Journal of Marine Systems 146 (2015) 82–88

Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

Seabird diet predicts following-season commercial catch of Gulf of California Pacific Sardine and Northern Anchovy

Enriqueta Velarde [a,*], Exequiel Ezcurra [b], Daniel W. Anderson [c]

[a] Instituto de Ciencias Marinas y Pesquerías, Universidad Veracruzana, Hidalgo 617, Col. Río Jamapa, Boca del Río, Veracruz C.P. 94290, Mexico
[b] UCMEXUS, CCB, Department of Botany and Plant Sciences, University of California, Riverside, 900 University Avenue, Riverside, CA 92521, United States
[c] Wildlife, Fish and Conservation Biology Department, University of California, Davis, CA 95616, United States

ARTICLE INFO

Article history:
Received 13 February 2014
Received in revised form 4 August 2014
Accepted 17 August 2014
Available online 23 August 2014

Keywords:
CPUE predictors
Fishery predictors
Gulf of California
Pacific Sardine and Northern Anchovy fishery
Seabirds' diets
Small pelagic fish

ABSTRACT

The highly productive Gulf of California exhibits high biodiversity and an abundance of small pelagic, schooling fishes, important both to the ecosystem and to fisheries. These fishes show wide fluctuations in abundance due to oceanographic–atmospheric phenomena such as El Niño-Southern Oscillation, constituting a problem for effective fisheries management. In this work we propose several parameters in the diet of three seabird species as useful predictors of the eventual commercial catch per unit effort (CPUE) of Pacific sardine (*Sardinops sagax*) and northern anchovy (*Engraulis mordax*) in the Midriff Island Region of the Gulf of California. We found that seabirds are sensitive to fluctuations in the abundances of these fishes, their proportions in the diet becoming suitable predictors of future commercial CPUE. The precision of our prediction is high because the birds feed on pre-recruit fish, and the time between the sampling of the diets and the initiation of the fishing season is short, minimizing stochastic effects on recruitment and subsequent abundance due to environmental fluctuations.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Diverse measures have been designed to implement fishery management, in many cases based on evaluations of absolute and relative abundance of fish stocks, as well as predictions of future abundance of the stock. Included are several models for evaluating the abundance of the population, size of the stock, and related parameters such as total allowable catch and catch per unit effort (CPUE). Many of these models are based on age-structure of the fish population, geographic distribution, spawning biomass, yield and other parameters (Abramson and Tomlinson, 1972; Arreguín-Sánchez, 1996; Caswell, 1988; Cisneros-Mata et al., 1996; De Anda-Montañez et al., 1994; Fox, 1974; Gulland, 1983; Harley et al., 2001; Hilborn and Walters, 1992; Megrey, 1989; Shepherd, 1987; Winters and Wheeler, 1985). Some of these models combine information from multiple sources to increase management effectiveness. For instance, some common indirect methods are based on correlations between parameters such as growth rates, age, sexual maturity and environmental variation, such as sea surface temperature. In other studies, based on predator parameters, significant correlations between their diet and fishery parameters, such as total catch and CPUE, have demonstrated the value of this information as a tool to indirectly monitor the condition of the respective fish stocks (Anderson et al., 1980; Bailey et al. 1989; Barrett, 1991; Crawford and Dyer, 1995; Furness and Barrett, 1991; MacCall, 1984; Montevecchi and Myers, 1995; Sánchez-Velasco et al., 2000; Sunada et al., 1981; Velarde et al., 2004).

Most small pelagic fishes are key commercial species in many coastal marine ecosystems, due to their high biomasses and availability. Many also are part of "wasp-waist" food webs (Bakun et al. 2009), in that they feed at lower trophic levels (mainly phyto- and zooplankton), but are important prey for higher trophic level species, such as marine mammals, seabirds, and larger fish species (Anderson and Gress, 1984; Bakun, 2006; Cury et al. 2000; Furness and Barrett, 1991; Montevecchi and Berruti, 1991, Velarde et al., 1994). In upwelling regions, such as the Gulf of California (GoC), and the eastern boundary current systems such as the California, Humboldt and Benguela, an important conflict often occurs as fisheries target the same pelagic fish species on which predators importantly feed.

Unfortunately, most fisheries have not been managed sustainably. Many regional economies have been or are threatened by fishery collapse (Botsford et al., 1997; Radovich, 1982; Schwartzlose et al., 1999; WRI [Worl Resources Institute]., 1994). At present, most of the world's fisheries are overexploited, or very close to it, and small pelagic fish comprise about 25% of the world's fishery landings (Botsford et al., 1997; Christensen et al., 2003; Clover, 2006; Froese, 2004; Myers and Worm, 2003; Sadovy, 2001). These latter fisheries show wide fluctuations in their catches, because their exploited fish populations are strongly affected by oceanographic phenomena such as the El Niño-Southern Oscillation (ENSO; Schwartzlose et al., 1999; Sánchez-Velasco et al., 2000),

* Corresponding author. Tel.: +52 229 956 7070.
E-mail address: enriqueta_velarde@yahoo.com.mx (E. Velarde).

http://dx.doi.org/10.1016/j.jmarsys.2014.08.014
0924-7963/© 2014 Elsevier B.V. All rights reserved.

the Pacific Decadal Oscillation (PDO; Sydeman et al. 2001, Mantua and Hare 2002), and other short- to medium-term environmental variations. Without frequent fishery-independent data acquisition, it is hard to obtain robust indicators of the abundance and availability of these fish populations to inform commercial fishery management strategies and regulatory decisions to safeguard future catches and the ecosystem. On the other hand, CPUE has traditionally been used as an indicator of the abundance of exploited fish. However, recently, two severe problematic implications of this application have been demonstrated: 1) CPUE is not constant, nor directly proportional to abundance, and 2) severe repercussions from the assumption of proportionality in the methods to evaluate stock abundance have been demonstrated, particularly for small pelagic fish (Arreguín-Sánchez, 1996; Martínez-Aguilar et al., 1997, 2009). To mitigate this complexity, the use of a constant quota has been recently suggested for fishery management (Martínez-Aguilar et al., 1997; Walters and Parma, 1996), seemingly having important implications for fish stock sustainability depending on what that quota might be relative to the ecosystem needs, i.e. effective ecosystem-based fisheries management.

The GoC produces close to 50% of Mexico's fishery landings: small pelagic fish contribute 40% to total landings with the GoC contributing 70% of this value. The Pacific sardine (*Sardinops sagax*) has been the most important species in the GoC catches (particularly in the north, where mainly vessels from Sonora state are active), followed by northern anchovy (*Engraulis mordax*), Pacific mackerel (*Scomber japonicus*), thread-fin herring (*Opistonema libertate*), and other species in lesser proportions (Cisneros-Mata et al., 1996; Sánchez-Velasco et al., 2000). This fishery is multi-specific and is locally-known as the "sardine fishery." The total Pacific sardine landings increased between 1970 (about the time when the fishery started in the GoC) and 1989, and collapsed abruptly in the 1991/1992 fishery season (Cisneros-Mata et al., 1995). During this first period there was a strong significant correlation between fishing effort and total catch, but after 1989 this correlation disappeared, indicating that the catches in this second stage were not related to the invested effort, particularly when the effort was high (Velarde et al., 2004). For the next two decades landings did not increase in proportion to the increment in effort, indicating that the stock was overexploited.

The GoC, being one of the most productive natural ecosystems on the planet (Álvarez-Borrego, 1983; 2002), contains as well some of the most important seabird concentrations in the world, particularly in the Midriff Island Region, this is the case for species such as most of the world populations of Least and Black Storm-Petrels (*Oceanodroma microsoma*, *O. melania*), California Brown Pelican (*Pelecanus occidentalis californicus*), Heermann's and Yellow-footed Gulls (*Larus heermanni*, *L. livens*), Elegant Terns (*Thalasseus elegans*), and Craveri's Murrelet (*Synthliboramphus craveri*) (Anderson, 1983; Anderson et al. 2013; Tershy and Breese, 1997; Velarde and Anderson, 1994; Velarde et al., 2005). Most of these seabirds feed on small pelagic fish and are highly sensitive to fluctuations in their availability.

The nesting status of piscivorous seabirds that nest in the Midriff Region (Fig. 1) is strongly tied to the availability of small pelagic fish populations as well as the trophic complexities of the region's ecosystem. For this reason, it seems worthy of consideration to assess the utility of using the information obtained from piscivorous seabirds to inform managers about the availability of the resource to the fleet. In 2004, Velarde et al. developed a predictive model for Pacific sardine total catch and CPUE for the commercial fleet of the state of Sonora, which operates mainly in the Guaymas Basin and the Midriff Island Region (Fig. 1). One of the main predictive components was the proportion of Pacific sardine in the diet of elegant terns. Velarde et al. (1994) demonstrated that the proportion of Pacific sardine in the diet of the studied seabirds was highly correlated with the proportion of this fish species in the commercial fleet landings; they also showed that seabirds are more sensitive than the fleet to the reduction in sardine availability because the consumption of sardine by the seabirds decreases much earlier than when the commercial fleet registers a substantial decrease in their catches (see also Anderson and Gress, 1984). This seems to be the result of the changes in the behavior of the fish with the variation on their abundance. Some authors (Csirke, 1988; Fox, 1974; Harley et al., 2001; MacCall, 1976; Martínez-Aguilar et al. 1997, 2009; Radovich, 1982; Ulltang 1980, 1986) have studied the effect of the

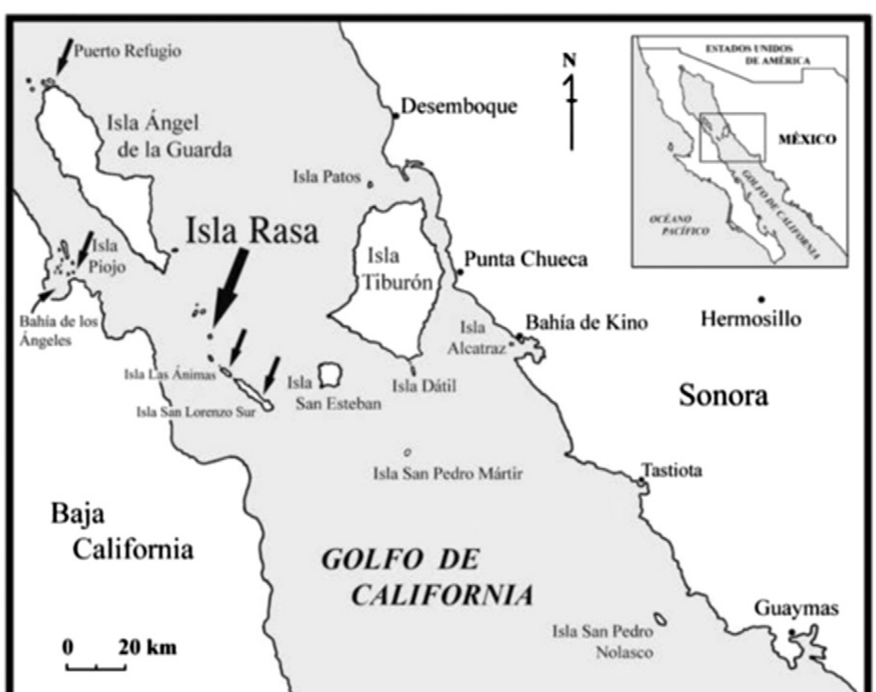

Fig. 1. Midriff Island Region in the Gulf of California (map modified from C. M. Marlett in Moser and Marlett, 2004). Elegant tern and Heermann's gull diet was sampled at Isla Rasa. Brown pelican diet was sampled at Puerto Refugio, Islas Piojo, Las Ánimas and San Lorenzo Sur.

abundance of the sardine on its behavior, and have demonstrated that, within a certain size range of individuals, there is a higher tendency to aggregate into schools when abundance is low. This phenomenon has been called "hyperstability," and results in a higher "catchability" when the abundance of the resource is low. These same authors describe an inverse relationship for the anchovy, which they call "hyperdepletion."

In this work, for important small pelagic fishes in their diets, we propose the use of dietary parameters from seabirds that nest in the Midriff Island Region in the GoC (Fig. 1) as "tools" to help predict the subsequent total catch and, particularly, CPUE of the fleet from the state of Sonora. We also propose that this information be considered as important and used for the management of the fishery, integrating the seabird information with parameters proposed by other authors in other systems (Ainley et al 2014, Ianelli et al. 2006, Leet et al. 2001, Wells et al. 2013). The potential ecological and management importance of these parameters, in the case of the GoC especially, is related to the fact that they are derived during the seabird breeding season well before the start of the fishing season. The specific objectives of the present analysis are to further examine and clarify the demonstrated relationships between the diets of three picivorous seabird species – elegant tern, Heermann's gull and California brown pelican – and the commercial capture of Pacific sardine and northern anchovy for the Sonora fleet.

2. Methods

2.1. Data acquisition

We analyzed the relationship between total catch and CPUE of the small pelagic fishing fleet based on the ports of Guaymas and Yavaros, Sonora, Mexico, and the dietary composition of three seabird species mentioned above. We used information on commercial captures from Cisneros-Mata et al. (1995) and Velarde et al. (2004). These data were extracted from the monthly and annual reports of the Centro Regional de Investigacion Pesquera (CRIP) in Guaymas. The fleet of Sonora operates mainly in the northern part of the central GoC (Guaymas Basin and Midriff Island Region) (Fig. 1).

The proportion of each fish species in the diet of the three seabird species was obtained from regurgitations collected on several islands of the region (Fig. 1). We assumed that each regurgitation was comprised of a single species of fish (generally true), and only the relative frequency or proportion of each fish species, but not their weight in the regurgitation, was considered in this analysis. The proportion of each fish species in each bird species' diet was defined as the number of regurgitations containing each fish species, divided by the total number of regurgitations. These proportions were compared with the fleet landings. Due to the consistency of the results, regardless of the seabird species analyzed, we considered these proportions to be a reliable index of the availability of sardines and anchovies in seabirds' foraging ranges (several 10's of km outward from nesting islands), rather than a reflection of individual seabird species preferences.

Fish identification was based on easily-distinguishable external characteristics if a particular prey item was in good condition or only slightly digested. In the case of heavily digested boluses by terns and gulls, otoliths were identified to determine these relative proportions. The pelican food samples were obtained from chick regurgitations during banding operations by D.W.A. on the Midriff islands Ángel de la Guarda, Piojo, Las Ánimas and San Lorenzo (also known as San Lorenzo Sur), during the months of May and June of 1986–1988, 1992, 1993, 1996 and 1997 (Fig. 1). Heavily digested Brown Pelican boluses were not recorded but were rare. Not all sites were collected in all years but, due to the great mobility of these birds, we assumed that there are few differences in the diet of the birds between islands in the region. The food samples for Heermann's Gull and Elegant Tern were collected during the same years, in the way described in Velarde et al. (1994), all at Isla Rasa (Fig. 1).

2.2. Statistical analysis

All statistical analyses were done using the R package (R Core Team 2013). A Pearson correlation test was run comparing the proportion of sardine and anchovy among all the food samples for the three seabird species, and the significance of the correlation was tested through a t-test (Sokal and Rohlf 1994). Besides the correlation test, a simple exponential function model ($y = ax^b$) was adjusted between the proportion of sardine and anchovy in the diet of the three seabird species (x variable) and the CPUE of the commercial fleet (y variable) using a non-linear estimation. The logic and assumptions of this model were: the proportion of sardine in the diet is a direct function of the abundance of sardine in the ocean (Z) and, by definition, the "catchability" of the sardine for the birds, is defined by the equation $dz / dt = k_a z$, that may be rewritten as $d(\ln(z_a)) / dt = k_a$. Similarly, we define the "catchability" of the sardine for the fleet as $d(\ln(z_f)) / dt = k_f$. If we divide these two equations it may be deduced that $d(\ln(z_f) / d(\ln(z_a) = k_f / k_a$. In order to simplify $k_f / k_a = b$ it is clear that if $b > 1$ then $k_f > k_a$, if $b < 1$ then $k_f < k_a$, and if $b = 1$ then $k_f = k_a$. Similarly, the proportion of sardine in the diet of the seabirds (variable x of the initial model) is directly proportional to the amount of sardine that is catchable for the birds (z_a). Besides, the CPUE (variable y of the initial model) is also proportional to the amount of sardine that is catchable for the fleet (z_f). Then, the model may be re-parameterized as the initially described exponential equation: $y = ax^b$.

There are several ways to adjust this model to the data, but, in order to keep the original structure of the data and avoid its transformation just for the sake of the adjustment, we used a simple method of non-linear programming, searching for the combination of parameters (a and b) that produced a minimal function of square deviations as an estimation of the error (Himmelblau 1972). The resulting curves provided an estimation of the values of the CPUE for sardine and anchovy during the following fishing season, based on the proportion of each of these species in the diet of the seabirds, during the previous breeding season. This value does not pretend to be an indicator of the abundance of the resource, but rather of its availability to the fishing fleet (and by the previous definition, availability to the birds).

3. Results

The proportions of Pacific sardine and northern anchovy in the diet of the seabirds, as well as proportions in the catch, were inversely related for each year (Fig. 2). Also, the diets of the three seabird species were remarkably similar for both species of fish. However, the diets of

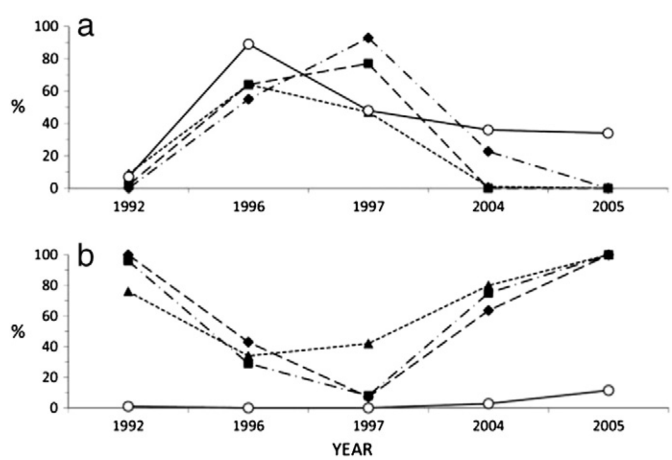

Fig. 2. Proportion (%) of regurgitations containing Pacific sardine (a) or northern anchovy (b) in the diets of the Heermann's gull (■), California brown pelican (◆) and elegant tern (▲) and percentage in the fleet catch (o).

pelicans and gulls were more similar to one-another than to the catch, but the diet of terns was closer to the fleet catch for the years with matching data (Table 1, Figs. 2a, b).

Few significant correlations (only five of 15) were found between the proportions of the two pelagic fishes when compared within and among the three seabird species. These were mostly negative correlations between the proportions of sardine and anchovy when compared within each of the three seabird species. These negative correlations were to be expected, because as one increases, the other decreases very significantly in the diet of the pelican ($r = -0.989$, $t = 6.634$, $p = 0.009$), to a lesser degree for the gull ($r = -0.969$, $t = 3.911$, $p = 0.03$) and finally the tern ($r = -0.961$, $t = 3.453$, $p = 0.041$). Also, a negative and highly significant correlation was found between the proportion of sardine in the diet of the pelican, and the anchovy in the diet of the gull ($r = -0.986$, $t = 5.987$, $p = 0.007$). Only one positive significant correlation was found between the proportion of the anchovy in the diet of the pelican and that of the gull ($r = 0.975$, $t = 4.392$, $p = 0.022$).

The results of the exponential regression analysis showed that the functional relationship between the proportion of sardine in the diet of the three seabird species with the values for CPUE of the commercial fleet is significantly convex ($b < 1$; see Fig. 3a, b and c), showing a significantly non-linear relationship between both variables (Table 2).

These data demonstrate that small increments of sardine in the diet of the birds are associated with a large increment in commercial CPUE, or that the fleet is more efficient capturing sardines than the seabirds when the availability of this small pelagic fish is low. Thus, if the proportions of Pacific sardine in the seabird diets are known, particularly for the elegant tern ($p < 0.0001$), it is possible to estimate sardine CPUE for the commercial fleet for the subsequent fishing season.

In the case of the northern anchovy (Fig. 4a, b and c), the same exponential function produced a significantly concave curve, quite different from that for the Pacific sardine ($b > 1$). This implies that in order to observe a small increment in the anchovy CPUE of the fishing fleet, it is necessary to observe a large increment in the proportion of this fish in the diet of the birds or, conversely, either the fleet is less efficient than the seabirds at capturing anchovy or the fleet is unwilling to pursue this species when its availability is low. In the case of the anchovy analysis, compared to that of the sardine, statistical significances were lower both for the gull and the tern. However, in the case of the pelican, the proportion of anchovy in its diet was not a suitable parameter for the prediction of the anchovy CPUE of the commercial fleet during the following fishing season ($b = 1$; Table 1), unlike the case for the other two seabird species.

4. Discussion

According to our analysis, three species of dominant, piscivorous seabirds in the GoC exhibited similar, although not identical, trends in their relative consumptions of Pacific sardine and northern anchovy. The lack of positive correlation between the proportions of each fish species in the diet of the three seabirds may be indicative of different prey preferences among the three seabird species.

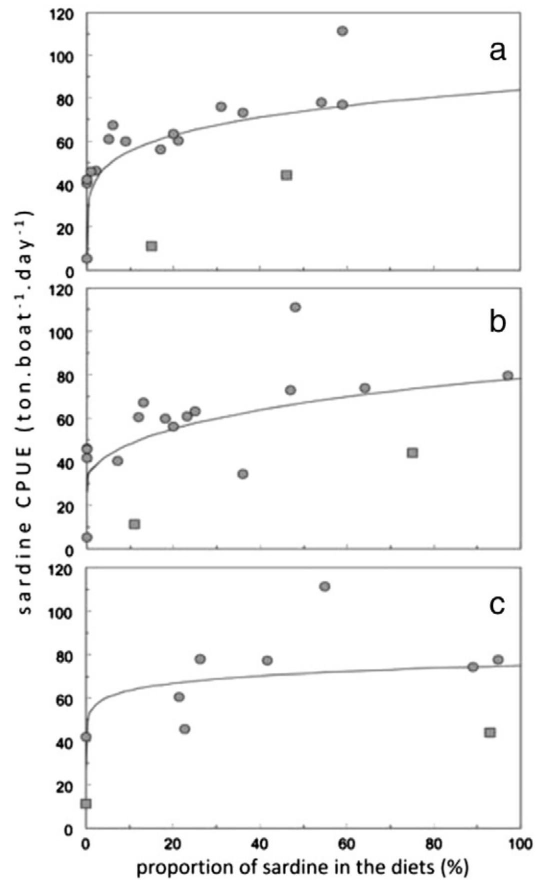

Fig. 3. Proportion of Pacific sardine in the diets of the elegant tern (a), Heermann's gull (b) and California brown pelican (c), in relation to CPUE of the commercial fleet.

It is evident that the proportion of these small pelagic fish in the seabird diet, particularly that of the elegant tern, are suitable indicators of fish-availability to the fishery. This is a useful prediction because the birds feed on the fish during their pre-recruit stage and the time between the diet sampling and the start of the fishing season (which supposedly targets recruits) is relatively short, minimizing the stochastic effects of changed oceanographic factors on recruitment. Indeed, sea surface temperature, depth of the thermocline, and upwellings, have been shown to play an important role on the final catches (Velarde et al. 2004). The proportion of Pacific sardine in the diet of the three seabird species is thus a suitable variable for predicting fishery CPUE for sardine (Table 2), as indicated in the years when matching data were available. In the case of the California brown pelican, the lack of significance between the proportion of anchovy in its diet and fleet CPUE may be due to the fact that the pelican may be catching anchovies that are the same size and age as the ones caught by the fleet during the same season, but not pre-recruits such as is done by the gull and tern.

Table 1
Percentages (%) of Pacific sardine (*S.s.*) and northern anchovy (*E.m.*) in the diets of the elegant tern, Heermann's gull and California brown pelican in the study area, also indicating sample-sizes (*n*), *t*-value and calculated binomial confidence limits (*s.e.*).

		1992				1996				1997				2004				2005			
		n	%	*t*	*s.e.*	*n*	%	*t*	*s.e.*	*n*	%	*t*	*s.e.*	*n*	%	*t*	*s.e.*	*n*	%	*t*	*s.e.*
T.e.	*S.s.*	55	9	2.00	5.5	109	64	1.98	6.5	107	47	1.98	6.8	59	1	2.00	1.8	83	0	1.99	0.0
	E.m.	55	76	2.00	8.2	109	34	1.98	6.4	107	42	1.98	6.7	59	80	2.00	7.4	83	100	1.99	0.0
L.h.	*S.s.*	50	2	2.01	2.8	95	64	1.99	6.9	76	77	1.99	6.8	49	0	2.01	0.0	38	0	2.02	0.0
	E.m.	50	96	2.01	3.9	95	29	1.99	6.6	76	8	1.99	4.4	49	75	2.01	8.8	38	100	2.02	0.0
P.o.	*S.s.*	8	55	2.31	0.0	40	55	2.02	11.2	14	93	2.14	10.0	22	23	2.07	12.9	3	0	3.18	0.0
	E.m.	8	43	2.31	0.0	40	43	2.02	11.1	14	7	2.14	10.0	22	64	2.07	14.7	3	100	3.18	0.0

Table 2
Results of the exponential regression test between proportion of Pacific sardine and northern anchovy in the diets of the three seabird species to predict the CPUE of these two forage fish species by the commercial fleet (see Figs. 3, 4 for details). The numbers in parentheses are the standard errors of the estimates, and the probability values correspond to the null hypothesis that the exponent is equal to one (H_0: $b = 1$; see details in the text).

	Sardine			Anchovy		
	r^2	b (se)	P	r^2	b (se)	P
Pelecanus occidentalis	0.47	0.16 (0.12)	0.0004	0.41	7.20 (14.9)	0.69
Thalasseus elegans	0.34	0.19 (0.11)	<0.0001	0.53	7.00 (2.3)	0.009
Larus heermanni	0.22	0.22 (0.15)	0.0001	0.50	2.82 (1.1)	0.02

In the model, the relationship between the proportion of sardine in the bird diets and that of the commercial CPUE is strongly non-linear so that when the dietary proportion of sardine is relatively low (sardines are less accessible to the surface feeding birds examined here), the sardine CPUE is proportionately much higher. The proportion of Pacific sardine in the seabird diet is thus a suitable variable for predicting fishery CPUE for sardine (Table 2). In contrast, it is interesting that the model for the anchovy predicts a high CPUE only when the proportion of this small pelagic in seabirds' diet is extremely high. This is evident in our models, when the sardines are captured by the fleet in a larger proportion than captured by the seabirds, particularly when their availability is low (therefore resulting in an exponential, instead of a linear, relationship — convex for the sardine and concave for the anchovy).

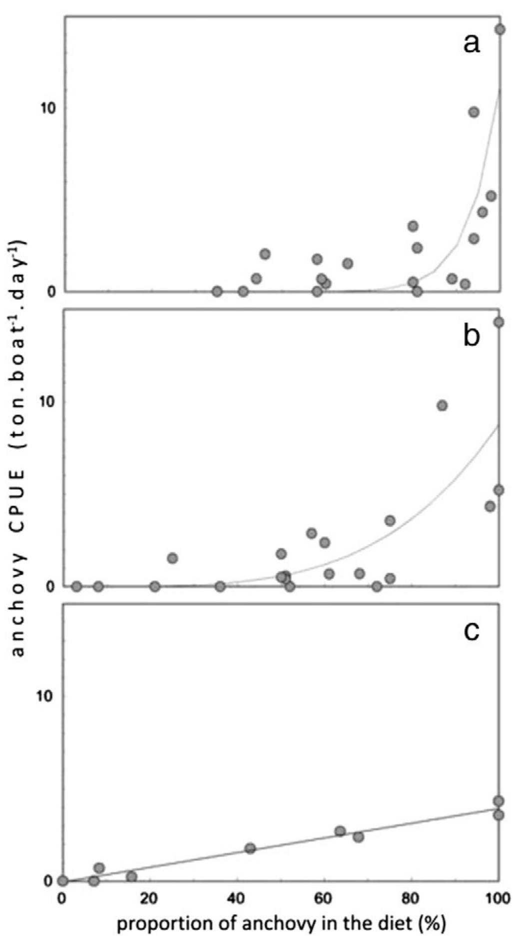

Fig. 4. Proportion of northern anchovy in the diets of the elegant tern (a), Heermann's gull (b) and California brown pelican (c), in relation to the CPUE of the commercial fleet.

This is probably partly due to the higher commercial value of sardines and their being targeted more intensely than anchovies by the commercial fishery.

There are several factors that influence decisions for conducting the fishery, such as the price of the product in the market, the mesh size of the nets, how well the product is preserved in the vessels, and how adequate the product is for processing for canning or reduction for fishmeal (pers. comms. with industry personnel). It is interesting that catchability and related models (Csirke, 1988; Fox, 1974; Harley et al., 2001; MacCall, 1976; Martínez-Aguilar et al. 1997, 2009; Radovich, 1982; Ulltang 1980, 1986) predict a relationship between CPUE and the real fish stock abundance, which is practically identical to that obtained in our work, that is, the relationship between CPUE and sardine abundance follows a convex exponential function, and that of the anchovy follows a concave function. The similarity of these statistical behaviors, derived from totally different models, corroborates the strength of the observed seabird pattern and the importance of the proportion of fish in their diet as a robust indicator of their abundance in the ocean (schematically represented in Fig. 5).

4.1. Sustainability of the fishery

Recently, the multi-species fishery of Sonora was certified as being sustainable by the Marine Stewardship Council (MSC, 2011). The veracity of this certification will depend on the capacity to demonstrate that, in fact, the fishery will continue into the future, and that industry complies with a series of requirements related to by-catch and the conservation of higher trophic level species. The MSC will ratify the certification when industry demonstrates achievement of the corresponding MSC goals. Goals that apply to the health of the ecosystem are intended to maintain a sustainable fishery and a continuing rich and productive food web, i.e. effective ecosystem-based management, a universal goal of FAO (FAO 1996). Without sustainable use of the commercial resource, its abundance will almost certainly decrease and induce a long-term ecosystem-change throughout the Midriff Region.

If this fishery is to be sustainable, avoiding both economic and ecological collapse, it will be necessary for managers to have reliable indicators of the availability of the target species. In the North Sea, for example, when trying to manage the fishery of the sand eel (*Ammodytes hexapterus*), it was found that the breeding success of a seabird, the black-legged kittiwake (*Rissa tridactyla*), was a reliable indicator of the eel abundance. When the breeding success of this seabird dropped below a certain level, the eel fishery was stopped within the species fairly large foraging area until breeding success recovered (ICES 2000, 2001; Lewis et al., 2001). In our case, the proportion of sardine in the diet of the seabirds, particularly that of the elegant tern, is the best parameter from our data set to be used as a reliable predictor of Pacific sardine CPUE, fortunately several months in advance of the fishing season.

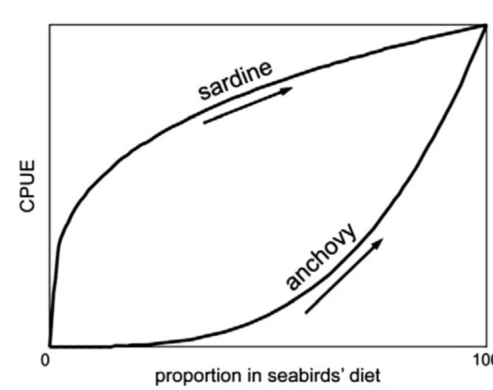

Fig. 5. Tendencies of CPUE for the Pacific sardine and northern anchovy by the commercial fleet in relation to the proportion (%) of these forage fish species in seabirds' diets.

Such information could be used to more effectively and sustainably manage the GoC fishery.

5. Conclusions

We have demonstrated the significant potential of using the proportions of Pacific sardine and northern anchovy in the diet of three seabird species, but particularly the elegant tern for effective prediction of commercial CPUE in the following fishing season in the Gulf of California. If the goal of fishery management is for the fleet to indefinitely operate within sustainable ecological and economic limits (ecosystem-based fishery management), the fishing effort must adjust to the predicted catch, minimizing costs to industry and ecosystem that produce little or no gain. If the relationship between CPUE and the proportion of sardine in the tern diet is known, it is possible to predict the former based on the latter and adjust fleet's activities. The lack of positive correlation between the proportions of each fish species in the diet of the three seabirds may be indicative of different prey preferences among the three seabird species. However, the significant correlations of all three seabird species diets with CPUE are indicative of patterns in sardine abundance in the ocean. Other parameters, or a combination of several of them, such as using the model proposed by Velarde et al. (2004), which also considers the Southern Oscillation Index, sea surface temperature anomaly, and clutch-size and breeding success of the Heermann's gull, with very accurate results, also could be integrated into future, effective sardine management. However, we believe that the most simple, but still realistic model, such as seen here for elegant terns, will have the best likelihood of being used to inform fishery management.

Acknowledgments

We thank the Secretaria de Medio Ambiente y Recursos Naturales (SEMARNAT) and the Secretaría de Gobernación (SEGOB) for permits to stay in Isla Rasa and conduct research in all the study area. We express our gratitude to the Mexican Navy for transportation of personnel and provisions to the island during the 3 month-field season for the last 30 years. We thank Centro Regional de Investigación Pesquera in Guaymas, of the Instituto Nacional de Pesca (INAPESCA), and Cámara de la Industria Pesquera de Sonora, particularly Ma. de los Ángeles Martínez Zavala, Manuel Nevárez Martínez, and Ing. Leon Tissot, for the information of the fleet landings. We are grateful to Miguel Angel Cisneros Mata, involved in the small pelagic fish fishery and analysis, first as personnel of CRIP Guaymas and, more recently, as the Director in Chief of the National Fisheries Institute (INAPESCA), for historic information of the landings, as well as for his constant participation, interest and support during the development of our research, from its beginnings. We thank the regional offices of the Comisión Nacional de Áreas Naturales Protegidas (CONANP), from the states of Baja California and Sonora, for their continued support with logistics and field work. For economic support for the research in the past three decades we want to thank the following institutions and people: Baja Expeditions, Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, Consejo Nacional de Ciencia y Tecnología, Conservación Internacional, Fondo Mexicano para la Conservación de la Naturaleza, Instituto Nacional de Ecología, Lindblad Expeditions, National Geographic Society, Packard Foundation, Programa PROMEP of Secretaría de Educación Pública, UCMEXUS Program at the University of California at Riverside, San Diego Natural History Museum, Comunidad y Biodiversidad, A.C., Walton Family Foundation, The Living Desert, The Nature Conservancy (TNC), Unidos para la Conservación/Agrupación Sierra Madre, Universidad Veracruzana, University of California at Davis, U.S. Fish and Wildlife Service, Universidad Nacional Autónoma de México, Ruth Applegarth, Sue Adams and an anonymous donor through TNC. We are grateful to dozens of students and volunteers for their help in sample and data collection in the field, and to T. Morales for his help in the design of the Graphical Abstract of this publication. We want to thank an anonymous reviewer for constructive editorial work on the original manuscript, and last, but certainly not least, we want to acknowledge David G. Ainley for inviting us to participate in the Workshop: Toward Ecosystem-Based Fishery Management in the California Current System — Predators and the Preyscape, from which this work is derived, and for his precise, thorough and enriching editorial comments to several versions of the manuscript.

References

Abramson, N.J., Tomlinson, P.K., 1972. An application of yield models to a California shrimp population, U.S. Fish. Bull. 70, 1021–1041.

Ainley, D., P. Adams, and J. Jahncke. 2014. Towards ecosystem based-fishery management in the California Current System — Predators and the preyscape: a workshop. Unpublished report to the National Fish and Wildlife Foundation. Point Blue Conservation Science, Petaluma, California. Point Blue contribution number 1979.

Álvarez-Borrego, S., 1983. Gulf of California. In: Detchum, B.H. (Ed.), Estuaries and enclosed seas. Elsevier Press, pp. 427–449.

Álvarez-Borrego, S., 2002. Physical Oceanography. In: Case, T.J., Cody, M.L., Ezcurra, E. (Eds.), A new island biogeography of the Sea of Cortés. Oxford University Press, pp. 41–59.

Anderson, D.W., 1983. The Seabirds. In: Case, T.J., Cody, M.L. (Eds.), Island biogeography in the Sea of Cortéz. University of California Press, pp. 246–264 (474-481).

Anderson, D.W., Gress, F., 1984. Brown Pelicans and the Anchovy Fishery Off Southern California. In: Nettleship, D.N., Sanger, G.A., Springer, P.F., Nettleship, D.N., Sanger, G.A., Springer, P.F. (Eds.), Marine birds: their feeding ecology and fisheries relationships. Canadian Wildlife Service, pp. 128–135.

Anderson, D.W., Gress, F., Mais, K.F., Kelly, P.R., 1980. Brown pelicans as anchovy stock indicators and their relationships to commercial fishing. Ocean. Fish. Rep. 21, 54–61.

Anderson, D.W., Henny, C.J., Godinez-Reyes, C., Gress, F., Palacios, E.L., Santos del Prado, K., Gallo-Reynoso, J.P., Bredy, J., 2013. Size and distribution of the California Brown Pelican Metapopulation in a Non-ENSO year. Mar. Ornithol. 41, 95–106.

Arreguín-Sánchez, F., 1996. Catchability: a key parameter for fish stock assessment. Rev. Fish. Biol. Fish. 6, 221–242.

Bailey, R.S., Furness, R.W., Gauld, J.A., Kunzlik, P.A., 1989. Recent changes in the population of the sandeel (*Ammodytes marinus* Raitt) at Shetland in relation to estimates of seabird predation. Mar. Sci. 193, 209–216.

Bakun, A., 2006. Wasp-waist populations and marine ecosystem dynamics navigating the "predator pit" topographies. Prog. Oceanogr. 68, 271–288.

Bakun, A., Babcock, E.A., Lluch-Cota, S.E., Santora, C., Salvadeo, C.J., 2009. Issues of ecosystem-based management of forage fisheries in "open" non-stationary ecosystems: the example of the sardine fishery in the Gulf of California. Rev. Fish. Biol. Fish. http://dx.doi.org/10.1007/s1116-009-9118-1.

Barrett, R.T., 1991. Shags (*Phalacrocorax aristotelis* L.) as potential samplers of juvenile saithe (*Pollachius virens* L.) stocks in northern Norway. Sarsia 76, 153–156.

Botsford, L.W., Castilla, J.C., Peterson, C.H., 1997. The management of fisheries and marine ecosystems. Science 277, 509–515.

Caswell, H., 1988. Approaching Size and Age in Matrix Population Models. In: Eberman, L., Peterson, L. (Eds.), Size-structured populations. Springer Verlag, pp. 85–105.

Christensen, V., Guénette, S., Heymans, J.J., Walters, C.J., Watson, R., Zeller, D., Pauly, D., 2003. Hundred-year Decline in North Atlantic Predatory Fishes. Fish and Fisher. 4, pp. 1–24.

Cisneros-Mata, M.A., Nevárez-Martínez, M.O., Hammann, M.G., 1995. The rise and fall of the Pacific sardine, *Sardinops sagax caeruleus* Girard, in the Gulf of California, Mexico. Calif. Coop. Oceanogr. Fish. Rep. 36, 136–143.

Cisneros-Mata, M., Montemayor-López, G., Nevárez-Martínez, M.O., 1996. Modeling deterministic effects of age structure, density dependence, environmental forcing and fishing in the population dynamics of the Pacific sardine (*Sardinops sagax caeruleus*) stock of the Gulf of California. Calif. Coop. Oceanogr. Fish. Rep. 37, 201–208.

Clover, C., 2006. The End of the Line: How Overfishig is Changing the World and What we Eat. University of California Press, Berkeley.

Crawford, R.J.M., Dyer, B.M., 1995. Responses by four seabird species to a fluctuating availability of Cape anchovy *Engraulis capensis* off South Africa. Ibis 137, 329–339.

Csirke, J., 1988. Small Shawling Pelagic Fish Stocks. In: Gulland, J. (Ed.), Fish Population Dynamics: The implication for Management. John Wiley & Sons. Ltd, pp. 271–302.

Cury, P., Bakun, A., Crawford, R.J.M., Jarre-Teichmann, A., Quiñones, R.A., Shannon, L.J., Verheye, H.M., 2000. Small pelagic in upwelling systems: patterns of interaction and structural changes in "wasp-waist" ecosystems. J. Mar. Sci. 210, 603–618.

De Anda-Montañez, J.A., Seijo, J.C., Martínez-Aguilar, S., 1994. Reclutamiento y variabilidad ambiental en la pesquería de sardina Monterrey (*Sardinops sagax*) del Golfo de California. Mex.Invest. Pesq. 38, 23–36.

FAO, 1996. Precautionary Approach to Capture Fisheries and Species Introductions. FAO Technical Guidelines for Responsible Fisheries. Food and Agriculture Organization Council, 94th Session. FAO/Swedish National Board of Fisheries.

Fox, W.W., 1974. An overview of production modeling. Colloq. Sci. Pap. 3, 142–156.

Froese, R., 2004. Keep it Simple: Three Indicators to Deal with Overfishing. Fish and Fisher. 5, pp. 86–91.

Furness, R.W., Barrett, R.T., 1991. Ecological responses of seabirds to reductions in fish stocks in North Norway and Shetlend. Int.Ornithol. 4, 2241–2245.

Gulland, J.A., 1983. Fish Stock Assessment: A Manual of Basic Methods. Willey Interscience, FAO/Willey series of Food and Agriculture. vol. 1.

Harley, S.J., Myers, R.A., Dunn, A., 2001. Is catch-per-unit-effort proportional to abundance? Can. J. Fish. Aquat. Sci. 58, 1760–1772.

Hilborn, R., Walters, C.J., 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Chapman and Hall.
Himmelblau, D.M., 1972. Applied Nonlinear Programming. McGraw-Hill, (416 pp).
Ianelli, J., Barbeaux, S., Honkalehto, T., Kotwicki, S., Aydin, K., Williamson, N., 2006. Assessment of Alaska Pollock Stock in the Eastern Bering Sea. Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions. North Pac. Fish. Mgmt. Council, Anchorage, AK, pp. 35–138 (section 1).
ICES [International Council for the Exploration of the Sea]., 2000. Report of the ICES Advisory Committee on the Marine Environment, 1999. Internat. Council Explor. Sea Coop. Res. Report 239. ICES.
ICES [International Council for the Exploration of the Sea]., 2001. Report of the ICES Advisory Committee on Ecosystems, 2001. Internat. Council Explor. Sea Coop. Res. Report 249.
Leet, W.S., Dewees, C.M., Klingsbeil, R., Larson, E.J., 2001. California's Living Marine Resources: A Status Report. California Department of Fish & Game, Sacramento.
Lewis, S., Wanless, S., Wright, P.J., Harris, M.P., Bull, J., Elston, D.A., 2001. Diet and breeding performance of black-legged kittiwakes *Rissa tridactyla* at a North Sea colony. Mar. Ecol. Prog. Ser. 221, 277–284.
MacCall, A.D., 1976. Density dependence of catchability coefficient in the California Pacific sardine, *Sardinops sagax caerulea*, purse seine fishery. Calif. Coop. Oceanogr. Rep. 18, 136–148.
MacCall, A.D., 1984. Seabird-fishery Trophic Interactions in Eastern Pacific Boundary Currents: California and Peru. In: Nettleship, D.N., Sanger, G.S., Springer, P.F. (Eds.), Pacific Seabird Group, Canadian Wildlife Service, pp. 136–146.
Mantua, N.J., Hare, S.R., 2002. The Pacific decadal oscillation. J. Oceanogr. 58, 35–44.
Martínez-Aguilar, S., De Anda-Montañez, J.A., Arreguín-Sánchez, F., 1997. Densidad y “capturabilidad” de la sardina monterrey, *Sardinops sagax* (Pisces: Clupeidae) del Golfo de California, México. Rev. Biol. Trop. 4(3)/45(1), 527–535.
Martinez-Aguilar, S., de Anda-Montañez, J.A., Arreguín-Sánchez, F., Cisneros-Mata, M.A., 2009. Constant harvest rate for the Pacific sardine (*Sardinops caeruleus*) fishery in the Gulf of California based on catchability-at-length-estimations. Fish. Res. 99, 74–82.
Megrey, B.A., 1989. Review and Comparison of Age-structured Stock Assessment Models From Theoretical and Applied Points of View. In: Edwards, E.F., Magrey, B.A. (Eds.), Mathematical Analysis of Fish Stock Dynamics. Am. Fish. S. S. 6, pp. 8–48.
Montevecchi, W.A., Berruti, A., 1991. Avian indication of pelagic fishery conditions in the Southeast and Northwest Atlantic. Int.Ornithol. 4, 2246–2256.
Montevecchi, W.A., Myers, R.A., 1995. Prey harvests of seabirds reflect pelagic fish and squid abundance on multiple spatial and temporal scales. Mar. Ecol. Prog. Ser. 117, 1–9.
Moser, M.B., Marlett, S.A., 2004. Comcáac Quih Yaza Quih Hant Ihíip hac. Diccionario seri-español-inglés. Universidad de Sonora.
MSC, 2011. http://www.msc.org/sala-de-prensa/noticias/mexican-gulf-of-california-pacific-sardine-fishery-now-msc-certified?searchterm=sardina+golfo+de+calif.
Myers, R.A., Worm, B., 2003. Rapid worldwide depletion of predatory fish communities. Nature 423, 280–283.
R Core Team, . A Language and Environment for Statistical Computing, Foundation for Statistical Computing;. Vienna, Austria (available at http://www.R-project.org).
Radovich, J., 1982. The collapse of the California sardine fishery: what have we learned? Calif. Coop. Oceanogr. Fish. Rep. 28, 56–78.
Sadovy, Y., 2001. The threat of fishing to highly fecund fishes. J. Fish Biol. 59, 90–108.
Sánchez-Velasco, L., Shirasago, B., Cisneros-Mata, M.A., Ávalos-García, C., 2000. Spatial distribution of small pelagic fish larvae in the Gulf of California and its relation to the El Niño 1997–1998. J. Plankton Res. 22, 22–29.
Schwartzlose, R.A., Alheit, J., Bakun, A., Baumgartner, T.R., Cloete, R., Crawford, R.J.M., Fletcher, W.J., Green-Ruiz, Y., Hagen, E., Kawasaki, T., Lluck-Belda, D., Lluch-Cota, S.E., MacCall, A.D., Matsuura, Y., Nevárez-Martínez, M.O., Parrish, R.H., Roy, C., Serra, R., Shust, K.V., Ward, M.N., Zuzunaga, J.Z., 1999. Worldwide large-scale fluctuations of sardine and anchovy populations. J. Mar. Sci. 21, 289–347.
Shepherd, J.G., 1987. Towards a Method for Short-term Forecasting of Catch rates Based on Length Compositions. In: Pauly, D., Morgan, G.R. (Eds.), Length-based Methods in Fisheries Research. International Center for Living Aquatic Resources Management. Manila Philippines and Kuwait Institute for Scientific Research 13. ICLARM Conference Proceedings, Safat, Kuwait (468 p).
Sokal, R.R., Rohlf, F.J., 1994. Biometry: The Principles and Practices of Statistics in Biological Research. W.H. Freeman, San Francisco.
Sunada, J.S., Yamashita, L.S., Kelly, P.R., Gress, F., 1981. The brown pelican as a sampling instrument of age group structure in the northern anchovy population. Calif. Coop. Oceanogr. Fish. Rep. 22, 65–68.
Sydeman, W.J., Hester, M.M., Thayer, J.A., Gress, F., Martin, P., Buffa, J., 2001. Climate change, reproductive performance, and diet composition of marine birds in the southern California Current system, 1969–1997. Program. Oeanogr. 49, 309–329.
Tershy, B.R., Breese, D., 1997. The birds of San Pedro Martír Island, Gulf of California, Mexico. Western Birds. 28, pp. 96–107.
Ulltang, O., 1980. Factors affecting the reaction of pelagic fish stocks to exploitation and requiring a new approach to management. Cons. Int. Explor. 177, 489–504.
Ulltang, O., 1986. Catch per unit of effort in the Norwegian purse seine fishery for Atlanto-Scandinavian herring. FAO Fish. Tech. Pap. 155, 91–101.
Velarde, E., Anderson, D.W., 1994. Conservation and Management of Seabird Islands in the Gulf of California: Setbacks and Successes. In: Nettleship, D.N., Burger, J., Gochfeld, M. (Eds.), Seabirds on islands: threats, case studies and action plans. Birdlife Conservation Series. 1, pp. 229–243.
Velarde, E., Tordesillas, M.S., Vieyra, L., Esquivel, R., 1994. Seabirds as indicators of important fish populations in the Gulf of California. Calif. Coop. Oceanogr. Fish. Rep. 35, 137–143.
Velarde, E., Ezcurra, E., Cisneros-Mata, M.A., Lavín, M.F., 2004. Seabird ecology, El Niño anomalies, and prediction of sardine fisheries in the Gulf of California. Ecol. Appl. 14 (2), 607–615.
Velarde, E., Cartron, J.-L.E., Drummond, H., Anderson, D.W., Rebon-Gallardo, F., Palacios, E., Rodríguez, C., 2005. Nesting Seabirds of the Gulf of California's Offshore Islands: Diversity, Ecology, and Conservation. In: Cartron, J.-L.E., Ceballos, G., Felger, R.S. (Eds.), Biodiversity, ecosystems, and conservation in northern Mexico. Oxford University Press, pp. 452–470.
Walters, C., Parma, A.M., 1996. Fixed exploitation rate strategies for coping with effects of climate change. Can. J. Fish. Aquat. Sci. 53, 148–158.
Wells, B.K., Schroeder, I.D., Santora, J.A., Hazen, E.L., et al., 2013. State of the California Current 2012–13 No Such Thing as An “Average” Year. 54. CalCOFI Reports, pp. 27–71, (http://calcofi.org/publications/calcofireports/v54/Vol_54_StateOfCurrent_37-71.pdf.).
Winters, G.H., Wheeler, J.P., 1985. Interaction between stock area, stock abundance and catchability coefficient. Can. J. Fish. Aquat. Sci. 42, 989–998.
WRI [Worl Resources Institute]., 1994. World Resources 1994–95. Oxford University Press.