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SEABIRD ECOLOGY, EL NIÑO ANOMALIES, AND PREDICTION OF SARDINE FISHERIES IN THE GULF OF CALIFORNIA

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Abstract. Small pelagic fish constitute 25–40% of the fisheries landings in Mexico. More than 70% of these landings, predominantly Pacific sardine (*Sardinops caeruleus*), are captured in the Gulf of California. Small pelagic fishes are a key component of the Gulf's ecosystem; they are eaten by seabirds, sea mammals, and other fishes. The sardine fishery within the Gulf has been showing signs of overfishing since the early 1990s. To contribute to the sustainable management of this fishery, we developed two statistical models that use oceanographic conditions and seabird breeding and feeding data to predict total fishery catch and catch per unit effort (CPUE) of Pacific sardine in the central Gulf. Total catch was predicted with an accuracy of 54% by a linear model incorporating the Southern Oscillation Index (SOI), the clutch size of Heermann's Gulls (*Larus heermanni*), and the proportion of sardine mass in the diet of Elegant Terns (*Sterna elegans*). CPUE was predicted with an accuracy of 73% by a model based on the proportion of sardines in the diet of Elegant Terns, the reproductive success of Heermann's Gulls, and the springtime sea surface temperature anomaly in the Gulf region. Our results show that the reproductive ecology of seabirds is coupled to the global and local oceanographic conditions and that this information can be used to predict in advance the outcome of fishing efforts. We propose the use of models of this kind to reduce the effort of the fleet in years when it can be anticipated that CPUE will be low.

Key words: Elegant Terns; El Niño; fisheries; Heermann's Gulls; Larus heermanni; *Pacific sardine;* Sardinops caeruleus; *seabirds; Southern Oscillation;* Sterna elegans.

Introduction

Fisheries have been difficult to manage in a sustainable manner, and the collapse of some fisheries has threatened many regional economies (Radovich 1982, WRI 1994, Botsford et al. 1997, Schwartzlose et al. 1999). The majority of the world's fisheries are in a state of, or near, overexploitation (Botsford et al. 1997). Worldwide, small pelagic fisheries such as sardines and anchovies constitute 25% of total commercial landings (WRI 1994, Botsford et al. 1997). These fisheries often show wide population fluctuations, as their fish stocks are strongly affected by oceanographic-atmospheric phenomena such as the El Niño Southern Oscillation (ENSO) (Schwartzlose et al. 1999, Sánchez-Velasco et al. 2000). Consequently, their populations are hard to monitor, and it is thus difficult to obtain robust indicators of their abundance and availability to the commercial fleets.

Small pelagic fishes form the basis of many important coastal marine ecosystems, being a fundamental food source for a variety of larger fish (many of them also of economic importance), marine mammal, and seabird species (Anderson and Gress 1984, Burger and Cooper 1984, Furness 1984, MacCall 1984, Furness and Barrett 1991, Furness and Nettleship 1991, Montevecchi and Berruti 1991, Velarde et al. 1994, Sánchez-Velasco et al. 2000). Several studies have shown the value of seabird diet and breeding success data as tools to indirectly monitor the status of the fish species on which the seabirds feed. Many of these studies have reported similar trends, showing significant correlations between seabird reproduction and diet and fisheries parameters (Anderson et al. 1980, Anderson and Gress 1984, Burger and Cooper 1984, Furness 1984, 1999, MacCall 1984, Berruti and Colclough 1987, Bailey et al. 1989, Martin 1989, Barrett 1991, Furness and Barrett 1991, Furness and Nettleship 1991, Hamer et al. 1991, Montevecchi and Berruti 1991, Velarde et al. 1994, Crawford and Dyer 1995, Montevecchi and Myers 1995, Phillips et al. 1996, Crawford 1998, Ratcliffe et al. 1998, Sánchez-Velasco et al. 2000). Some researchers have used seabird data as a decision element in the management of fisheries (e.g., ICES 1999, 2000, Lewis et al. 2001). Most fishery studies attempt to es-

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PLATE 1. An Elegant Tern (*Sterna elegans*) with prey, flying over the Gulf of California. This species is integral in the ecology of fisheries in Mexico. Photo credit: Fulvio Eccardi.

timate total biomass or give a post hoc correlation between real and estimated catch (MacCall 1979, Jacobson and MacCall 1995, Cisneros-Mata et al. 1996, Deriso et al. 1996, Furness and Tasker 1999, 2000). In some cases monthly catch and catch per unit effort (CPUE) have been estimated through models that are only valid within certain recruitment rates (Fletcher 1992; R. J. Conser, K. T. Hill, P. R. Crone, and D. Bergen, 2001, *unpublished report* [available online][6]). In this work we use quantitative data on the breeding and feeding ecology of Heermann's Gulls (*Larus heermanni*) and the diet of Elegant Terns (*Sterna elegans*; see Plate 1) in combination with ambient oceanographic data to predict Pacific sardine (*Sardinops caeruleus*) catch by commercial vessels, and we show that a good prediction of the fishery can be developed on the basis of seabird data.

The study area

The Gulf of California is one of the most productive marine ecosystems in the world (Álvarez-Borrego 1983). It harbors large populations of seabirds and 36% of the cetacean species of the planet (Anderson 1983, Velarde and Anderson 1994), and it produces about 50% of the Mexican fishery catches. Small pelagic fisheries constitute 25–40% of the total national landings, and the Gulf provides, on average, over 70% of these landings, of which the most important species is the Pacific sardine (Cisneros-Mata et al. 1996, Sánchez-Velasco et al. 2000). The fishing season begins in October and ends in July.

The total sardine catch in the Gulf of California rose steadily between 1970 and 1989, and after that period the fishery abruptly collapsed (Cisneros-Mata et al. 1995). That is, during the last decade it has not paid to invest in large fishing efforts. Accurate annual predictions of the potential catch are needed in order to reduce fishing efforts to levels proportionate to the availability of sardines. Such predictions could reduce both the overharvesting of the fishing stock and increase the margin of profit for the fishing fleet.

METHODS

We used seabird populations nesting at Isla Rasa in the Gulf of California, Mexico (Fig. 1; see Velarde [1999], Velarde and Ezcurra [2002]), to estimate both annual reproductive success and diet. For this purpose, we used the database developed by the senior author on the reproductive success of banded, known-age Heermann's Gull individuals at Isla Rasa during nine

[6] URL: ⟨http://swr.ucsd.edu/fmd/sardine.pdf⟩.

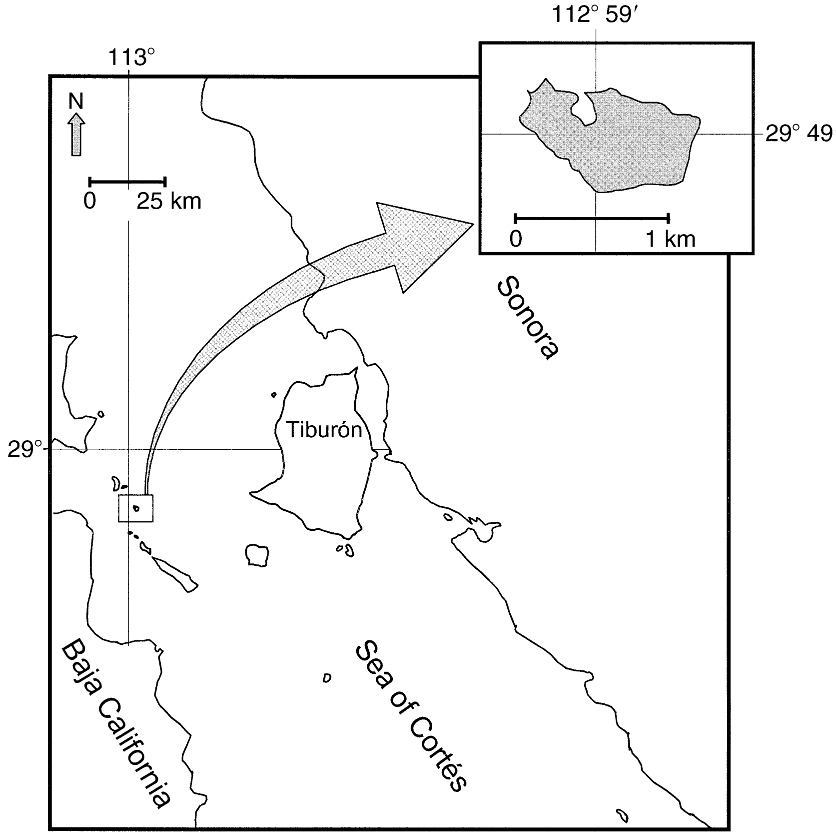

FIG. 1. Slightly larger than 1 km in length, Isla Rasa is one of the smallest islands of the highly productive Midriff region of the Sea of Cortés. The island is flat, with a maximum elevation of 35 m (''Rasa'' means low-lying in Spanish). It consists mainly of 56 ha of low hills of volcanic rock and large valleys with deep guano deposits. In 1999 there were ~260 000 Heermann's Gulls and 200 000 Elegant Terns (>95% of the world populations of each of these two species) nesting in the island and feeding on sardines and other small pelagic fish that crowd the surrounding waters.

nesting seasons. The database contains information collected annually during the seabird nesting season (April–June) from 1989 to 1999 (because of logistic problems, sampling was not done in 1993 and 1994) and includes data on clutch size, egg and chick survival, and mass of nesting adults for Heermann's Gulls, as well as information on seabird diet for both Heermann's Gulls and Elegant Terns. The number of sampled nests depended on available field support staff, and it ranged from a minimum effort of 63 nests in 1990 to a maximum of 325 in 1997, with a mean value of 143 nests per year. From these data we calculated breeding success (number of fledged chicks/number of eggs laid) and averaged for the whole sample of nests each year. The diet of both species was evaluated from regurgitations obtained throughout the season from the sampled nesting adults of Heermann's Gulls and a similar number of Elegant Terns. The proportion of sardines in the diet was estimated from the fresh mass of identifiable sardine remains in the samples relative to the total mass of the regurgitated material (Sánchez-Velasco et al. 2000).

Data on total catch and CPUE of Pacific sardines between 1970 and 1999 were obtained from the official statistics for the fishing fleet of Guaymas and Yavaros in the State of Sonora that fishes mainly in the mid-Gulf region (Cisneros-Mata et al. 1996). In order to develop a predictive model, we compared in all cases data of each seabird nesting season (April–June) with data of the subsequent fishing season (October to the following July, starting with the 1991–1992 season and ending with the 1999–2000 season).

We obtained the monthly values of the Southern Oscillation Index (SOI) index for the 1984–2000 period from the Commonwealth Bureau of Meteorology (data available online).[7] The SOI is a measure of air pressure anomalies in the Pacific Ocean (i.e., ENSO conditions) and is calculated as the normalized difference in sea-level pressure readings between Tahiti (~18° S, 150° W) and Darwin, Australia (~12° S, 132° E). This index is used as an indicator of a warm phase in the eastern Pacific. Typically, pressure at Tahiti is greater, which

[7] URL: ⟨http://www.bom.gov.au⟩.

results in equatorial trade winds blowing towards northern Australia. As a consequence, surface waters of the equatorial Pacific are carried to the west, producing a pile-up of warm water in the central western Pacific. During the warm El Niño phase, this pressure gradient slackens, and the easterly currents slow down, or even reverse, which results in transport of warm sea surface water eastward. ENSO conditions are potentially an important predictor of fisheries, as warm surface water reduces the intensity of oceanic upwellings, deepens the thermocline, reduces the productivity of phytoplankton, and in general depresses marine productivity (Velarde and Ezcurra [2002] and references therein).

We also used monthly sea surface temperature data for the mid-Gulf of California for the 1984–2000 period (NASA's Physical Oceanography Distributed Active Archive Centre; available online).[8] Each data point is an eight-day mean of infrared satellite data with an approximate resolution of 18 × 18 km. Data points were averaged to obtain monthly means, and the long-term mean was removed from the monthly data to obtain the variable signal. The annual and semi-annual harmonics were removed from the signals to obtain the anomalies and then these were averaged across the Gulf to get a single monthly value for the mid-Gulf region (Lavín et al. 2003). Additionally, we also used the sea surface temperature anomalies for the 1989–1999 period estimated from direct readings of water temperature in the port of Guaymas, provided by the Centro Regional de Investigación Pesquera (CRIP). Expectedly, both methods yielded data sets that were highly correlated. The associations between the means of variables measured at monthly intervals (such as the SOI or the temperature anomalies) and annual variables (such as the proportion of sardine in the Elegant Tern's diet or the breeding success of the Heermann's Gull) were explored through correlogram analysis, using Bonferroni corrections to allow for multiple comparisons (Chatfield 1996, Warner 1998).

Multiple regression analyses were used to test for associations between variables and fisheries catch data. We first checked for significant colinearity effects between predictor variables by extracting the principal component axes of the correlation matrix and comparing the variance explained by each axis against the predictions of the ''broken-stick'' distribution as a random null model (Jackson 1993). As the variation explained by the largest axes of our data matrix was lower than the predictions of the broken stick, we accepted our independent variables as sufficiently uncorrelated for multiple regression purposes. When regression models were used as predictors of processes in the field, such as sardine total catch, the predictive capacity of the models was tested by jackknifing the data (Efron 1982, Efron and Gong 1983). For this purpose, we eliminated the first year from the series and used the remainder of the series to estimate the regression parameters. With these parameters we predicted the catch value for the year that had been eliminated. We then dropped the second year out of the complete series and, using the same procedure, predicted its catch. We followed the procedure by eliminating each year in turn and estimating an expected catch for that year. These expected values are true predictions, as the original data points did not take part in the prediction of their own values. The predictive capacity of the model was estimated by calculating the amount of the variance that was explained by the jackknifed regression: $r^2 = 1 - (\Sigma(\text{observed} - \text{predicted})^2/\Sigma(\text{observed} - \text{mean})^2)$.

[8] URL: ⟨http://podaac.jpl.nasa.gov⟩.

Results

Between 1970 and 1989, a highly significant correlation existed between fishing effort and total catch ($r = 0.96$, df = 17, $P < 0.00001$; Fig. 2). After 1989, the correlation between catch and effort was nonsignificant ($r = 0.43$, df = 17, $P = 0.21$), i.e., the catch was largely independent of the effort invested, especially when efforts were high.

A significant negative correlation was found between the SOI and the sea surface temperature (SST) anomaly in the mid-Gulf measured from infrared satellite sensors (Fig. 3; $r = -0.38$, df = 199, $P < 0.00001$). As expected, the SST anomaly estimated from satellite sensors was also significantly correlated with the anomaly estimated from direct readings at the port of Guaymas ($r = 0.74$, df = 16, $P = 0.0005$).

The reproductive success (expressed both as breeding success and mean number of fledglings) of Heermann's Gulls showed its lowest values during 1992 and 1998, two El Niño years (Fig. 4). These dramatic decreases in reproductive success coincided with warm-phase anomalies in the Pacific Ocean. Although we found a significant correlation between SOI values and both breeding success and fledged chicks ($r = 0.81$, $P = 0.01$, and $r = 0.68$, $P = 0.04$, respectively), Fig. 5 shows two distinct, separate data clusters: one containing the data points from non-El Niño years, and the other containing the data points from El Niño years (1992, 1998). Within each cluster, no significant linear trend was found between SOI and estimates of reproductive success. That is, the system seems to have two distinct reproductive outcomes: when the winter–spring SOI index is below −1.5 (representing strong El Niño conditions), the reproductive success of Heermann's Gulls collapses to near-zero values. When the index is above −1.0 (representing a mild El Niño or cool-phase conditions), breeding success rises to 40–50% and the mean number of fledglings 0.8–1.0 chicks per nest.

The stepwise regression model of observed total catch of sardine in the Gulf of California (Table 1, Fig. 6a) included the SOI averaged from January to December of the year in which the fishery started, the

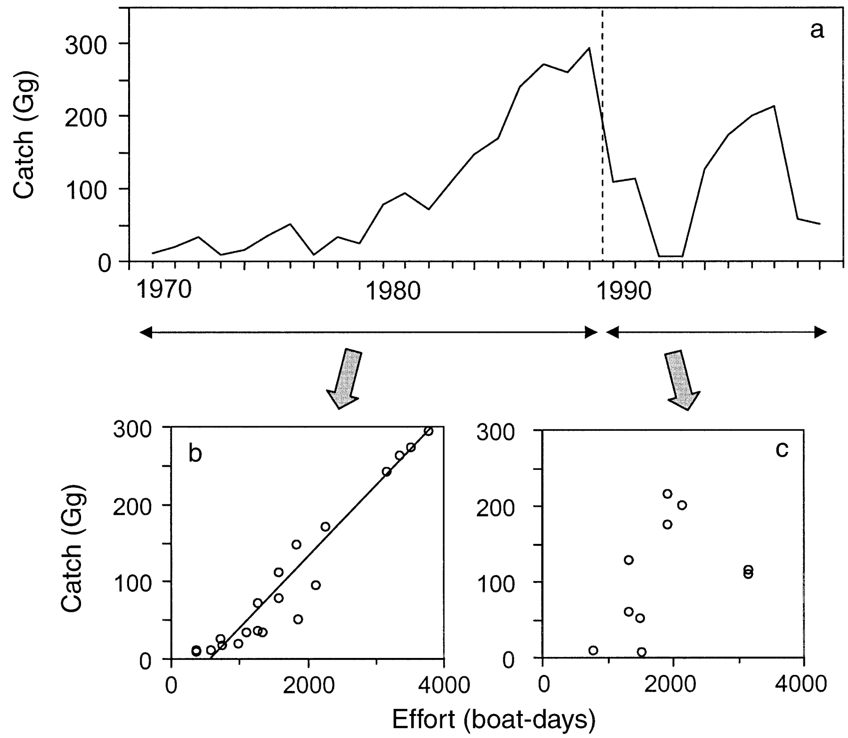

FIG. 2. Relationship between fishing effort and landings: (a) total sardine catch in the Gulf of California between 1970 and 1999; (b) linear relationship between effort and catch from 1970 to 1989; and (c) nonsignificant relationship between effort and catch from 1990 to 1999. Data were reported in thousands of metric tons.

proportion of sardines in the diet of the Elegant Tern, and the clutch size of Heermann's Gull. Although the regression model accounted for 81% of the variance in the sardine catch, the true predictive capacity of the model, as estimated by the extrapolated predictions of the jackknifed model, accounted for 54% of the variation in the catch data. In the case of sardine CPUE (Table 1, Fig. 6b), the best predictor was the proportion of sardines in the diet of the Elegant Tern, followed by the breeding success of the Heermann's Gull and by the interaction between the SST anomaly of May–June in the mid-Gulf and the proportion of sardines in the diet of the Elegant Tern. In this case, the regression accounted for 96% of the observed variation, and the

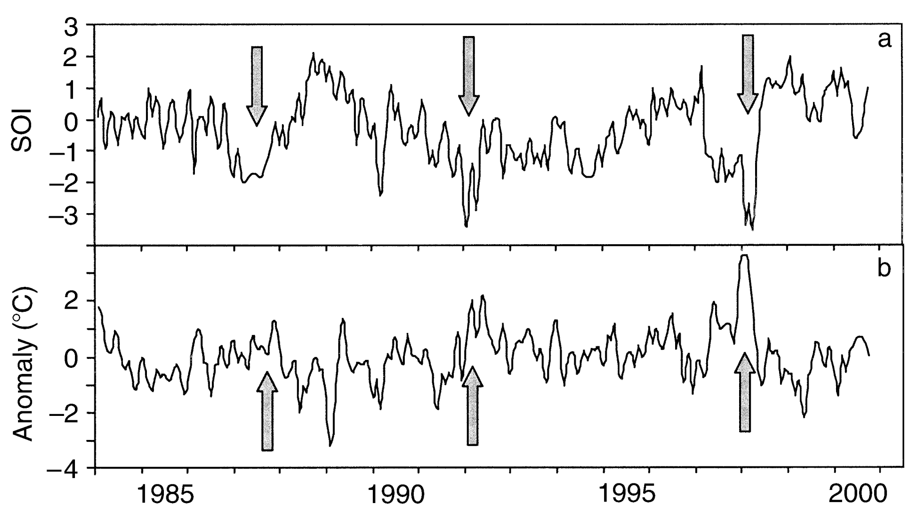

FIG. 3. El Niño and local temperature anomalies in the Gulf of California: (a) monthly values of the Southern Oscillation Index (SOI) and (b) monthly mean temperature anomaly in the mid-Gulf of California, 1984–2000. Arrows indicate extreme El Niño Southern Oscillation (ENSO) events.

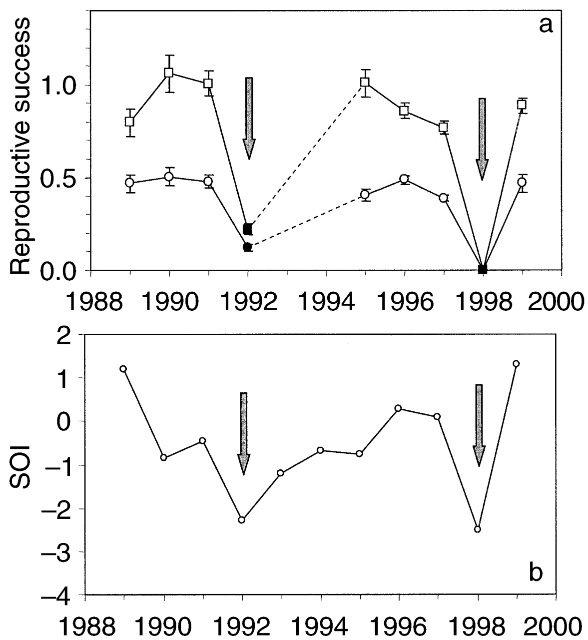

FIG. 4. Effect of El Niño on seabird breeding success: (a) reproductive success of Heermann's Gull in the Gulf of California between 1989 and 1999 (excluding 1993 and 1994, in which sampling was interrupted). Squares indicate number of fledglings per nest; circles indicate breeding success (means ± 1 SE). (b) Values of the December–May mean Southern Oscillation Index (SOI) between 1989 and 1999. In both figures, the arrows indicate years in which the mean December–May SOI reached extreme negative values (less than −1.5).

predictions of the jackknifed model accounted for 73% of the variation in CPUE.

DISCUSSION

Our results show (1) that the reproductive ecology of seabirds is strongly coupled to the conditions of their environment and (2) that, as the causal mechanism of this linkage is food availability, data on seabird ecology can be used to predict the success of fisheries. Because the seabird nesting season in Isla Rasa ends in June and the fishing season starts in October, our model can predict the total sardine catch and the CPUE three months before the onset of the fishing season. In the total catch model we found that the SOI (an indicator of global conditions of the ocean) was the best single predictor of the fishery performance. This result is unsurprising, as the abundance of small pelagic fish near the surface tends to drop during El Niño seasons (Velarde and Ezcurra [2002] and references therein). It is interesting to note that, although local SST values were also good predictors of the success of the fishery, the SOI, a more global indicator, provided better results. This is possibly a result of the fact that SSTs used in this study represented ocean conditions in the mid-Gulf, while sardines occupy a wider distributional range.

In the case of the CPUE model, the proportion of sardines in the diet of Elegant Terns showed up as the best predictor. The proportion of sardines in the diet is a good proxy for CPUE because this variable depends largely on the ease with which terns are able to get sardines relative to other fish (Velarde et al. 1994). Finally, the negative interaction term between tern diet and the late spring SST anomaly in the mid-Gulf suggests that even if sardines are abundant in the early spring, the occurrence of a warm phase later in the season could still bring down the CPUE.

A trophic relationship similar to the one discussed in this paper has been described in great detail for the seabirds that feed on sandeel (*Ammodytes hexapterus*), a small fish of the North Sea. In particular, it has been shown that the breeding success of the Black-legged Kittiwake (*Rissa tridactyla*) is strongly correlated with sandeel stock abundance (ICES 1999, 2000, Lewis et al. 2001). For this reason, the management of the sandeel fishery is based on kittiwake breeding performance: where kittiwake breeding success falls below

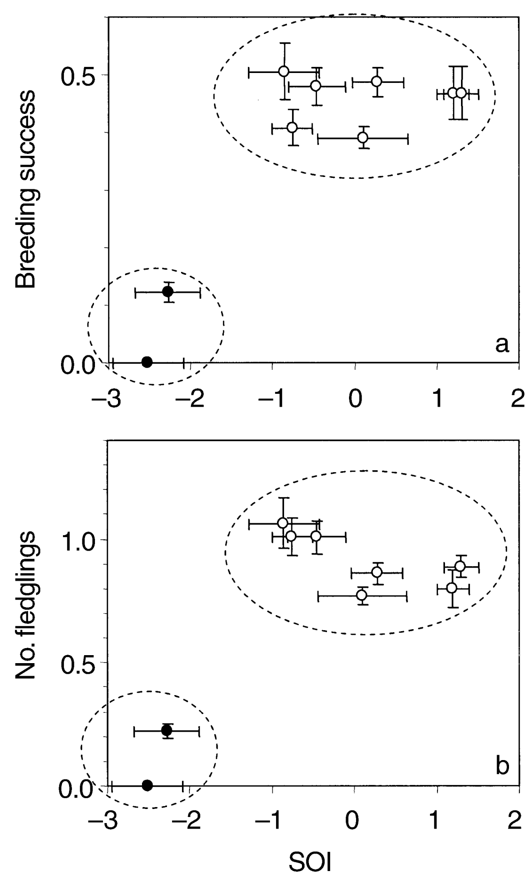

FIG. 5. Relationship between the mean December–May Southern Oscillation Index (SOI) and breeding success of Heermann's Gulls between 1989 and 1999: (a) breeding success and (b) mean number of fledglings per nest. The dotted lines separate El Niño years (black circles) from cold-phase years (white circles). The interval lines indicate standard errors.

TABLE 1. Predictors of total sardine catch and sardine catch per unit effort in the Sea of Cortés.

Predictor variables	r^2	P
Predictors of total sardine catch		
Total model	0.81	0.032
Annual mean SOI	0.31	0.027
Proportion of sardines in Elegant Tern diet	0.30	0.029
Heermann's Gulls clutch size	0.20	0.052
Jackknifed model	0.54	···
Predictors of catch per unit effort		
Total model	0.96	0.005
Proportion of sardines in Elegant Tern diet	0.55	0.002
Breeding success of Heermann's Gulls	0.17	0.016
May–June SST anomaly × proportion of sardines in tern diet	0.24	0.009
Jackknifed model	0.73	···

a threshold level, the sandeel fishery is closed in that segment of the North Sea until kittiwake breeding success recovers in subsequent years. In our study, however, the best predictor of seabird breeding success is simply the SOI index, but both this index and the seabirds' breeding success are very good predictors of the success of the sardine fishery. The sandeel–kittiwake model, however, is based on a post hoc correlation, while our model is of a more predictive nature.

Our results confirm a large set of previous studies showing that seabird nesting ecology is strongly coupled to the oceanographic and food availability conditions of their environment (Anderson et al. 1980, Anderson and Gress 1984, Burger and Cooper 1984, Furness 1984, MacCall 1984, Berruti and Colclough 1987, Furness and Barrett 1991, Furness and Nettleship 1991, Montevecchi and Berruti 1991, Velarde et al. 1994, Crawford and Dyer 1995, Montevecchi and Myers 1995, Crawford 1998). Large-scale oceanographic fluctuations, including ENSO events, have also been identified as possible causes of population fluctuations in Pacific sardines (Lluch-Belda et al. 1986), among other causes such as population structure and fishing effort during the preceding year (Cisneros-Mata et al. 1995). These previous papers suggest that reduced abundance of sardine during ENSO years is chiefly due to poor recruitment more than shifts in sardine distribution.

The modeling approach introduced here offers several advantages over previous prediction models. One of us (Cisneros Mata et al. 1996) has used demographic, oceanographic, and catch data to predict bulk landings of small pelagic fish in the Sea of Cortés. This model was less accurate than the one presented in this paper, and its forecast is obtained 5–6 months later than with our approach, making it of limited use to plan the effort of the fishing fleet. As a result of the difficulty in predicting its stock, no formal forecast model for Pacific sardines is included in Mexico's official fisheries chart (DOF 2000).

We conclude that catch-independent predictions based on oceanographic and seabird data can complement at a relatively low cost the fisheries information obtained from commercial and research vessels, a possibility suggested previously by other researchers (Cairns 1987, Montevecchi 1993, Monaghan 1996,

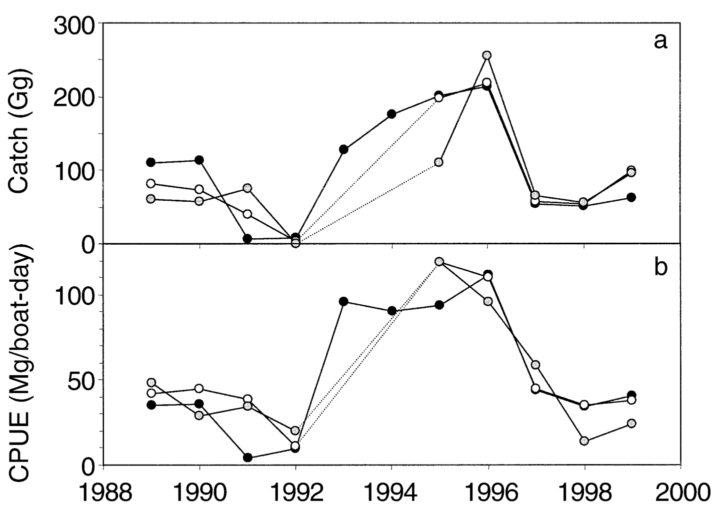

FIG. 6. Predictions of sardine fisheries in the Gulf of California, 1989–1998. Black circles show the actual values for the Gulf; gray circles show the predictions of the multiple regression model; white circles show the predictions of the jackknifed model, which are true predictions and not regression-interpolated values. (a) Total catch (in thousands of metric tons); (b) catch per unit effort (CPUE; in metric tons per boat-day). No predictions were made for 1993 and 1994, as no seabird data were gathered during those years.

Furness and Camphuysen 1997). In addition, our approach also yields valuable information about the breeding ecology of key or threatened species, such as the seabirds studied in this work. Information on seabird breeding and feeding ecology can provide reliable and accurate reference parameters on which to base fisheries management.

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