# Quantifying Species Abundance Trends in the Northern Gulf of California using Local Ecological Knowledge

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ARTICLE

# Quantifying Species Abundance Trends in the Northern Gulf of California Using Local Ecological Knowledge

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### Abstract

   Ecosystem-based fisheries management requires data on all parts of the ecosystem, and this can be a barrier in data-poor systems. Marine ecologists need a means of drawing together diverse information to reconstruct species abundance trends for a variety of purposes. This article uses a fuzzy logic approach to integrate information from multiple data sources and describe biomass trends for marine species groups in the northern Gulf of California, Mexico. Forty-two species groups were analyzed, comprising fish, invertebrates, birds, mammals, turtles, and algae. The most important new data series comes from recent interviews with fishers in the northern part of the gulf. Respondents were asked to classify the abundance of various targeted and untargeted marine species groups from 1950 to the present. The fuzzy logic method integrates their responses with catch-per-unit-effort series, intrinsic vulnerability to fishing determined from life history parameters, biomass predicted by a Schaefer harvest model, and other simple indices. The output of the fuzzy logic routine is a time series of abundance for each species group that can be compared with known trends. The results suggest a general decline in species abundance across fished and unfished taxa, with a few exceptions. Information gathered from interviews indicated that older fishers tended to recognize a greater relative decrease in species abundance since 1970 than did younger fishers, providing another example of Pauly's (1995) shifting cognitive baselines.

Resource managers face an expanding array of challenges in the northern Gulf of California, Mexico. The area has ecological significance as a biodiversity "hotspot" with a high degree of endemism in fish (Gilligan 1980; Enriquez-Andrade et al. 2005), invertebrates (Brusca 2006; Hendrickx 2007), and plants (Felger 2000), and it contains critical habitat for migratory and endangered species (Velarde and Anderson 1994; Jaramillo-Legorreta et al. 2007; Lercari and Chávez 2007). Unfortunately, marine conservation is often at odds with the fisheries that are so critical to the economic and food security of coastal communities (Guerroero-Ruíz et al. 2006; Lluch-Cota et al. 2007). Agriculture, aquaculture, ecotourism, and other marine-use sectors also continue to grow and compete with fisheries for space and resources.

Some have advocated ecosystem-based fisheries management (EBFM) as an integrated approach to managing human activities and a means of reconciling human needs with those of the natural system (Garcia et al. 2003; Pikitch et al. 2004). However, EBFM is broad by definition, and quantitative tools and analyses meant to support EBFM decisions can have large data requirements; this has proved to be a barrier to implementation of management decisions (Frid et al. 2006). Deficiency in scientific survey information is most evident in developing tropical and subtropical nations like Mexico, where species diversity is high and food web dynamics are complex, yet resources for stock assessment and monitoring are scarce (Silvestre and Pauly 1997). Here, there is a need for systematized information on species abundance (Lluch-Cota et al. 2007),

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particularly time series data, to support ecological modeling and other endeavors.

To patch together the history of marine populations it is sometimes necessary to draw on unconventional sources of information. One useful and largely untapped resource is the local ecological knowledge (LEK) held by fishers and community members (Johannes et al. 2000). Although there are many examples in which LEK has been collected and used for study and management purposes, there are few examples in which such data are used quantitatively. Previous publications have used LEK to define species ranges (Gerhardinger et al. 2009). Some have applied statistical models to identify critical population declines (Turvey et al. 2009) or even estimate species abundance in terrestrial (Anadón et al. 2009) and marine systems (Ainsworth et al. 2008). Local ecological knowledge offers some important advantages over other types of scientific data: it is inexpensive to collect, it can be pertinent to a wide range of species, and it can inform our understanding of ecosystem changes over long time periods and wide geographic ranges. The data also reveal how the fishing industry perceives the resource and resource supply. This is a useful perspective for understanding fisher's motives and using the LEK data in applications.

This article presents the results from a series of LEK interviews recently conducted in the northern Gulf of California. The interviews help identify changes in the marine ecosystem from 1950 to the present as perceived by artisanal fishers. Considered in this study is whether the information conveyed by fishers is affected by their reliance on stocks for food and livelihood and whether younger and older fishers perceive ecosystem changes differently. Specifically, the analysis looks for evidence of the psychosocial phenomenon called shifting cognitive baselines (Pauly 1995), in which each generation of resource users accepts a lower standard as normal and so does not have an accurate appreciation of the true magnitude of historical resource decline.

The abundance trends from the LEK data are combined with five other data series developed here (simple stock size and fishery indicators) to produce composite trends detailing the likely changes in relative abundance for 42 species groups in the northern Gulf of California. The intention is that these time series for fish, invertebrates, mammals, birds, and reptiles will be useful in a variety of quantitative EBFM applications, including ecosystem modeling. A fuzzy logic algorithm (Zadeh 1965; Bellman and Zadeh 1970) is used here as a method of deriving numerical trends from ordinal LEK data, standardizing the various data streams, and combining them into a composite time series while resolving disagreements according to a transparent-rule matrix.

## METHODS

Six data series are developed here and then integrated using a fuzzy logic system in order to reconstruct species abundance trends. Three series can be considered directly representative of species abundance, and the other three relate to the exploitation trends of fisheries. The abundance indicators are (1) species abundance trends from LEK interviews, (2) a catch-per-unit-effort (CPUE) series compiled from published and unpublished literature that represents relative species abundance over time, and (3) a separate yes/no indicator from LEK interviews corresponding to whether fishers had noticed a stock depletion during their careers. The exploitation indicators include (4) biomass predictions from a simple Schaefer (logistic growth) harvest model, (5) a measure of species groups' vulnerability to fishing, and (6) a yes/no indicator from LEK interviews corresponding to whether fishers had noticed a reduction in animal body size. Two parallel analyses are conducted and compared, one processing the abundance indicators and one processing the exploitation indicators. The next section explains the development of these indicators. The fuzzy logic implementation is described later.

### Indicators from LEK Interviews

Researchers interviewed 81 fishers in the towns of Puerto Peñasco, Golfo de Santa Clara, Rodolfo Campodónico, Bahia Kino, Desemboque, and Puerto Libertad (Sonora) between April and June 2008 and September 2008 and February 2009. This represents around 2% of the estimated 3,800 artisanal fishers in the northern Gulf of California (P. Turk-Boyer, Centro Intercultural de Estudios de Desiertos y Océanos [CEDO], unpublished data). Interviewees ranged in age from 20 to 89 years and had expertise in the following gear types: gill net, cast net, shrimp and finfish trawls, longline, hand line, harpoon, compressor diving, and traps. On average, respondents had 28.5 years of fishing experience. The interview forms used are available from C. H. Ainsworth.

Interviewees were asked to characterize the abundance of fish, invertebrates, mammals, birds, and reptiles into one of three categories (low, medium, or high) for each of the six decades since 1950. Species were aggregated into groups; the structure was chosen to be compatible with species-aggregated, trophic-modeling approaches for fisheries research. The format of the groups generally aggregates invertebrate species, and it represents species of commercial interest and ecological importance, such as keystone species, in more detail. A statistical test is used here to show whether fishers' perceptions of species abundance varies depending on whether or not they rely on the stock for their livelihoods. For this, respondents were divided into two pools, those that targeted a given species group and those that did not. Relative abundance trends from LEK interviews were developed for 24 species groups (Table A.1 in the appendix) for each decade and used as input in the fuzzy logic procedure.

In addition to the abundance trends, simple indicators were collected in the form of yes/no questions. The questions for each species group were whether the respondents had noticed localized depletions or extirpations of the species and whether they had noticed a reduction in average body size. The yes/no responses were obtained for 36 species groups (Table A.1). They were not recorded by decade; a single response was assumed to represent the net change over a respondent's career.

## Catch per Unit Effort

Catch-per-unit-effort trends were determined based on CPUE or catch-and-effort data from Mexican government statistics (Diario Oficial de la Federación 2004, 2006 [see Table A.2]; CONAPESCA 2009). Additional information was obtained from unpublished statistics (V. M. Valdéz-Ornelas and E. Torreblanca, Pronatura Noroeste). Data from a concurrent study to estimate unreported catch provided port-level information (S. Perez-Valencia, CEDO, unpublished data), while a study of fishery logbooks also provided high-quality information for a small number of vessels (J. Torre and M. Rojo, Comunidad y Biodiversidad, unpublished data). Finally, the remaining data gaps were filled by other literature sources listed in Table A.2.

Catch data for major commercial species were taken from Diario Oficial de la Federación (2004, 2006) and CONAPESCA (2009), while the unpublished information, surveys, logbooks, and literature sources provided estimates of catch for minor targets and bycatch species. Where statistics were available by state, total catch in the northern gulf was assumed equal to that of Sonora and Baja California combined. The catch values also include estimates of unreported catch and discards, which are largely based on expert opinion (L. E. Calderón-Aguilera, Centro de Investigación Científica y de Educación Superior de Ensenada, personal communication). Effort trends in artisanal fisheries were based on the number of vessels operating (Galindo-Bect 2003); this approach has the advantage that it can capture trends for unregistered vessels, which may constitute as much as one-third of the fleet, judging by recent aerial surveys (Rodríguez-Valencia et al. 2008). Other effort series were located for lobsters (Vega-Velásquez 2006), small pelagic organisms (Arreguín-Sánchez et al. 2006), groupers (Arreguín-Sánchez et al. 2006), totoaba *Totoaba macdonaldi* (Lercari and Chávez 2007), and shrimp (Galindo-Bect 2003). As a last resort, effort was based on human population growth rate in two Sonoran cities, Puerto Peñasco and San Felipe (INEGI and Government of Sonora 2008a, 2008b). Catch and effort references are listed in Table A.2. Full documentation of development of catch, effort, and CPUE series is available from the author (cameron.ainsworth@noaa.gov). The CPUE series were developed for 34 species groups (Table A.1) as annual trends (units vary) and averaged to the decade level for input into the fuzzy logic procedure.

## Harvest Model

A logistic growth model with harvests provides biomass ($B$) estimates at each year $t$, as in equation (1) (Schaefer 1954; Hilborn and Walters 1992),

$$B_t = B_{t-1} + r B_{t-1} \left( 1 - \frac{B_{t-1}}{K} \right) - C_{t-1}. \qquad (1)$$

Catch ($C$) was obtained from the assembled catch series (Table A.2). The carrying capacity of the ecosystem ($K$) was assumed to be the unfished biomass ($B_0$) estimated by Lozano-Montes (2006) and Lozano-Montes et al. (2008). The $B_0$ values are highly uncertain, but they cover a large number of data-poor species and represent the best available estimates. The intrinsic rate of population increase ($r$) was estimated according to the equation $r = 4MSY/B_0$. Where possible, the maximum sustainable yield (MSY) was taken from Mexican stock assessments (Diario Oficial de la Federación 2004, 2006; Table A.2). In the absence of species distribution data, the MSY for the northern Gulf of California was assumed to be equal to the MSY values for Sonora and Baja California combined. In some cases, only values for Sonora were available, and these were inflated 20% to account for missing areas. Where the MSYs referred to Pacific Ocean stocks, the MSYs for gulf stocks were assumed to be similar on a per-area basis (the stock area was assumed to be 10% for pelagic species and 20% for other species in the gulf). If MSY estimates were not available, $r$ was estimated using the empirical formula of Pauly (1984), that is,

$$r \approx 9.13 \bar{W}^{-0.26},$$

where $\bar{W}$ is mean body weight, approximated as $\bar{W} = (W_{max} + W_m)/2$ (Pauly 1984), with $W_{max}$ = maximum weight and $W_m$ = weight at maturity. These weight data were collected from FishBase (references provided in Tables A.3, A.4).

The model was initialized at 1950 using $B_0$ and run to 2008, calculating annual biomass estimates $B_t$ in $t$/km². These were then averaged to produce decadal values ($B_{1950}, B_{1960}, \ldots, B_{2000}$) and used as inputs to the fuzzy logic algorithm. Series were developed for 26 species groups (Table A.1). Between averaging these biomass values over decades, using fuzzy sets to describe them, and combining these estimates with other abundance series, the method presented here should be insensitive to the large uncertainties involved in these calculations.

## Vulnerability Index

As a final indicator of species abundance, the relative vulnerability to fishing of each exploited species group is estimated based on the method of Cheung et al. (2005). Those authors combined life history characteristics, including maximum length, the Von Bertalanffy growth constant, maximum age, fecundity, age at first maturity, and natural mortality, in a fuzzy logic framework to produce a composite vulnerability-to-fishing score. The index was shown empirically to predict species status better than common alternative proxies. Their method was recreated here. Life history information for Gulf of California species was taken from FishBase and other sources (see Tables A.3, A.4); then, using the published membership functions and expert rule set, the data were collated to produce a final vulnerability score for each species in a procedure analogous to the one described in this article. The only notable difference between this treatment and the one by Cheung et al. (2005) is that the geographic range of a species was not considered as an indicator of vulnerability because it is not relevant when considering a localized area like the Gulf of California. The vulnerability scores were calculated for individual species and averaged to the level of species groups. The available life history data allowed the

calculation for 21 species groups (Table A.1). The scores are time independent, and so the same score is used for each decade in the analysis.

## Fuzzy Logic Overview

Fuzzy set theory, also called fuzzy logic (Zadeh 1965; Bellman and Zadeh 1970), emulates an expert's judgment by combining inputs through a heuristic IF–THEN rule matrix to reach a conclusion regarding the data. It is a means of computing with words (Zadeh 1999), where "linguistic variables," representing a wide range of possible data types, combine according to relationships similar to "rules of thumb" contained in a rule matrix. However, where classical logic requires that a variable be categorizable into a single class (e.g., a Boolean variable belonging exclusively to a yes or no category), the linguistic variables in a fuzzy set can hold varying degrees of membership in multiple classes. For example, if "purple" is a fuzzy set that describes all colours composed of red and blue light, then indigo, violet, and fuchsia could be said to hold increasing membership in the "red" category relative to the "blue."

## A Worked Example

A simple example (Figure 1), in which two data streams (abundance from interviews and CPUE) are combined to produce relative abundance, demonstrates the fuzzy logic procedure. The procedure begins by assigning an analog abundance indicator ($x$), such as the abundance score derived from interviews (Figure 1A). The analog indicator is then translated into fuzzy sets containing several linguistic abundance categories (Figure 1B). In the case of abundance from interviews, there are five categories ranging from low to high. The partial membership ($\mu$) in each abundance category ($n$) is determined by consulting membership functions. The membership function $\mu_n(x) \in [0, 1]$ describes the degrees of membership of $x$ in linguistic categories 1 though $N$, where $\Sigma_n \mu_n(x) = 1$. Piecewise linear membership functions are used for simplicity throughout this study.

Membership in the linguistic variable categories determines what rules operate (or "fire") in the rule matrix. In this paper, the strength at which the rules fire is determined by the algebraic sum of the intersecting memberships (Figure 1C). Many conclusions may be reached simultaneously (Figure 1D) with varying degrees of belief (firing strengths). Each time a cell in the rule matrix fires, it strengthens our belief in the corresponding conclusion. There are 50 different possible conclusions. Numbered 1 to 50, each conclusion represents a linear interpretation of abundance, so that a conclusion of 40 indicates twice the abundance of one numbered 20. Whenever a cell is fired, the partial membership that elicited that action is added to a running total for the corresponding conclusion category (Figure 1E). In this way, conclusions reached repeatedly (or fired with large partial memberships) will accrue a high score.

After all the information is passed through the matrix for a certain group–period combination, we are left with an array of
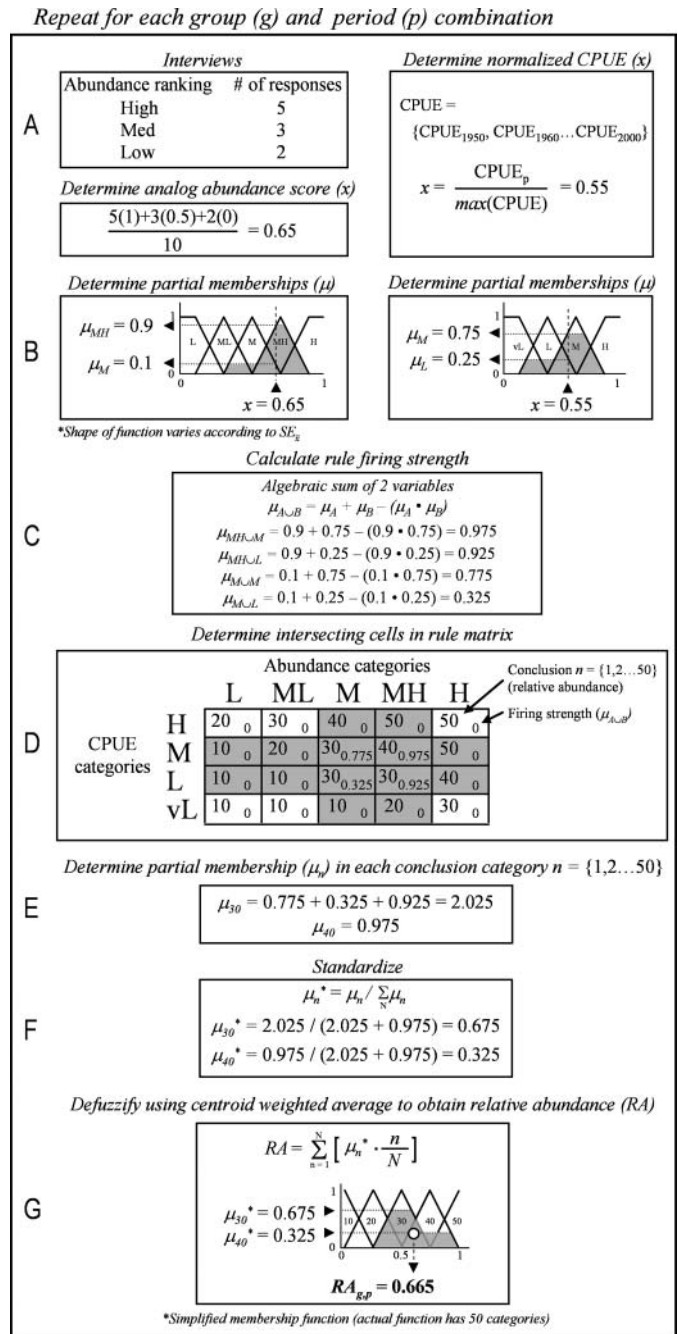


FIGURE 1. A worked example of the fuzzy logic method. A two-dimensional analysis is presented for clarity; it processes two data streams, abundance from interviews and CPUE (values are hypothetical). The algorithm presented here is repeated for each species group and time period.

50 elements; the partial memberships in each category represent our relative confidence, or degree of belief, in that abundance conclusion. The partial memberships are normalized as in Figure 1F, after which they are passed as inputs to the defuzzification membership function (Figure 1G). Defuzzification is the process by which partial memberships are converted to a single
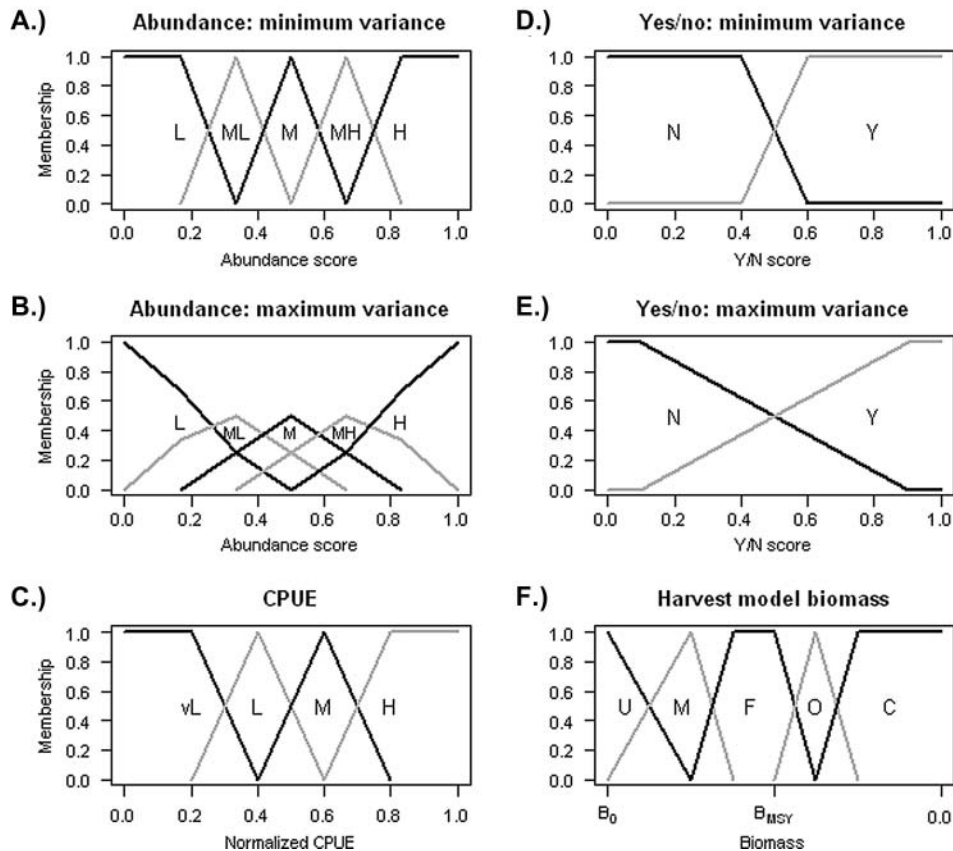
FIGURE 2. Fuzzy set membership functions. These relationships convert an analog indicator of abundance (*x*-axis) to partial memberships in linguistic abundance categories (*y*-axis). The partial memberships sum to 1 and represent the degree of belief in the abundance categories. Panels **(A)** and **(B)** show the membership in abundance categories under minimum and maximum variance between interview scores (low [L], medium–low [ML], medium [M], medium–high [MH], and high [H]); panel **(C)** shows the membership in CPUE categories (very low [vL], low [L], medium [M], and high [H]); panels **(D)** and **(E)** show the membership in yes/no (Y/N) categories under minimum and maximum variance between interview scores; and panel **(F)** shows the membership in biomass categories predicted by the harvest model (underexploited [U], moderately exploited [M], fully exploited [F], overexploited [O], and critically overfished [C]).

number representing relative abundance (i.e., a "crisp" number that is no longer part of a fuzzy set). It is therefore the reverse of the procedure described earlier to calculate memberships (i.e., Figure 1B). The defuzzification function in Figure 1G is a simplification; the actual one employed has 50 categories with triangular functions. The centroid-weighted average method of Cox (1999) is used, in which we multiply the centroid of each category (0.02, 0.04, 0.06, ..., 1.00) by the relative weighting (or confidence) in that conclusion to obtain a weighted average between 0 and 1 that represents the relative abundance for that species group and period.

*Fuzzy logic implementation.*—In the worked example, the rule matrix uses two dimensions (i.e., abundance and CPUE in Figure 1D). Scaling up, the implementation for both abundance and exploitation indicators uses three dimensional matrices. The next section describes the membership functions used to characterize the six data series involved. Later, combinatorial rules, the rule matrices, and defuzzification are discussed.

*Membership functions.*—The abundance information obtained in interviews was evaluated according to the membership functions in Figure 2A, B. The *x*-axis in Figure 2A, B represents the analog abundance (*x*) score obtained from the interviews. It is averaged across respondents, "low" responses being assigned a value of 0, "medium" ones being assigned 0.5, and "high" ones being assigned 1.0. An average abundance score of 0.5 could be achieved through (at least) two scenarios: one in which every fisher reported medium abundance and one in which half of the fishers reported high abundance and half reported low abundance. To account for agreement between respondents, a dynamic membership function was used in which the angle subtended by the triangular functions increases from a minimum (Figure 2A) to a maximum (Figure 2B) if there was high or low agreement between respondents, respectively.

As a measure of agreement, the standard error of the mean was determined for each group–period combination as $SE_{\overline{X}} = \sigma^2/n$, where *n* is the number of respondents. Variance ($\sigma^2$) was calculated assuming a binomial distribution in which the majority response category (low, medium, or high) was considered "correct" and all other responses were considered "incorrect"; thus $\sigma^2 = np(1 - p)$, where *p* is the fraction of correct responses.

Using the $SE_{\overline{X}}$ in this way corrects for the varying number of respondents per decade (e.g., fewer people contributed to the 1950s estimates than to the 2000–2009 estimates). The $SE_{\overline{X}}$ was next standardized so that the group–decade combination that had the best agreement (lowest error) adopted the membership function in Figure 2A, that with the poorest agreement adopted the function in Figure 2B, and other responses adopted intermediate functions, where slopes and intercepts were scaled linearly between the extremes.

Membership was evaluated in each of five fuzzy set abundance categories: low (L), medium–low (ML), medium (M), medium–high (MH), and high (H). Categories L and H use trapezoidal forms: beyond a certain threshold, full membership was assigned to these extreme categories. This allowed us to ignore the influence of a small number of responses that contradict the majority belief. Although the level of fishing effort, fishing skill, gear efficiency, catchability, and other factors will affect the amount of catch a fisher obtains for any given level of fish abundance, this methodology trusts that fishers can integrate over a wide range of externalities and thus have valid cognitive models of resource supply. Averaging their responses to obtain $x$ should also eliminate many possible biases. For this reason, we restricted the analysis to consider only group–period combinations that had at least eight respondents.

The membership function used to categorize (normalized) CPUE per species group and decade is provided in Figure 2C. It categorizes the analog CPUE score into four linguistic categories: very low (vL), low (L), medium (M), and high (H). The membership functions used to categorize "yes/no" depletion and body size indicators into yes (Y) and no (N) categories again use a dynamic membership function to reflect the level of agreement between respondents (Figure 2D, E). As with the abundance indicators from interviews, the form of the membership function varies according to $SE_{\overline{X}}$, which was calculated assuming a binomial distribution of yes and no answers. The membership function used to evaluate biomass predictions from the logistic harvest model is provided in Figure 2F. Here, membership is evaluated in five linguistic categories: overexploited (O) or critically overfished (C) if the decadal biomass value (e.g., $B_{1950}$, $B_{1960}$,..., $B_{2000}$) was below $B_{MSY}$, or underexploited (U), moderately exploited (M), or fully exploited (F) if biomass was above $B_{MSY}$. In the case of the Cheung et al. (2005) vulnerability index, our input membership function is identical to their output (defuzzification) membership function; it is equivalent to Figure 2C with four linguistic categories: low (L), medium (M), high (H), and very high (vH).

*Combining the data series.*—Having determined the partial memberships in linguistic categories through the use of membership functions, we next consult the rule matrices to combine the information; Tables 1A and 1B show the abundance and exploitation matrices, respectively.

Membership in the three indicators (on $X$, $Y$, and $Z$ axes of each matrix) leads us to a conclusion regarding the abundance for each species in each time period. The conclusions are found inside the matrix cells (color coded in Table 1). Each cell fires with a strength proportional to the algebraic sum of the intersecting memberships. All axes are assumed to be independent, and the strength of memberships is combined using the probability-OR operator for three variables, namely,

$$\mu_{A \cup B \cup C} = \mu_A + \mu_B + \mu_C - (\mu_A \cdot \mu_B) - (\mu_A \cdot \mu_C) \\ - (\mu_B \cdot \mu_C) + (\mu_A \cdot \mu_B \cdot \mu_C), \quad (2)$$

where $\mu_{A \cup B \cup C}$ is representative of our degree of belief in the corresponding conclusion. This fuzzy union operator was used based on the algebraic sum rather than the alternative union operator ($\mu_A$ OR $\mu_B$ OR $\mu_C$ = max[$\mu_A$, $\mu_B$, $\mu_C$]) or fuzzy intersection operator ($\mu_A$ AND $\mu_B$ AND $\mu_C$ = min[$\mu_A$, $\mu_B$, $\mu_C$]) used by previous authors (Cheung et al. 2005; Ainsworth et al. 2008) so that all operands contribute something to the output; the algorithm is thus useful for a wider range of data availabilities (see Table A.1).

Various parts of the rule matrix were accessed for each time period (1950, 1960, 1970, 1980, 1990, and 2000). If the value of the depletion indicators (i.e., stock depletion or body size reduction) is "yes," this has the effect of lowering the relative abundance score of the conclusion for recent periods (1980 to 2000) but increasing the abundance score of the conclusion for older periods (1950 to 1970) (i.e., the slope between 1950 and 2000 becomes more negative; Table 1). Matrices for the intermediate periods (1960, 1970, 1980, and 1990) are not shown, but they apply a smooth linear transition between the extreme values in 2000 (top row of Table 1) and 1950 (middle row of Table 1). If the value of the depletion indicator is "no," then the bottom row of Table 1 is accessed regardless of decade.

After all data series pass through the matrix, we are left with 50 different abundance conclusions with varying degrees of belief (partial memberships), as described in the worked example. The partial memberships are combined through defuzzification and are converted to a single crisp number representing the relative abundance. This process is repeated for each species group and period to produce time series of relative abundance that can be compared with observational series (Table 2).

*Summary.*—The data series used here for abundance indicators consisted of decadal abundance trends from LEK interviews, annual CPUE data averaged to decades, and a yes/no population-level depletion indicator from LEK interviews that referred to all decades. The data series used for the exploitation indicators consisted of annual stock biomass from a logistic growth harvest model averaged to decades, a vulnerability-to-fishing index that referred to all decades, and a yes/no body size change indicator from LEK interviews that referred to all decades. These numerical indicators were translated into memberships in ordinal linguistic categories (e.g., low, medium, or high) using membership functions, where membership in each category represents our relative belief in that category's being true. The memberships in each category determined the firing

TABLE 1. Heuristic rule matrices used by the fuzzy logic algorithm to combine data sources. Two parallel matrices deal with abundance and exploitation indicators, respectively. Abundance indicators include abundance estimated by interviews, catch per unit effort (CPUE) estimated from literature values, and stock depletion suggested by interviews. Exploitation indicators include exploitation status suggested by the Schaefer harvest model, vulnerability to fishing based on life history characteristics, and body size reduction suggested by interviews. The conclusions resulting from these $X$–$Y$–$Z$ linguistic variables are identified in the cells. They represent a linear abundance index that ranges from 1 to 50. The presence of depletion or size-reduction indicators upgrades the abundance conclusion for past periods (e.g., 1950) and downgrades it for recent periods (e.g., 2000). Matrices for the intermediate periods (1990, 1980, 1970, and 1960; not shown) apply a smooth transition between the extremes 2000 and 1950. Abbreviations are as follows: L = low, ML = medium–low, M = medium, MH = medium-high, H = high, vL = very low, vH = very high, C = critically overfished, O = overexploited, F = fully exploited, M = moderately exploited, u = underexploited, Y = yes, and N = no.

## (A) Abundance indicators

**Evaluation period 2000**

Abundance from interviews

| CPUE | L | ML | M | MH | H |
|---|---|---|---|---|---|
| H | 20 | 30 | 40 | 50 | 50 |
| M | 10 | 20 | 30 | 40 | 50 |
| L | 10 | 10 | 20 | 30 | 40 |
| vL | 10 | 10 | 10 | 20 | 30 |

Depletion? Y

**Evaluation period 1950**

| CPUE | L | ML | M | MH | H |
|---|---|---|---|---|---|
| H | 40 | 50 | 50 | 50 | 50 |
| M | 30 | 40 | 50 | 50 | 50 |
| L | 20 | 30 | 40 | 50 | 50 |
| vL | 10 | 20 | 30 | 40 | 50 |

Depletion? Y

**Evaluation period ALL**

| CPUE | L | ML | M | MH | H |
|---|---|---|---|---|---|
| H | 30 | 40 | 45 | 50 | 50 |
| M | 20 | 30 | 40 | 45 | 50 |
| L | 15 | 20 | 30 | 40 | 45 |
| vL | 10 | 15 | 20 | 30 | 40 |

Depletion? N

## (B) Exploitation indicators

**2000**

Harvest model exploitation

| Vulnerability | C | O | F | M | U |
|---|---|---|---|---|---|
| L | 20 | 30 | 40 | 50 | 50 |
| M | 10 | 20 | 30 | 40 | 50 |
| H | 10 | 10 | 20 | 30 | 40 |
| vH | 10 | 10 | 10 | 20 | 30 |

Size reduction? Y

**1950**

| Vulnerability | C | O | F | M | U |
|---|---|---|---|---|---|
| L | 40 | 50 | 50 | 50 | 50 |
| M | 30 | 40 | 50 | 50 | 50 |
| H | 20 | 30 | 40 | 50 | 50 |
| vH | 10 | 20 | 30 | 40 | 50 |

Size reduction? Y

**ALL**

| Vulnerability | C | O | F | M | U |
|---|---|---|---|---|---|
| L | 30 | 40 | 45 | 50 | 50 |
| M | 20 | 30 | 40 | 45 | 50 |
| H | 15 | 20 | 30 | 40 | 45 |
| vH | 10 | 15 | 20 | 30 | 40 |

Size reduction? N

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strength of cells in a rule matrix, where each cell leads to a particular conclusion regarding species abundance. Finally, a crisp abundance score was determined through defuzzification, the reverse of the process that created the membership scores from the numerical indicators. Abundance per decade is plotted for each species group, representing its stock status since 1950.

## RESULTS

For many species groups, the respondents in the LEK interviews were likely to indicate high biomass in the 1950s and low biomass in 2000–2009 (Figure 3). The trends are not often monotonic and there are conspicuous exceptions, like pinnipeds and seabirds. For these groups, the respondents were more likely to indicate high biomass in recent years. For pinnipeds, this conflicts with known population trends in the Gulf of California as a whole (Szteren et al. 2006; Wielgus et al. 2008). However, census data suggest that California sea lion *Zalophus californianus* rookeries in the north, where interviews occurred, may have seen population increases since the early 1990s (Szteren et al. 2006). The status of seabird populations in the gulf

is poorly known from scientific studies (Palacios and Alfaro 2005).

Comparing the abundance scores offered by people who depend on the resource economically with the scores from those who do not revealed no significant difference for any species in responses for the 2000 period (two-tailed Mann–Whitney $U$-test: $P > 0.05$). This held true for all 15 species groups tested (i.e., all exploited fish and invertebrate species; minimum sample size = 6). This suggests that fishers offered an unbiased view regardless of whether or not they depend on the stock for their livelihood, and being specialized in catching a certain type of animal did not improve or alter their assessment relative to that of a "nonexpert" fisher.

When asked to characterize the abundance of species groups for the decades between 1950 and the present, fishers showed the most agreement for the earliest decade, the 1950s (Figure 4). They generally agreed that abundance was high during this period (irrespective of the species group). Each subsequent decade had less agreement, except for the most recent decade, 2000, in which interviewees tended to agree that abundances were low. This pattern was consistent across species groups, with a few exceptions.

TABLE 2. Taxa included in the current study and those in previous studies estimating abundance and biomass trends in the northern Gulf of California.

| Functional group | Species in source material | Type of information | Reference |
|---|---|---|---|
| Blue crab | Arched swimming crab *Callinectes arcuatus*, blue swimming crab *C. bellicosus* | Relative biomass | INP (2006) |
| Blue shrimp | Blue shrimp *Litopenaeus stylirostris* | CPUE | Galindo-Bect et al. (2000) |
| Crabs and lobsters | Spiny lobsters (*Panulirus interruptus*, *P. inflatus*, *P. gracilis*) | CPUE | INP (2006) |
| Groupers and snappers | Snapper *Lutjanus* spp., barred pargo *Hoplopagrus guntherii* | CPUE | INP (2006) |
| Herbivorous echinoderms | Red urchin *Strongylocentrotus franciscanus* | Biomass | INP (2006) |
| Large pelagic sharks | Large sharks *Carcharhinus* spp., *Alopias* spp., scalloped hammerhead *Sphyrna lewini*, whitenose shark *Nasolamia velox* | CPUE | INP (2006) |
| Penaeid shrimp | Brown shrimp *Penaeus californiensis*, blue shrimp *P. stylirostris*, and white shrimp *P. vannamei* | CPUE | Magallon-Barajas (1987) |
| Pinnipeds | California sea lion *Zalophus californianus californianus* | Relative biomass | Szteren et al. (2006) |
| Small pelagics | Small pelagics (Pacific sardine *Sardinops sagax caeruleus,* herrings *Opisthonema* spp., Pacific chub mackerel *Scomber japonicus*, anchoveta *Cetengraulis mysticetus*, round herring *Etrumeus teres*, leatherjacks *oligoplites* spp., northern anchovy *Engraulis mordax*) | CPUE | INP (2006) |
| Squid | Jumbo squid *Dosidicus gigas* | Relative biomass | Nevárez-Martínez et al. (2006) |
| Totoaba | Totoaba *Totoaba macdonaldi* | Biomass | Larcari and Chavez (2007) |

Analyzing only the remarks from the interviewees concerning species abundance, we found that older fishers tended to recognize a greater degree of population decline since 1970 than did younger fishers (Figure 5). We considered the time since 1970 rather than that since 1950 in order to include a greater number of respondents. All species groups tested are aggregated into the six categories shown in Figure 5. The relationship between fisher age and reported abundance change is significant for mammals, other fish, turtles, and invertebrates, weakly significant for reef fish, and nonsignificant for birds ($F$-test). However, the results are not significant when we contrast the perceived decline against the number of years of fishing experience rather than fishers' ages: reef fish ($P = 0.087$), mammals ($P = 0.35$), birds ($P = 0.31$), other fish ($P = 0.18$), turtles ($P = 0.012$), and invertebrates ($P = 0.51$). Trusting the cognitive model of stock abundance held by older fishers (those above the median age of 43) produces a much different result in the hindcasted abundance trends resulting from the fuzzy logic routine than trusting that of the younger fishers (Figure A.1).

However, the differing opinions of these groups provide a range of plausible trajectories for relative abundance over time. The discrepancy is most noticeable in targeted and charismatic species.

The method of Cheung et al. (2005) provides an estimate of vulnerability to fishing based on life history patterns (Figure 6). Elasmobranchs, which tend to be long-lived and late maturing and have low fecundity, show the greatest overall vulnerability. This is consistent with their known biology (Stevens et al. 2000; Sadovy 2001) and the history of exploitation in the northern Gulf of California (Bizzarro et al. 2009). Also vulnerable are reef fish species, in particular, large-bodied piscivores that aggregate during breeding, such as the species included in the "groupers and snappers" group and the "large reef fish" group (Musick et al. 2000).

Crisp outputs of the fuzzy logic algorithm suggest that many species groups have suffered some degree of depletion since 1950 (Figure 7). There is satisfactory agreement between outputs from the abundance indicators and the exploitation
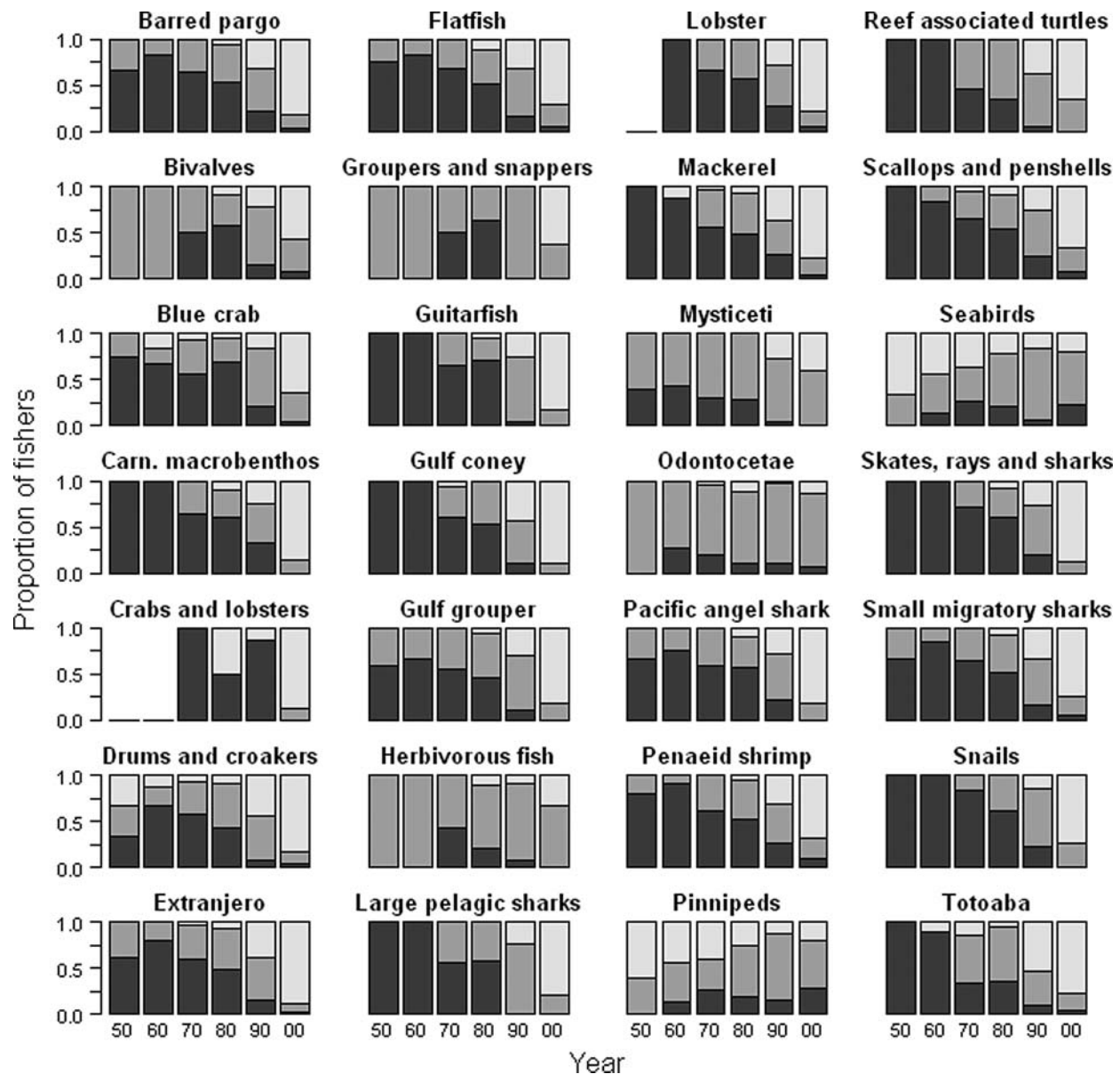
FIGURE 3.    Actual interview results, presented as the proportions of fishers reporting high (dark gray), medium (medium gray), and low biomass (light gray) for each species group and time period (50 = the 1950s and so forth). Species groups that had at least eight respondents are shown. The composition of the groups is given in Table A.5 in the appendix.

indicators. Groups that show serious discrepancy between these two series are pinnipeds and blue shrimp; all other groups achieved at least a qualitative similarity. The trend based on exploitation indicators suggests that pinniped numbers have decreased; this conclusion is largely based on a perceived body size decrease by interviewees. However, the trend based on abundance indicators suggests an increase for these animals, reflecting the source interview results mentioned earlier (see Figure 3). In the case of blue shrimp, the exploitation indicators suggest a steady depletion of the stock, a result also suggested by the harvest model. However, the population trend signified by

the abundance indicators suggests that the abundance increased from 1950 to 1980 and subsequently declined. This shows the influence of the CPUE series. The initial increase in CPUE may reveal population changes, or it may reflect the introduction of modern fishing methods that increased fishing efficiency. For both pinnipeds and blue shrimp, previously published abundance series support the apparent increase in abundance proffered by the abundance indicators and discredit the decrease in abundance proffered by the exploitation indicators. The abundance indicators consistently agree with the direction of change suggested by the observational data.
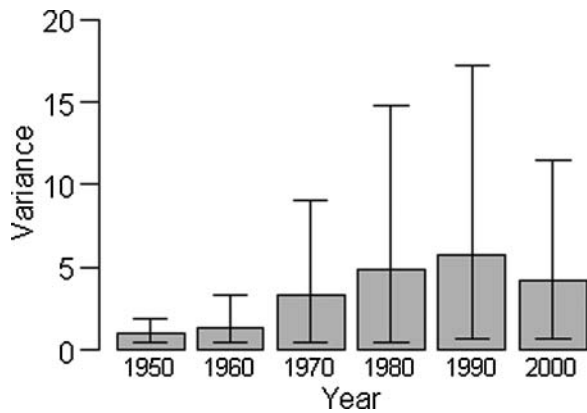
FIGURE 4. Variance among fishers' abundance scores from interviews. Variance is calculated assuming a binomial distribution (see text). Bars show the average score for all species groups analyzed; error bars show total range.

## DISCUSSION

The results from interviews consistently indicated a downward trend for most populations, although this could reflect a spatial bias in reporting if fishers are referring to localized depletions in fishing areas. The interviews also were concentrated in the most heavily populated and exploited region of the gulf, which is in the northeast; this also adds a potential bias. Nevertheless, the abundance and exploitation series usually agree, which lends credence to the overall trend. In other words, the

LEK data that informed the abundance trends are consistent with the catch and life history information that informed the exploitation trends. Estimates of relative biomass and abundance from previous studies tend to corroborate the fuzzy logic outputs despite a slight mismatch in species groupings and study area used. However, decreases in relative abundance (or body size) do not necessarily indicate overexploitation, as these are natural consequences of harvesting even in well-managed stocks and may be desirable (Hilborn 2007). Although the trends determined here are relative, being comparable only across species groups and between time periods, it would be possible to develop absolute trends by scaling the fuzzy logic output to match the available partial time series from scientific sampling (as in Ainsworth et al. 2008). As yet, it is not feasible to do this in the northern Gulf of California since so few groups have reliable survey information specific to the study area.

One noteworthy result is that even most untargeted species are reported by fishers to have declined. There could be psychological factors influencing this perception among fishers (Ainsworth et al. 2008); fishers' perceptions factor into both the abundance and exploitation indicators. Unfortunately, the suggestion that both predator and prey are declining may be plausible given the major ecological changes in the Gulf of California over the last century. Regulation of the Colorado River flow by numerous dams and increased freshwater consumption in the southwestern United States and Mexico has altered the marine assemblage (Rodríguez et al. 2001; Lozano-Montes
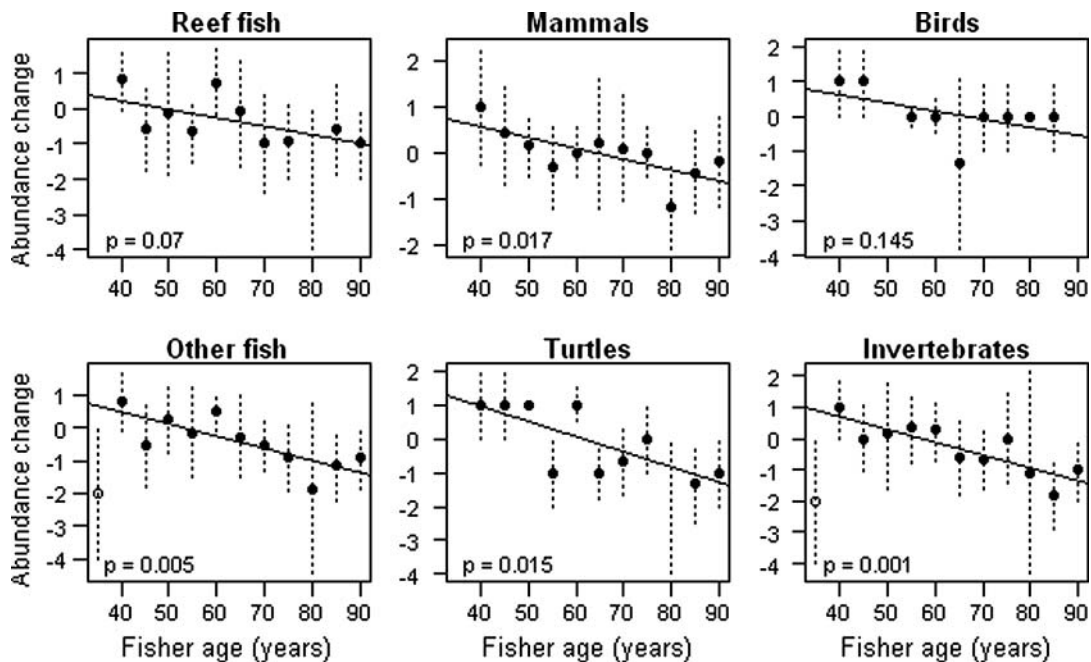


FIGURE 5. Evidence of shifting baselines in the northern Gulf of California. The $y$-axis shows the change in average perceived abundance between 1970 and 2000, the $x$-axis the age of fishers. A change of $-1.0$ corresponds to a reduction from high to medium or medium to low in terms of the average interview abundance score. All relationships are significant at $\alpha = 0.05$ ($F$-test) except those for reef fish and birds. Outliers (open circles) were removed from the data for invertebrates and other fish; error bars = SDs.
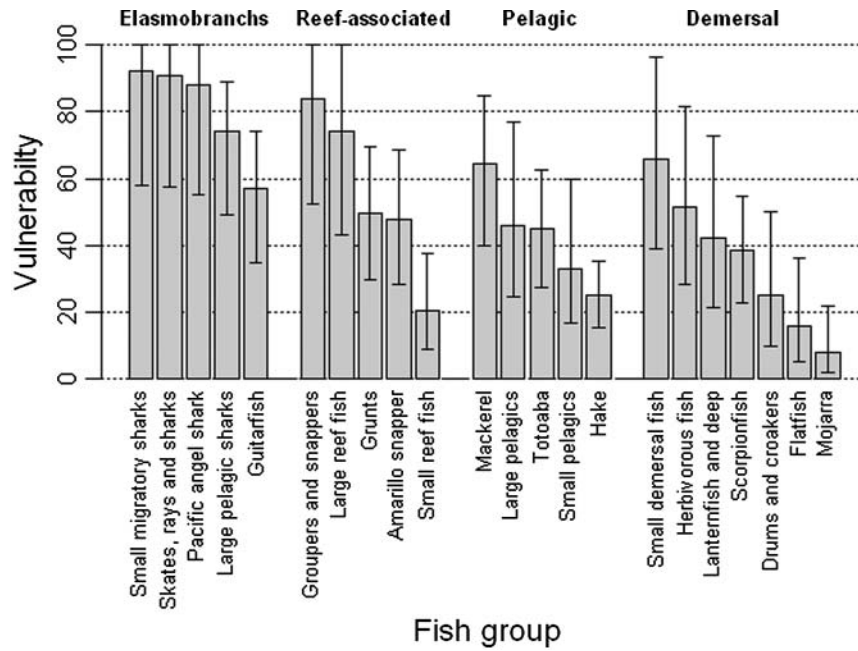
FIGURE 6. Vulnerability to fishing as predicted by the algorithm of Cheung et al. (2005) based on life history characteristics. The error bars show the upper and lower bounds of the conclusion fuzzy membership function designed by Cheung et al. and reflect the precision of their estimates based on the width of their output membership functions. The composition of the groups is given in Table A.5.
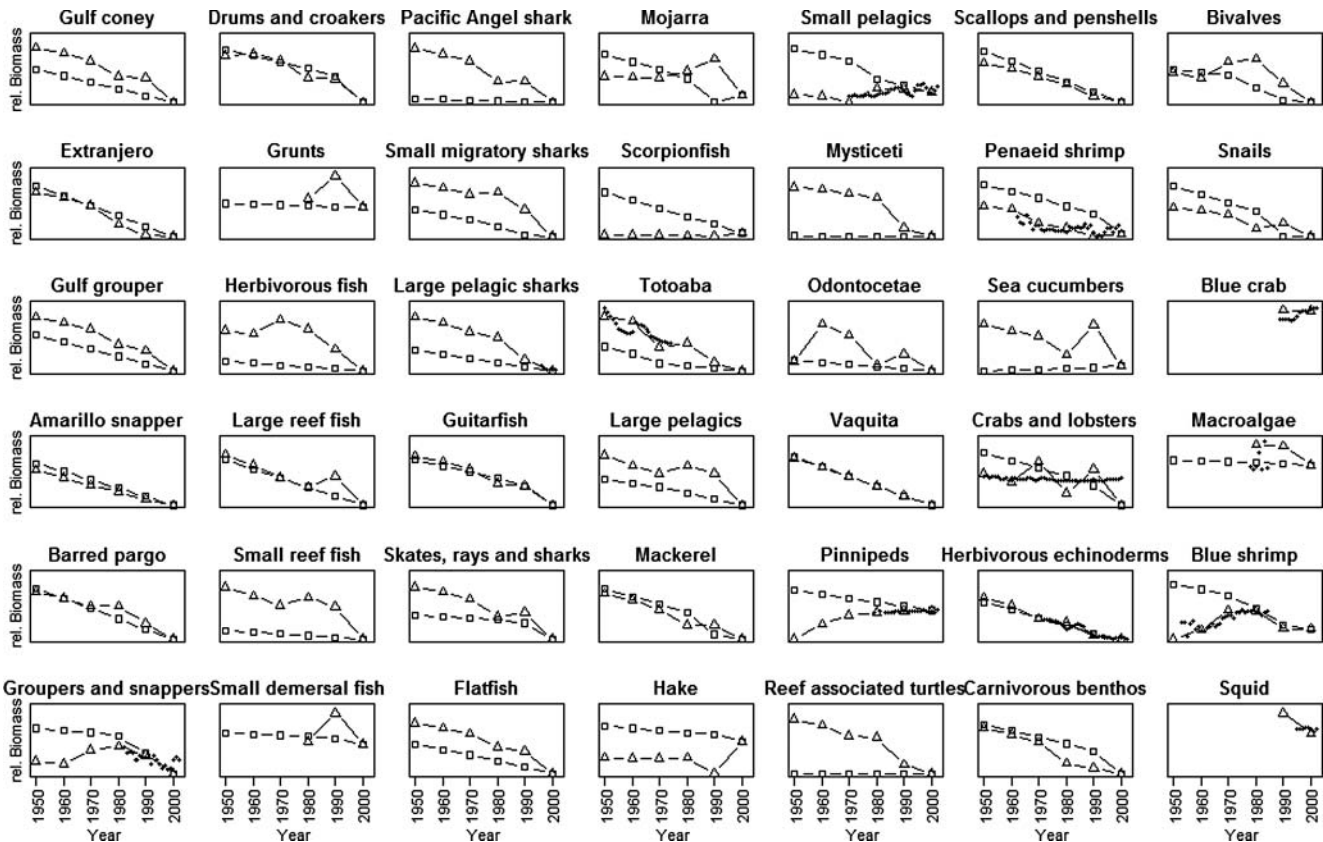


FIGURE 7. Abundance of species groups predicted by the fuzzy logic algorithm, as suggested by abundance indicators (triangles) and exploitation indicators (squares). Trends have been scaled to agree in the year 2000. Bullet points show the relative abundance trends of representative species from previous studies (Table 2); residuals are minimized with respect to abundance indicators. See Figure A.1 for the effect of respondent's age on abundance indicators. The composition of the groups is given in Table A.5.

2006), affecting the salinity gradient, estuarine habitat conditions, nutrient loading, and other factors important to fish and invertebrate production (Lavín and Sanchez 1999; Galindo-Bect et al. 2000). Therefore, management of this area may consider whether forcing factors unrelated to fishing effort have had a major influence on ecosystem structure.

Even in a region like the northern Gulf of California, which is poor in scientific data, it is possible to identify which species are likely to require special attention by fishery managers with a minimal investment in effort and no regional data using Cheung et al.'s (2005) vulnerability method. In this application, life history values were averaged across all constituent species in the aggregated species groups, so the vulnerability scores in Figure 6 represent the "average" fish in each of these groups. Individual species within groups will vary in life history parameters. We may expect the most vulnerable species to decline first under fishing pressure and perhaps even to be extirpated before the group has become seriously depleted. Methods exist to predict the most vulnerable species within a species group (Cheung and Pitcher 2004). Aggregating similar species into groups is a useful convenience for generalizing fishers' perceptions, and it is necessary for many EBFM ecosystem modeling approaches in order to simplify the food web and manage data gaps (although aggregating species carries a strong set of assumptions) (Chalcraft and Resetarits 2003).

Analysis of interview results suggests that older fishers perceive a greater decline in abundance since 1970 than do younger fishers. This confirms the results of two earlier studies in the Gulf of California suggesting that the true magnitude of stock decline is not well appreciated by those who rely on the resource (Sáenz-Arroyo et al. 2005; Lozano-Montes et al. 2008). These findings add to a growing body of literature on the subject of shifting cognitive baselines. Similar studies have been conducted in many areas of the world, with consistent results that validate Pauly's (1995) premise (e.g., North America [Baum and Myers 2004], Asia [Ainsworth et al. 2008], Africa [Bunce et al. 2008], and Europe [Airoldi and Beck 2007]).

The quantitative aspects of EBFM require some ability to forecast ecosystem-level population effects, but the data requirements of EBFM models are a barrier to their use, especially in regions like the northern Gulf of California where sufficient sampling data are unavailable. The fuzzy logic technique presented here, which was adapted and improved from Ainsworth et al. (2008), can provide numerical abundance trends that substitute for formal stock assessment. The method relies heavily on qualitative information. Nevertheless, it offers a transparent, replicable, and flexible tool that can be updated as new information becomes available. The quality of outputs is still limited by the available data. For example, difficulties in applying LEK information (Brook and McLachlan 2005) or CPUE data (Beverton and Holt 1957; Hilborn and Walters 1992) still apply. In other ecosystems, available data may support the use of a more sophisticated harvest model. However, when several sources of data are combined, reliance on any one source is reduced. This work represents the first attempt to describe abundance trends for many of the species it considers. The fuzzy logic approach is flexible enough to accommodate a range of data, and it can provide marine ecologists with time series information on abundance for a variety of EBFM applications in data-limited situations.

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## Appendix: Supplemental Material for Quantifying Species Abundance Trends

TABLE A.1. Availability of data by functional group. The composition of the groups is given in Table A.5.

| Functional group | Abundance indicator | | | Exploitation indicator | | |
|---|---|---|---|---|---|---|
| | Abundance | CPUE | Depletion | Harvest model exploitation | Vulnerability | Size reduction |
| Gulf coney | ✓ | ✓ | ✓ | | | ✓ |
| Extranjero | ✓ | ✓ | ✓ | | | ✓ |
| Gulf grouper | ✓ | ✓ | ✓ | | | ✓ |
| Amarillo snapper | | | ✓ | | ✓ | ✓ |
| Barred pargo | ✓ | ✓ | ✓ | | | ✓ |
| Groupers and snappers | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Drums and croakers | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Grunts | | ✓ | | ✓ | ✓ | |
| Herbivorous fish | | ✓ | ✓ | | ✓ | ✓ |
| Large reef fish | | ✓ | ✓ | | ✓ | ✓ |
| Small reef fish | | ✓ | ✓ | | ✓ | ✓ |
| Small demersal fish | | ✓ | | ✓ | ✓ | |
| Pacific angel shark | ✓ | ✓ | ✓ | | ✓ | ✓ |
| Small migratory sharks | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Large pelagic sharks | ✓ | | ✓ | ✓ | ✓ | ✓ |
| Guitarfish | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Skates, rays and sharks | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Flatfish | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Mojarra | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Scorpionfish | | | ✓ | ✓ | ✓ | ✓ |
| Totoaba | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Large pelagics | | ✓ | ✓ | | ✓ | |
| Mackerel | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Hake | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Small pelagics | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Mysticeti | ✓ | | ✓ | ✓ | | ✓ |
| Odontocetae | ✓ | | ✓ | ✓ | | ✓ |
| Vaquita | | | ✓ | ✓ | | ✓ |
| Pinnipeds | ✓ | | ✓ | ✓ | | ✓ |
| Reef-associated turtles | ✓ | ✓ | | | | ✓ |
| Scallops and penshells | ✓ | ✓ | ✓ | | | ✓ |
| Penaeid shrimp | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Sea cucumbers | | ✓ | ✓ | | | ✓ |
| Crabs and lobsters | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Herbivorous echinoderms | | | ✓ | | | ✓ |
| Carnivorous macrobenthos | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Bivalves | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Snails | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Adult blue crab | | ✓ | | | | |
| Macroalgae | | ✓ | | ✓ | | |
| Adult blue shrimp | | ✓ | | ✓ | | |
| Squid | | ✓ | | | | |

TABLE A.2. Catch and effort references.

**Catch**

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**Effort**

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TABLE A.3. Life history parameter references. Numbers preceded by the letters FB are Fishbase reference numbers searchable at www.fishbase.org; all other numbers refer to the references in Table A.4. The composition of the groups is given in Table A.5.

| Functional group | References |
|---|---|
| Gulf coney | 1,29,45,50,80 |
| Extranjero | 1,8,29,52,FB9342 |
| Leopard grouper | 1,29,32,35,52,84,92 |
| Gulf grouper | 1,85,FB6323 |
| Amarillo snapper | 25,28,81,82,96,FB6323,FB30872 |
| Barred pargo | 3,29,FB6323 |
| Groupers and snappers | 7,14,29,46,50,52,FB55,FB2850,FB3083,FB3090,FB3094,FB3244,FB4841,FB5227,FB5592, FB6323,FB6852,FB7185,FB9342,FB26176,FB27020,FB39376,FB40592,FB46367,FB47696 |
| Drums and croakers | 6,18,19,29,39,52,59,60,64,71,73,79,88,98,FB1164,FB1166,FB1180,FB6323,FB6997,FB26176 |
| Grunts | 2,36,39,46,60,62,67,FB2850,FB9114,FB11035,FB26176,FB26585,FB40926 |
| Herbivorous fish | 43,46,51,59,62,71,93,94,95,FB268,FB273,FB1048,FB1049,FB1238,FB1396,FB1836,FB2334, FB2850,FB3678,FB3807,FB4617,FB5533,FB5592,FB5760,FB6380,FB6997,FB7253,FB8540, FB8571,FB9072,FB9267,FB9310,FB9338,FB11824,FB12360,FB12544,FB13715,FB26177, FB26587,FB28725,FB29555,FB30504,FB42001,FB48600 |
| Large reef fish | 10,14,16,19,26,37,38,52,59,60,71,101,FB1263,FB1602,FB1751,FB2850,FB3669,FB3678, FB3807,FB4525,FB4604,FB5227,FB5525,FB5592,FB6323,FB6390,FB6490,FB7142,FB8571, FB9276,FB9292,FB9311,FB9312,FB9328,FB9329,FB9341,FB11482,FB11824,FB12260,FB26112, FB26585,FB26587,FB27803,FB28688,FB37992,FB39266,FB39376,FB40789,FB40870,FB48600 |
| Small reef fish | 23,24,31,33,38,39,46,52,55,57,58,59,60,68,75,86,FB273,FB559,FB583,FB1602,FB1661,FB2272, FB2850,FB3141,FB3678,FB3807,FB5227,FB5525,FB5590,FB5592,FB6113,FB6323,FB6937, FB7247,FB9072,FB9269,FB9286,FB9289,FB9299,FB9307,FB9324,FB9333,FB9334,FB9348, FB9349,FB9710,FB11482,FB11824,FB26176,FB26177,FB26585,FB26587,FB28023,FB30504, FB30573,FB37955,FB50710 |

TABLE A.3. Continued.

| Functional group | References |
| --- | --- |
| Small demersal fish | 2,14,27,52,54,59,60,72,75,100,FB273,FB1371,FB2272,FB2850,FB3669,FB3678,FB4423, FB4461,FB4525,FB4925,FB5778,FB6323,FB6347,FB8571,FB8991,FB9269,FB9271,FB9277, FB9279,FB9284,FB9301,FB9307,FB9324,FB9348,FB9992,FB10887,FB11482,FB11824,FB26176, FB26585,FB26587,FB26773,FB27327,FB28023,FB31276,FB32350,FB34120,FB34613,FB35910, FB37955,FB38374,FB38398,FB39877,FB43481 |
| Pacific angel shark | 13,43,60,FB6147 |
| Small migratory sharks | 14,102,FB244,FB6097,FB6098,FB9253 |
| Large pelagic sharks | 14,43,60,66,FB244,FB273,FB1661,FB1671,FB3213,FB3222,FB3678,FB6084,FB6088,FB6090, FB6390,FB6937,FB7200,FB8571,FB9012,FB9165,FB11824,FB12489,FB13713,FB26587, FB27093,FB27603,FB27605,FB27971,FB31395,FB31509,FB32047,FB32086,FB32407,FB35388, FB36559,FB41862,FB42004 |
| Guitarfish | 14,83,FB2850,FB6323,FB9262 |
| Skates, rays, and sharks | 14,15,52,63,71,78,89,FB244,FB247,FB2850,FB3678,FB5255,FB6145,FB6323,FB6871,FB9255, FB9257,FB9259,FB9261,FB9265,FB28023,FB43028 |
| Flatfish | 14,34,41,52,56,59,60,76,77,FB2272,FB2850,FB6997,FB9047,FB9281,FB9294,FB9330,FB9331, FB11035,FB36656,FB41284,FB42865,FB43299,FB47359,FB47696 |
| Mojarra | 14,46,FB6937,FB6997,FB8540,FB8571,FB9303,FB11824,FB26176 |
| Scorpionfish | 59,60,61,71,FB2850,FB5592,FB5760,FB6937,FB7055,FB9341,FB9352,FB11824,FB26176, FB27129,FB41274 |
| Lanternfish and deep | 69,FB2850,FB4525,FB28499,FB40826 |
| Totoaba | 5,19,20,40,71,FB796 |
| Large pelagics | 4,11,12,14,39,43,44,49,52,59,60,70,71,74,91,99,FB14,FB26,FB168,FB238,FB268,FB273,FB515, FB1139,FB1263,FB1314,FB1333,FB1345,FB1374,FB1386,FB1392,FB1414,FB1447,FB1449, FB1462,FB1467,FB1475,FB1498,FB1656,FB2850,FB2885,FB3555,FB3605,FB3669,FB3678, FB3786,FB4332,FB4525,FB4560,FB4838,FB4972,FB5337,FB5338,FB5340,FB5525,FB5730, FB5760,FB5964,FB6323,FB6390,FB6814,FB6937,FB7161,FB7173,FB7253,FB8571,FB9283, FB9319,FB9345,FB9346,FB9898,FB9987,FB11482,FB11824,FB12193,FB12260,FB12451, FB12757,FB13304,FB26319,FB26340,FB26370,FB26587,FB26849,FB27030,FB28023,FB28050, FB28958,FB32349,FB33193,FB34133,FB34137,FB34148,FB35465,FB36276,FB36645,FB36658, FB36794,FB37040,FB37813,FB41559,FB41779,FB43794,FB46593 |
| Mackerel | 14,43,43,49,52,53,62,65,71,97,FB766,FB796,FB1662,FB3578,FB3730,FB3733,FB4332, FB4525,FB4530,FB5760,FB5960,FB5964,FB6014,FB6323,FB7032,FB7193,FB12393, FB13305,FB28200,FB33255,FB35185,FB39376,FB40755,FB42455 |
| Hake | 9,17,71,FB1139 |
| Small pelagics | 14,21,22,30,42,46,47,48,49,59,60,71,87,90,FB188,FB189,FB796,FB831,FB833,FB835, FB839,FB840,FB850,FB905,FB907,FB908,FB909,FB917,FB1139,FB1836,FB2197,FB2850, FB3231,FB3669,FB3678,FB3730,FB4525,FB5760,FB5769,FB5888,FB6997,FB9273,FB9291, FB9298,FB9300,FB9336,FB10851,FB11192,FB11482,FB26420,FB27758,FB33192,FB33520, FB34034,FB37813,FB39882,FB41293 |

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TABLE A.4. Continued.

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TABLE A.5. Species comprising the functional groups. Group names are in bold. The groups are based on an Atlantis ecosystem model by Ainsworth et al. (in press).

**Gulf coney**
*Epinephelus acanthistius*
**Extranjero**
*Paralabrax loro*
*Paralabrax auroguttatus*
**Leopard grouper**
*Mycteroperca rosacea*
**Gulf grouper**
*Mycteroperca jordani*
**Amarillo snapper**
*Lutjanus argentiventris*
**Barred pargo**
*Hoplopagrus guentherii*
**Groupers and snappers**
*Pronotogrammus multifasciatus*
*Hemanthias peruanus*
*Cephalopholis panamensis*
*Diplectrum labarum*
*Pronotogrammus eos*
*Serranus aequidens*
*Liopropoma longilepis*
*Alphestes immaculatus*
*Diplectrum euryplectrum*
*Diplectrum macropoma*
*Diplectrum pacificum*
*Diplectrum sciurus*
*Alphestes afer*
*Epinephelus analogus*
*Dermatolepis dermatolepis*
*Epinephelus itajara*
*Epinephelus labriformis*
*Alphestes multiguttatus*
*Epinephelus niphobles*
*Epinephelus niveatus*
*Lutjanus aratus*
*Lutjanus colorado*
*Lutjanus guttatus*
*Lutjanus novemfasciatus*
*Lutjanus peru*
*Lutjanus viridis*
*Mycteroperca prionura*
*Mycteroperca xenarcha*
*Paralabrax maculatofasciatus*
*Paranthias colonus*
*Pseudogramma thaumasium*
*Rypticus bicolor*
*Rypticus nigripinnis*
*Serranus fasciatus*
*Serranus psittacinus*

**Drums and croakers**
*Atractoscion nobilis*
*Bairdiella icistia*
*Cheilotrema saturnum*
*Cynoscion parvipinnis*
*Umbrina roncador*
*Ophioscion scierus*
*Odontoscion xanthops*
*Micropogonias megalops*
*Micropogonias ectenes*
*Micropogonias altipinnis*
*Menticirrhus nasus*
*Larimus effulgens*
*Larimus argenteus*
*Larimus acclivis*
*Isopisthus remifer*
*Elattarchus archidium*
*Cynoscion othonopterus*
*Cynoscion nannus*
*Ophioscion strabo*
*Stellifer illecebrosus*
*Umbrina wintersteeni*
*Umbrina xanti*
*Corvula macrops*
*Cynoscion squamipinnis*
*Bairdiella armata*
*Cynoscion reticulatus*
*Cynoscion xanthulus*
*Larimus pacificus*
*Menticirrhus undulatus*
**Grunts**
*Anisotremus interruptus*
*Conodon serrifer*
*Anisotremus caesius*
*Anisotremus davidsonii*
*Anisotremus dovii*
*Anisotremus taeniatus*
*Haemulon flaviguttatum*
*Haemulon maculicauda*
*Haemulon scudderii*
*Haemulon sexfasciatum*
*Haemulon steindachneri*
*Microlepidotus inornatus*
*Orthopristis chalceus*
*Orthopristis reddingi*
*Pomadasys panamensis*
*Xenistius californiensis*
**Herbivorous fish**
*Acanthurus xanthopterus*

*Prionurus punctatus*
*Acanthurus achilles*
*Acanthurus nigricans*
*Calotomus spinidens*
*Girella nigricans*
*Hermosilla azurea*
*Mugil cephalus*
*Mugil curema*
*Nicholsina denticulata*
*Scarus compressus*
*Scarus ghobban*
*Scarus perrico*
*Scarus rubroviolaceus*
**Large reef fish**
*Acanthurus triostegus*
*Balistes polylepis*
*Pseudobalistes naufragium*
*Sufflamen verres*
*Chlopsis kazuko*
*Gorgasia punctata*
*Heteroconger canabus*
*Heteroconger digueti*
*Ariosoma gilberti*
*Paraconger similis*
*Paraconger californiensis*
*Bathycongrus macrurus*
*Bathycongrus varidens*
*Gnathophis cinctus*
*Rhynchoconger nitens*
*Thalassoma lucasanum*
*Nemichthys larseni*
*Myrichthys maculosus*
*Myrophis vafer*
*Ophichthus triserialis*
*Ophichthus zophochir*
*Callechelys cliffi*
*Callechelys eristigma*
*Ethadophis byrnei*
*Apterichtus gymnocelus*
*Brotula clarkae*
*Lepophidium microlepis*
*Lepophidium negropinna*
*Lepophidium pardale*
*Lepophidium prorates*
*Lepophidium stigmatistium*
*Petrotyx hopkinsi*
*Neobythites stelliferoides*
*Regalecus glesne*

TABLE A.5.   Continued.

| | | |
|---|---|---|
| *Sebastes diploproa* | *Arcos erythrops* | *Doryrhamphus excisus excisus* |
| *Sebastes macdonaldi* | *Gobiesox adustus* | *Elacatinus digueti* |
| *Sebastes sinensis* | *Tomicodon humeralis* | *Elacatinus puncticulatus* |
| *Sebastes cortezi* | *Tomicodon zebra* | *Stegastes flavilatus* |
| *Sebastes exsul* | *Gobiosoma paradoxum* | *Stegastes redemptus* |
| *Trichiurus lepturus* | *Kyphosus elegans* | *Gobiosoma chiquita* |
| *Bodianus diplotaenia* | *Paraclinus altivelis* | *Gobiosoma nudum* |
| *Decodon melasma* | *Xenomedea rhodopyga* | *Gobulus hancocki* |
| *Halichoeres aestuaricola* | *Uropterygius macrocephalus* | *Gymneleotris seminuda* |
| *Halichoeres chierchiae* | *Gymnomuraena zebra* | *Hippocampus ingens* |
| *Halichoeres dispilus* | *Muraena lentiginosa* | *Holacanthus clarionensis* |
| *Halichoeres nicholsi* | *Echidna nocturna* | *Hypsypops rubicundus* |
| *Halichoeres notospilus* | *Enchelycore octaviana* | *Kuhlia mugil* |
| *Halichoeres semicinctus* | *Gymnothorax castaneus* | *Labrisomus multiporosus* |
| *Lobotes pacificus* | *Gymnothorax dovii* | *Labrisomus xanti* |
| *Nematistius pectoralis* | *Gymnothorax panamensis* | *Lactoria diaphana* |
| *Pareques fuscovittatus* | *Muraena argus* | *Lythrypnus pulchellus* |
| *Pareques viola* | *Muraena clepsydra* | *Malacoctenus gigas* |
| *Pseudojuloides inornatus* | *Holacanthus passer* | *Medialuna californiensis* |
| *Halichoeres melanotis* | *Pomacanthus zonipectus* | *Mnierpes macrocephalus* |
| *Semicossyphus pulcher* | *Abudefduf troschelii* | *Mulloidichthys dentatus* |
| *Stereolepis gigas* | *Chromis atrilobata* | *Myripristis leiognathus* |
| *Thalassoma lutescens* | *Abudefduf concolor* | *Ogilbia ventralis* |
| *Thalassoma purpureum* | *Chromis alta* | *Ophioblennius steindachneri* |
| **Small reef fish** | *Chromis limbaughi* | *Opistognathus scops* |
| *Antennarius sanguineus* | *Microspathodon bairdii* | *Paraclinus mexicanus* |
| *Apogon retrosella* | *Microspathodon dorsalis* | *Parapsettus panamensis* |
| *Ablennes hians* | *Stegastes leucorus* | *Plagiotremus azaleus* |
| *Hypsoblennius brevipinnis* | *Stegastes rectifraenum* | *Heteropriacanthus cruentatus* |
| *Entomacrodus chiostictus* | *Abudefduf declivifrons* | *Pristigenys serrula* |
| *Grammonus diagrammus* | *Synodus lucioceps* | *Pycnomma semisquamatum* |
| *Acanthemblemaria balanorum* | *Sphoeroides annulatus* | *Uropterygius polystictus* |
| *Acanthemblemaria crockeri* | *Arothron meleagris* | *Scuticaria tigrina* |
| *Coralliozetus angelicus* | *Canthigaster punctatissima* | *Malacoctenus tetranemus* |
| *Coralliozetus micropes* | *Enneanectes carminalis* | *Ostracion meleagris* |
| *Cirriemblemaria lucasana* | *Zanclus cornutus* | **Small demersal fish** |
| *Protemblemaria bicirrus* | *Acanthemblemaria macrospilus* | *Albula vulpes* |
| *Prognathodes falcifer* | *Aluterus scriptus* | *Bajacalifornia burragei* |
| *Forcipiger flavissimus* | *Apogon atricaudus* | *Phthanophaneron harveyi* |
| *Chaetodon humeralis* | *Apogon dovii* | *Antennarius avalonis* |
| *Johnrandallia nigrirostris* | *Apogon pacificus* | *Antennatus strigatus* |
| *Cirrhitichthys oxycephalus* | *Arothron hispidus* | *Notarius planiceps* |
| *Oxycirrhites typus* | *Bathygobius ramosus* | *Hexanematichthys platypogon* |
| *Cirrhitus rivulatus* | *Cosmocampus arctus arctus* | *Bagre pinnimaculatus* |
| *Diodon hystrix* | *Cantherhines dumerilii* | *Notarius troschelii* |
| *Diodon holocanthus* | *Caulolatilus princeps* | *Aulopus bajacali* |
| *Chaetodipterus zonatus* | *Chilomycterus affinis* | *Porichthys analis* |
| *Fistularia commersonii* | *Coralliozetus rosenblatti* | *Porichthys ephippiatus* |

TABLE A.5. Continued.

| | | |
|---|---|---|
| *Porichthys mimeticus* | *Gillichthys seta* | *Gobulus crescentalis* |
| *Strongylura exilis* | *Elacatinus limbaughi* | *Kathetostoma averruncus* |
| *Platybelone argalus pterura* | *Ilypnus luculentus* | *Kyphosus analogus* |
| *Tylosurus pacificus* | *Ophiodon elongatus* | *Labrisomus striatus* |
| *Tylosurus crocodilus fodiator* | *Oxylebius pictus* | *Lythrypnus dalli* |
| *Hypsoblennius gentilis* | *Zaniolepis frenata* | *Malacoctenus ebisui* |
| *Hypsoblennius jenkinsi* | *Sargocentron suborbitalis* | *Malacoctenus hubbsi* |
| *Hypsoblennius digueti* | *Exerpes asper* | *Malacoctenus margaritae* |
| *Bregmaceros bathymaster* | *Paraclinus tanygnathus* | *Malacoctenus zacae* |
| *Cataetyx rubrirostris* | *Starksia spinipenis* | *Malacoctenus zonifer* |
| *Carapus dubius* | *Cryptotrema seftoni* | *Microgobius cyclolepis* |
| *Echiodon exsilium* | *Labrisomus wigginsi* | *Myxodagnus opercularis* |
| *Centropomus nigrescens* | *Paraclinus beebei* | *Opistognathus punctatus* |
| *Centropomus medius* | *Starksia cremnobates* | *Opistognathus rhomaleus* |
| *Centropomus viridis* | *Paraliparis ulochir* | *Paraclinus sini* |
| *Centropomus robalito* | *Psednos pallidus* | *Pherallodiscus funebris* |
| *Ekemblemaria myersi* | *Psednos griseus* | *Quietula y-cauda* |
| *Emblemaria hypacanthus* | *Caelorinchus scaphopsis* | *Sector ocyurus* |
| *Emblemaria walkeri* | *Neoconger vermiformis* | *Sphoeroides lobatus* |
| *Stathmonotus sinuscalifornici* | *Gymnothorax mordax* | *Starksia grammilaga* |
| *Chaenopsis coheni* | *Anarchias galapagensis* | *Starksia hoesei* |
| *Coralliozetus boehlkei* | *Gymnothorax equatorialis* | *Synodus scituliceps* |
| *Dactyloscopus pectoralis* | *Gymnothorax verrilli* | **Pacific angel shark** |
| *Gillellus semicinctus* | *Gymnothorax eurygnathos* | *Squatina californica* |
| *Dactylagnus mundus* | *Eptatretus mcconnaugheyi* | **Small migratory sharks** |
| *Dactyloscopus byersi* | *Eptatretus sinus* | *Mustelus dorsalis* |
| *Gillellus ornatus* | *Barbantus curvifrons* | *Mustelus henlei* |
| *Myxodagnus macrognathus* | *Mentodus eubranchus* | *Mustelus lunulatus* |
| *Chilomycterus reticulatus* | *Synodus sechurae* | *Mustelus californicus* |
| *Zalembius rosaceus* | *Lagocephalus lagocephalus* | **Large pelagic sharks** |
| *Fistularia corneta* | *Sphoeroides sechurae* | *Alopias superciliosus* |
| *Rimicola eigenmanni* | *Sphoeroides lispus* | *Carcharhinus limbatus* |
| *Rimicola dimorpha* | *Lycenchelys folletti* | *Carcharhinus porosus* |
| *Tomicodon eos* | *Axoclinus nigricaudus* | *Ginglymostoma cirratum* |
| *Tomicodon boehlkei* | *Bollmannia marginalis* | *Alopias pelagicus* |
| *Gobiesox pinniger* | *Calamus brachysomus* | *Alopias vulpinus* |
| *Gobiesox schultzi* | *Caulolatilus hubbsi* | *Carcharhinus leucas* |
| *Tomicodon myersi* | *Chaenopsis alepidota alepidota* | *Carcharhinus obscurus* |
| *Rimicola sila* | *Chriolepis minutillus* | *Carcharodon carcharias* |
| *Aruma histrio* | *Chriolepis zebra* | *Isurus oxyrinchus* |
| *Barbulifer mexicanus* | *Coryphopterus urospilus* | *Rhizoprionodon longurio* |
| *Barbulifer pantherinus* | *Crocodilichthys gracilis* | *Sphyrna lewini* |
| *Bollmannia stigmatura* | *Ctenogobius sagittula* | *Sphyrna mokarran* |
| *Bollmannia macropoma* | *Dactyloscopus lunaticus* | *Sphyrna zygaena* |
| *Bollmannia longipinnis* | *Enypnias seminudus* | **Guitarfish** |
| *Bollmannia ocellata* | *Gillichthys mirabilis* | *Platyrhinoidis triseriata* |
| *Bollmannia pawneea* | *Girella simplicidens* | *Zapteryx exasperata* |
| *Evermannia longipinnis* | *Gobiesox papillifer* | *Rhinobatos leucorhynchus* |

TABLE A.5.   Continued.

*Rhinobatos glaucostigma*
*Rhinobatos productus*
**Skates, rays and sharks**
*Hydrolagus colliei*
*Dasyatis brevis*
*Gymnura marmorata*
*Gymnura crebripunctata*
*Heterodontus francisci*
*Heterodontus mexicanus*
*Aetobatus narinari*
*Myliobatis californica*
*Mobula thurstoni*
*Narcine entemedor*
*Diplobatis ommata*
*Apristurus kampae*
*Cephaloscyllium ventriosum*
*Triakis semifasciata*
*Urobatis halleri*
*Urotrygon chilensis*
*Urobatis concentricus*
*Urobatis maculatus*
*Urotrygon rogersi*
*Dasyatis dipterura*
*Myliobatis longirostris*
*Raja equatorialis*
*Rhinoptera steindachneri*
**Flatfish**
*Achirus mazatlanus*
*Achirus scutum*
*Trinectes fonsecensis*
*Bothus constellatus*
*Bothus leopardinus*
*Perissias taeniopterus*
*Symphurus atricaudus*
*Symphurus atramentatus*
*Symphurus callopterus*
*Symphurus chabanaudi*
*Symphurus fasciolaris*
*Symphurus gorgonae*
*Symphurus leei*
*Symphurus melanurus*
*Symphurus oligomerus*
*Symphurus prolatinaris*
*Symphurus williamsi*
*Symphurus elongatus*
*Paralichthys aestuarius*
*Citharichthys mariajorisae*
*Ancylopsetta dendritica*

*Citharichthys fragilis*
*Citharichthys stigmaeus*
*Citharichthys xanthostigma*
*Etropus crossotus*
*Hippoglossina bollmani*
*Hippoglossina stomata*
*Paralichthys californicus*
*Paralichthys woolmani*
*Pleuronichthys ocellatus*
*Pleuronichthys verticalis*
*Syacium ovale*
*Xystreurys liolepis*
**Mojarra**
*Gerres cinereus*
*Diapterus peruvianus*
*Eugerres axillaris*
*Eucinostomus currani*
*Eucinostomus entomelas*
*Diapterus aureolus*
**Scorpionfish**
*Pontinus sierra*
*Scorpaena sonorae*
*Bellator xenisma*
*Prionotus stephanophrys*
*Bellator loxias*
*Prionotus albirostris*
*Prionotus birostratus*
*Prionotus ruscarius*
*Scorpaena guttata*
*Scorpaena histrio*
*Scorpaena mystes*
*Scorpaena plumieri*
*Scorpaena russula*
*Scorpaenodes xyris*
**Lanternfish and deep**
*Triphoturus mexicanus*
*Benthosema panamense*
*Lampanyctus parvicauda*
*Zalieutes elater*
*Dibranchus hystrix*
*Dibranchus spinosus*
*Chauliodus macouni*
*Stomias atriventer*
*Bathophilus filifer*
**Totoaba**
*Totoaba macdonaldi*
**Large pelagics**
*Naucrates ductor*

*Caranx caballus*
*Caranx caninus*
*Carangoides otrynter*
*Caranx sexfasciatus*
*Caranx vinctus*
*Chloroscombrus orqueta*
*Decapterus macrosoma*
*Hemicaranx leucurus*
*Hemicaranx zelotes*
*Trachinotus kennedyi*
*Trachinotus paitensis*
*Trachinotus rhodopus*
*Gnathanodon speciosus*
*Coryphaena hippurus*
*Remora remora*
*Elops affinis*
*Lampris guttatus*
*Mola mola*
*Ranzania laevis*
*Physiculus nematopus*
*Rhincodon typus*
*Oncorhynchus tshawytscha*
*Katsuwonus pelamis*
*Auxis rochei eudorax*
*Auxis thazard brachydorax*
*Sphyraena lucasana*
*Peprilus ovatus*
*Peprilus snyderi*
*Xiphias gladius*
*Euthynnus lineatus*
*Oligoplites altus*
*Sarda chiliensis chiliensis*
*Seriola lalandi*
*Seriola rivoliana*
*Sphyraena ensis*
*Elagatis bipinnulata*
**Mackerel**
*Trachurus symmetricus*
*Gempylus serpens*
*Scomberomorus concolor*
*Scomber japonicus*
*Scomberomorus sierra*
**Hake**
*Merluccius angustimanus*
*Merluccius hernandezi*
**Small pelagics**
*Argentina sialis*
*Atherinops affinis*

TABLE A.5. Continued.

| | | |
|---|---|---|
| *Colpichthys regis* | *Eretmochelys imbricata* | *Pinctada mazatlanica* |
| *Atherinella eriarcha* | *Chelonia mydas* | **Penaeid shrimp** |
| *Atherinella nepenthe* | **Sea birds** | *Penaeus aztecus* |
| *Colpichthys hubbsi* | *Sula nebouxii* | *Penaeus duorarum* |
| *Leuresthes sardina* | *Sula leucogaster* | *Penaeus setiferus* |
| *Bathylagus stilbius* | *Larus heermanni* | *Sicyonia penicillata* |
| *Sardinops sagax* | *Larus californicus* | **Lobster** |
| *Harengula thrissina* | *Larus livens* | *Panulirus interruptus* |
| *Opisthonema libertate* | *Thalasseus elegans* | *Panulirus inflatus* |
| *Lile stolifera* | *Thalasseus maximus* | *Panulirus gracilis* |
| *Pliosteostoma lutipinnis* | *Sterna forsteri* | **Crabs and lobsters** |
| *Opisthopterus dovi* | *Oceanodroma melania* | *Callinectes* spp.[a] |
| *Anchoa curta* | *Halocyptena microsoma* | *Panulirus* spp.[a] |
| *Anchoa walkeri* | *Phalacrocorax penicillatus* | Carnivorous macrobenthos |
| *Anchovia macrolepidota* | *Phalacrocorax auritus* | **Class Polyplacophora** |
| *Cetengraulis mysticetus* | *Fregata magnificens* | Class Asteroidea |
| *Anchoa mundeoloides* | *Haematopus palliatus* | Class Ophiuroidea |
| *Anchoa mundeola* | *Egretta thula* | Class Cephalopoda, order Octopoda |
| *Anchoa ischana* | *Egretta rufescens* | Class Gastropoda, order Nudibranchia |
| *Anchoa exigua* | *Ardea alba* | **Sea cucumbers** |
| *Anchoa nasus* | *Ardea herodias* | Class Holothuroidea |
| *Anchoa argentivittata* | *Numenius phaeopus* | **Bivalves** |
| *Anchoa helleri* | *Calidris minutilla* | Class Pelecypoda |
| *Cheilopogon pinnatibarbatus* | *Arenaria melanocephala* | **Snails** |
| *Cypselurus callopterus* | *Pelecanus occidentalis* | Class Gastropoda |
| **Mysticeti** | *Puffinus griseus* | |
| *Balaenoptera edeni* | *Puffinus carneipes* | |
| *Balaenoptera physalus* | *Podiceps nigrocollis* | |
| *Balaenoptera musculus* | *Synthliboramphus craveri* | |
| *Eschrichtius robustus* | **Squid** | |
| *Megaptera novaeangliae* | *Dosidicus gigas* | |
| **Odontocetae** | *Argonauta argo* | |
| *Delphinus capensis* | *Histioteuthis hoylei* | |
| *Delphinus delphis* | *Loliolopsis diomedeae* | |
| *Tursiops truncatus* | *Ommastrephes bartramii* | |
| *Lagenorhynchus obliquidens* | *Pterygiotheuthis giardigiardi* | |
| *Berardius bairdii* | *Sthenoteuthis oualaniensis* | |
| *Physeter macrocephalus* | *Thysanoteuthis rhombus* | |
| *Globicephala macrorhynchus* | **Blue crab** | |
| *Pseudorca crassidens* | *Callinectes bellicosus* | |
| *Mesoplodon peruvianus* | *Callinectes arcuatus* | |
| **Vaquita** | *Callinectes toxotes* | |
| *Phocoena sinus* | **Scallops and penshells** | |
| **Pinnipeds** | *Spondylus calcifer* | |
| *Mirounga angustirostris* | *Spondylus princeps* | |
| *Zalophus californianus* | *Pteria sterna* | |
| **Reef associated turtles** | *Pinna rugosa* | |
| *Caretta caretta* | *Atrina tuberculosa* | |

[a]Species not included elsewhere.
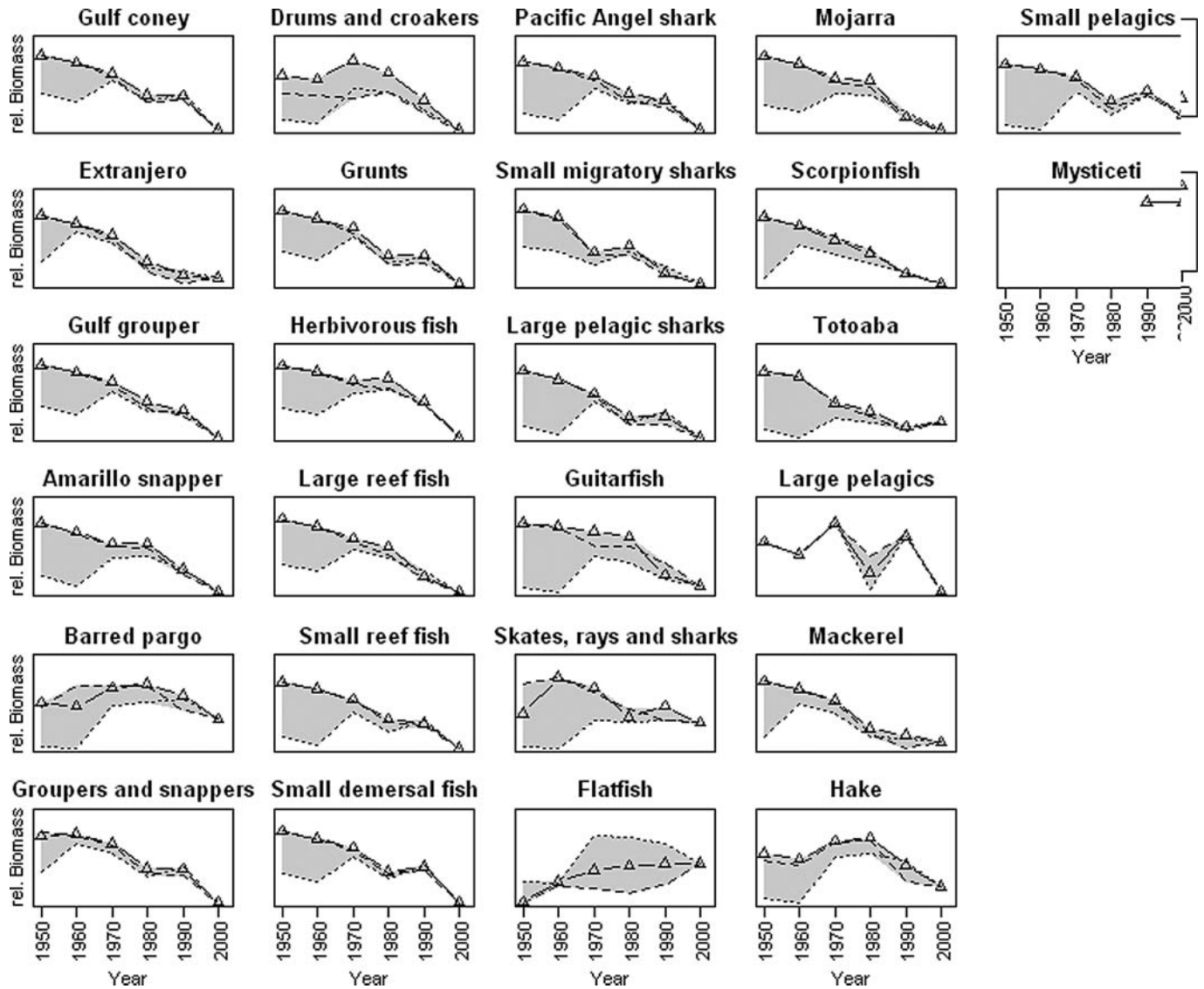
FIGURE A.1.   Abundance of functional groups predicted by the fuzzy logic algorithm based on abundance indicators only (see text). Triangles show the results when the responses from all fishers are included in the algorithm, dotted lines the results when only young (below the median age of 43) fishers' responses are included, dashed lines the results when only older fishers' responses are included. The shaded areas show the total potential range (minimum–maximum) of all series. Trends have been scaled to agree in the year 2000. Species groups that had at least eight respondents are shown.