011 by the Marine Stewardship Council 2013. For this reason, keeping fishing effort at less than 6,000 days seems reasonable, although the recent decline in catch led to a reduction by 900 days (5,108 days in 2011), and should not increase during the next few years so that the stock can be restored. Simulation of the expected catch by assuming that the climate will not cause an adverse effect on survival suggests that, with the fishing intensity just proposed, the stock biomass would allow twice the catch volume landed in 2012, which was more than 170,000 mt. Trends in catch and stock biomass suggest that other forces, apart from the fishing intensity, are responsible for its variability. Studies have looked for a reasonable explanation of this variability (Huato and D. Lluch-Belda 1987; Lluch-Belda et al. 1986, 1991, 2003; Lluch-Cota et al. 1999;

Hammann et al. 1988; Holmgren-Urba and Baumgartner, 1993; García-Morales et al. 2012). The comparison with other climatic indices was lower, however, the figures suggest that climate variability may play an important role of drastic changes in the stock biomass of this fishery, as occurs along the coast of California (Murphy 1966; MacCall 1979; Lluch-Belda et al. 1986, 1991). At present, it is not possible to conclude which one of these two factors is more important in the decline of the stock biomass—climate variability or fishing mortality. Both factors have played a very important role in the decline of catch. The gulf sardine is considered a migratory visitor by Bakun et al. 2009; however, others assume that the gulf stocks are separate from the West Coast (Schwartzlose et al. 1999). There is evidence that the stocks are essentially isolated and despite some connection, it is nonsignificant (Vrooman 2011).

Moreover, the simulation suggests that, by increasing the age of first catch from 1 to 3, the catch would increase from 88,800 mt to 93,000 mt, and the profits would increase from \$5.7 million to \$6.0 million. For some unexplained reason, there is no difference in catch or profits with $t_c = 2$.

Shin et al. 2005 states that regimes of exploitation of catching immature fish causes an evolutionary change in the size and age-structure of populations, leading to smaller size and average age of capture. In addition, an unexplained increase in ecological density caused by an unknown change in the habitat that may have stimulated an increase in schooling behavior is another aspect that should affect population structure. This may modify the predator-prey interactions (Froese et al. 2008), which may affect the stability of the community and the pelagic ecosystem (Bascompte et al. 2005) of sardines. This could induce a reduction of the *MSY* level affecting the economic value of this fishery (Trexler and Travis 2000). At current levels, this fishery has been economically efficient, and it is not clear whether a significant increase in *F* should be applied to achieve the *MEY* because the uncertainty induced by climate variability may lead to a sudden and unexpected decrease in the stock biomass available for exploitation. For this reason, it may be preferable to adopt a cautionary approach by keeping the fishery at reasonably low levels of fishing intensity of 4,000 to 6,000 fishing days per season. For a management regimen to ensure the highest possible stock biomass, the current fishing condition should be changed, not only because the size at sexual maturity is strongly correlated with growth, maximum size, and longevity (Froese and Binohlan 2000), but also because the yield and profits could be higher than the current situation. Additionally, overfishing of recruits has adverse effects on the population because this reduces the spawning stock (Pauly et al. 1989). Innovative management frameworks

may be required to determine defensible trade-offs between precaution and resource exploitation (Bakun et al. 2009). Unfortunately, the natural variability of the stock biomass evidenced in our results constrains the possibility to consider optimum exploitation values as reliable management options.

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