

# CHAPTER 4

## THE DISTRIBUTION OF EXPLOITED MARINE BIODIVERSITY<sup>1</sup>

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Ecosystem-based fisheries management (EBFM; Pikitch et al. 2004) must include a sense of place, where fisheries interact with the animals and plants of specific ecosystems. To assist researchers, managers, and policy makers attempting to implement EBFM schemes, the *Sea Around Us* presents biodiversity and fisheries data in spatial form onto a grid of about 180,000 half-degree latitude and longitude cells that can be regrouped into larger entities, such as the Exclusive Economic Zones (EEZs) of maritime countries (see chapter 2, and particularly figure 2.1), or the system of currently sixty-six Large Marine Ecosystems (LMEs) initiated by the National Oceanic and Atmospheric Administration (Sherman et al. 2007) and now used by practitioners throughout the world.

However, not all the marine biodiversity of the world can be mapped in this manner; thus, although FishBase ([www.fishbase.org](http://www.fishbase.org)) includes all marine fishes described so far (more than 15,000 spp.), so little is known about the distribution of the majority of these species that they cannot be mapped in their entirety. The situation is even worse for marine invertebrates, despite huge efforts (see [www.sealifebase.org](http://www.sealifebase.org)). This also applies

to commercially or otherwise exploited species of fishes and invertebrates, for many of which only rudimentary knowledge is available.

We define as “commercial” all marine fish or invertebrate species that are reported in the catch statistics of at least one of the member countries of the Food and Agriculture Organization of the United Nations (FAO) or are listed as part of commercial and noncommercial catches (retained as well as discarded) in country-specific catch reconstructions (see chapters 2 and 3). Fortunately, for most species occurring in the landings statistics of FAO, there were enough data in FishBase for at least tentatively mapping their distribution ranges. Similarly, most species of commercial invertebrates had enough information in SeaLifeBase for their approximate distribution range to be mapped. We discuss below the procedure we use for taxa that lacked sufficient data for mapping their distribution, which included few taxa in the FAO statistics and many from reconstructed catches, including discards. Note that the *Sea Around Us* works only on commercial species as defined above; the website of the AquaMap Project ([www.aquamap.org](http://www.aquamap.org)) should be consulted for distribution range maps of other marine species of fish and invertebrates, and marine biodiversity in general. This contribution presents the methods (updated and improved from Close et al. 2006) by which all commercial species distribution ranges (totaling more than 2,500 for the 1950–2010 time period) were constructed or updated. It consists of a set of rigorously applied filters that will markedly improve the accuracy of the *Sea Around Us* maps and other products.

The filters used here are listed in the order in which they are applied. Before applying the filters presented below, the identity and nomenclature of each species are verified using FishBase ([www.fishbase.org](http://www.fishbase.org)) or SeaLifeBase ([www.sealifebase.org](http://www.sealifebase.org)), two authoritative online encyclopedias covering the fishes of the world and marine nonfish animals, respectively, and their scientific and English common names are corrected if necessary. This information is then standardized throughout all *Sea Around Us* databases (see chapter 5). After the creation of all species-level distributions as described here, taxon distributions for higher taxonomic groups, such as genus and family, are generated by combining each taxon level's contributing components; for example, for the genus *Gadus*, all distributions of species within this genus are combined.

Note that the procedures presented here avoid the use of temperature and primary productivity to define or refine distribution ranges for any species, even though these factors strongly shape the distribution of marine fishes and invertebrates (Ekman 1967; Longhurst and Pauly 1987). This was done to allow subsequent analyses of distribution ranges to be legitimately performed using these variables, that is, to avoid circularity.

#### **FILTER 1: FAO AREAS**

The FAO has divided the world's oceans into nineteen statistical areas for reporting purposes (figure 2.1 in chapter 2). Information on the occurrence of commercial species within these areas is available primarily through FAO publications and the FAO website ([www.fao.org](http://www.fao.org)), FishBase, and SeaLifeBase. Figures 4.1A and 4.2A illustrate the occurrence by FAO area of Florida pompano (*Trachinotus carolinus*) and silver hake (*Merluccius bilinearis*), examples representing pelagic and demersal species, respectively.

#### **FILTER 2: LATITUDINAL RANGE**

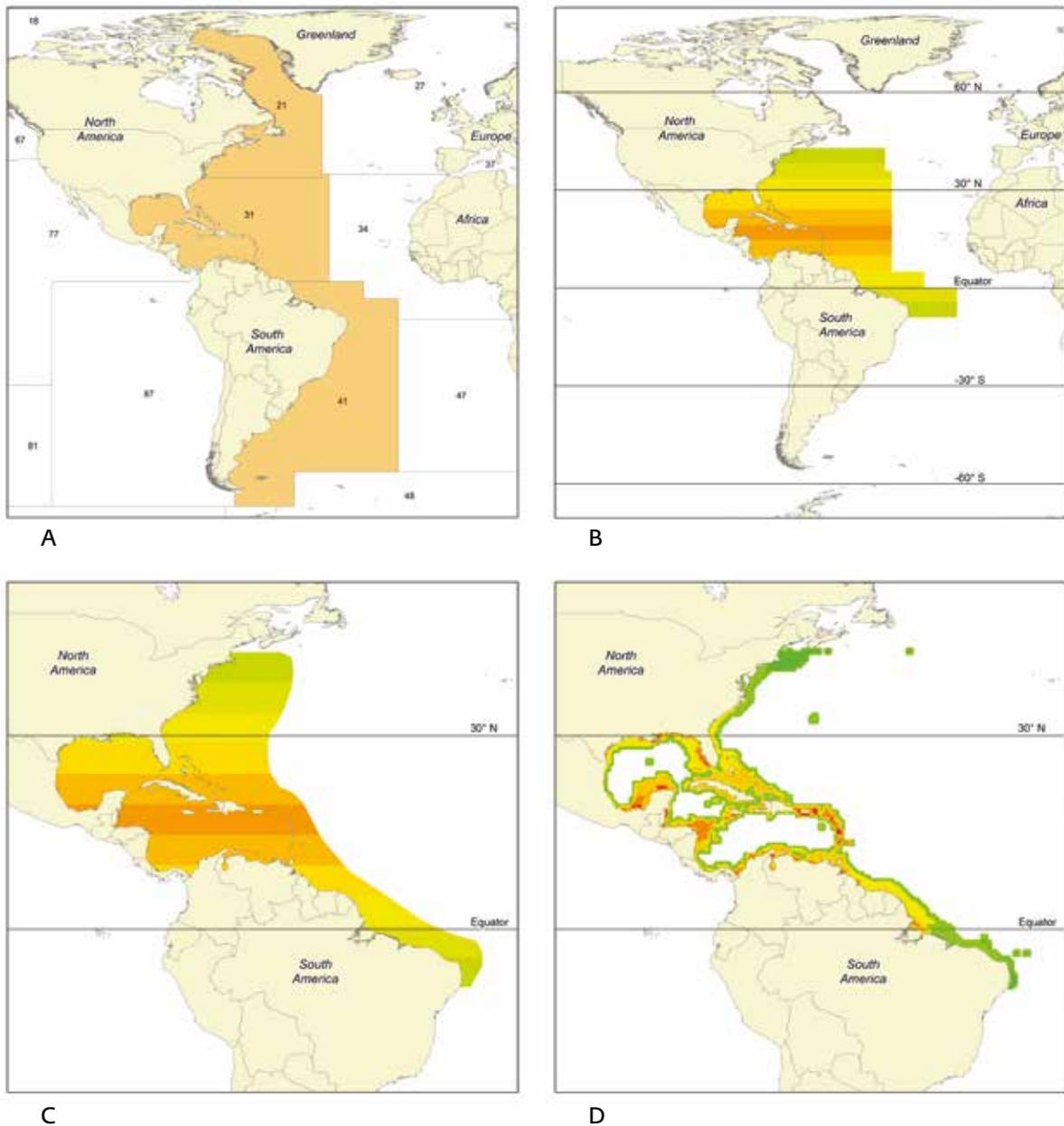
The second filter applied in this process is latitudinal ranges. After reviewing literature on the distribution of marine organisms, Charles Darwin concluded that "latitude is a more important element than longitude" (see Pauly

2004, p. 125, for the sources of this quote and one below). However, this does not mean that longitude and other factors do not play a role in determining a taxon's distribution. Still, in the following quote, Darwin illustrates how latitude provides the key to understanding the composition of certain fauna: "Sir J. Richardson says the Fish of the cooler temperate parts of the S. Hemisphere present a much stronger analogy to the fish of the same latitudes in the North, than do the strictly Arctic forms to the Antarctic."

The latitudinal range of a species is defined as the space between its northernmost and southernmost latitudes. This range can be found in FishBase for most fishes and in SeaLifeBase for many invertebrates. For fishes and invertebrates for which this information was lacking, latitudes were inferred from the latitudinal range of the EEZs of countries where they are reported to occur as endemic or native species, or from occurrence records in the Ocean Biogeographic Information System (OBIS) website ([www.iobis.org](http://www.iobis.org)). Note, however, that recent occurrence records (from the 1980s onward and known range extensions, e.g., of Lessepsian species) were not used to determine "normal" latitudinal ranges, because they tend to be affected by global warming (Cheung et al. 2009).

A species will not have the same probability of occurrence or relative abundance throughout its latitudinal range; it can be assumed to be most abundant at the center of its range (MacCall 1990). Defining the center of the latitudinal distribution range is done using the following assumptions:

- 1 For distributions confined to a hemisphere, a symmetrical triangular probability distribution is applied, which estimates the center of the latitudinal range as the average of the range:  $(\text{northernmost} + \text{southernmost latitude})/2$ .
- 2 For distributions straddling the equator, the range is broken into three parts: the outer two thirds and the inner or middle third. If the equator falls in one of the outer thirds of the latitudinal range, then abundance is assumed to be the same



**Figure 4.1.** Partial results obtained after application of the filters used for deriving a species distribution range map for the Florida pompano (*Trachinotus carolinus*): (A) illustrates the Florida pompano's presence in FAO areas 21, 31, and 41; (B) illustrates the result of overlaying the latitudinal range (43°N to 9°S; see Smith 1997) over the map in (A). (C) shows the result of overlaying the (expert-reviewed) range-limiting polygon over (B). (D) illustrates the relative abundance of the Florida pompano resulting from the application of the depth range, habitat preference, and equatorial submergence filters on the map in (C). (Modified from Close et al. 2006.)

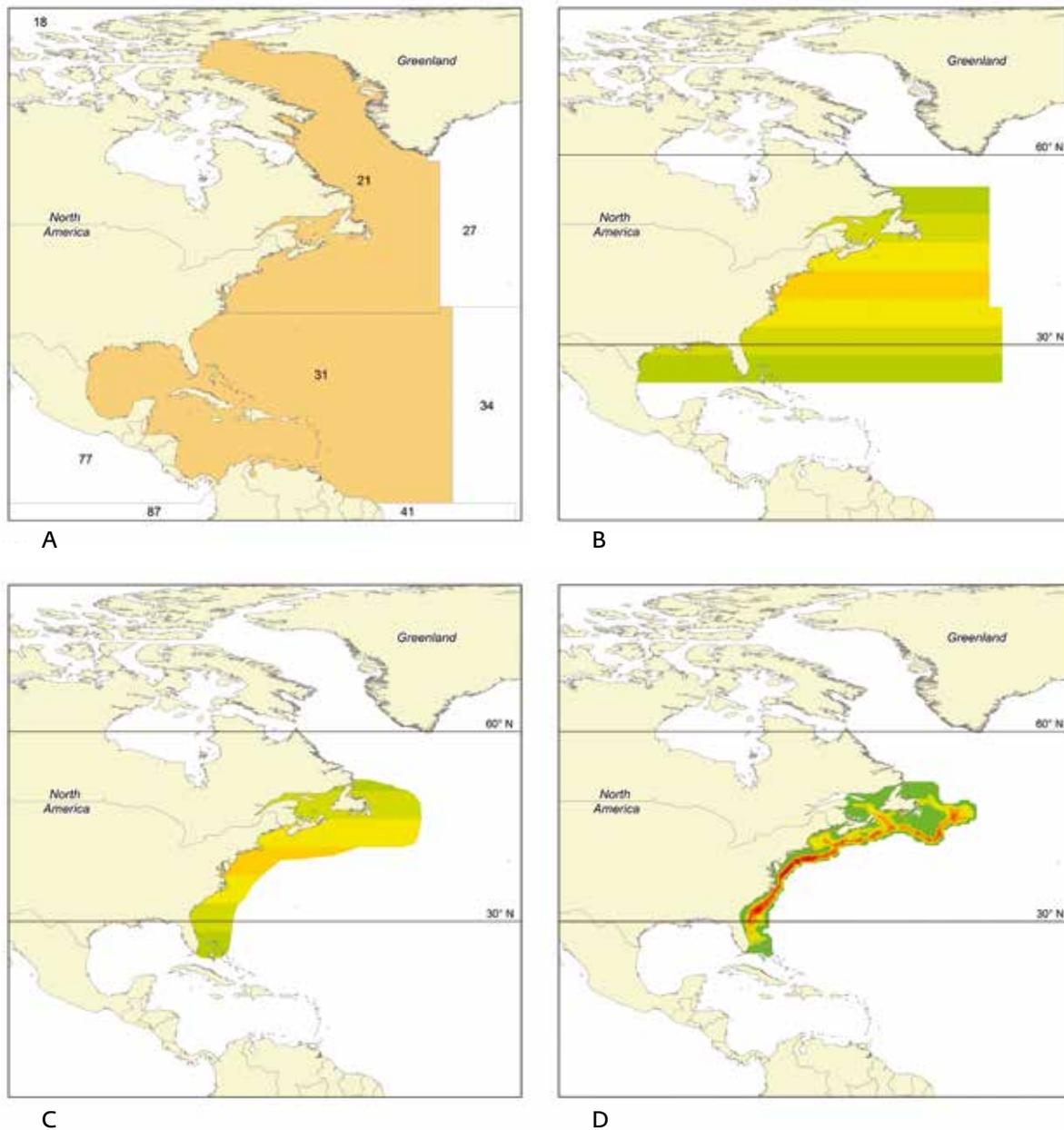
as in (1). However, if the equator falls in the middle third of the range, then abundance is assumed to be flat in the middle third and decreasing to the poles for the remainder of the range.

Figures 4.1B and 4.2B illustrate the result of the FAO and latitudinal filters combined. Both the Florida pompano and the silver hake

follow symmetrical triangular distributions as mentioned in (1) above.

### **FILTER 3: RANGE-LIMITING POLYGON**

Range-limiting polygons help confine species in areas where they are known to occur while preventing their occurrence in other areas where they could occur (because of environ-



**Figure 4.2.** Partial results obtained after the application of the filters used for deriving a species distribution range map for the silver hake (*Merluccius bilinearis*): (A) illustrates the silver hake's presence in FAO areas 21 and 31. (B) illustrates the result of applying the FAO and latitudinal range (55°N to 24°N; see FAO-FIGIS 2001). (C) shows the result of overlaying the (expert-reviewed) range-limiting polygon over (B). (D) illustrates the silver hake's relative abundance resulting from the application of the depth range, habitat preference, and equatorial submergence filters on the map in (C). (Modified from Close et al. 2006.)

mental conditions) but do not. Distribution polygons for a vast number of species of commercial fish and invertebrates can be found in various publications, notably FAO's (species catalogues, species identification sheets, guides to the commercial species of various countries or regions), and in online resources, some of which were obtained from model predictions,

such as AquaMaps (Kaschner et al. 2008; see also [www.aquamaps.org](http://www.aquamaps.org)). Such polygons are based mostly on observed species occurrences, which may or may not be representative of the actual distribution range of the species.

Occurrence records assume that the observer correctly identified the species being reported, which adds a level of uncertainty to the validity

of distribution polygons. More often than not, taxonomic experts are required to review and validate a polygon before it is published, for example, in an FAO species catalogue. This review process is also important, notably for polygons that are automatically generated via model predictions such as AquaMaps. Note that for commercially important endemic species, this review process can be skipped because the polygon is restricted to the only known habitat and country where such species occur.

For species without published polygons, range maps are generated using the filter process described here and compared with the native distribution generated in AquaMaps. Differences between these two model-generated maps are verified using data from the scientific literature and OBIS/Global Biodiversity Information Facility (i.e., reported occurrences, notably from scientific surveys). Note that FAO statistics, in which countries report a given species in their catch, can be used as occurrence records, the only exception occurring when the species was caught by the country's distant-water fleet, as defined in chapter 2.

Polygons are drawn based on the verified map (i.e., with unverified occurrences deleted). Additionally, faunistic work covering the high-latitude end of continents or semienclosed coastal seas with depauperate faunas (e.g., Hudson Bay or the Baltic Sea) were used to avoid, where appropriate, distributions reaching into these extreme habitats. The result of this step (i.e., the information gathered from the verification of occurrences) is also provided to FishBase and SeaLifeBase to fill data gaps in both databases.

All polygons, whether available from a publication or newly drawn, were digitized with Esri's ArcGIS and were later used for inferences on equatorial submergence (see below). Figures 4.1C and 4.2C illustrate the result of the combination of the first three filters (i.e., FAO, latitude, and range-limiting polygons). These parameters and polygons will be revised periodically, as our knowledge of the species in question increases.

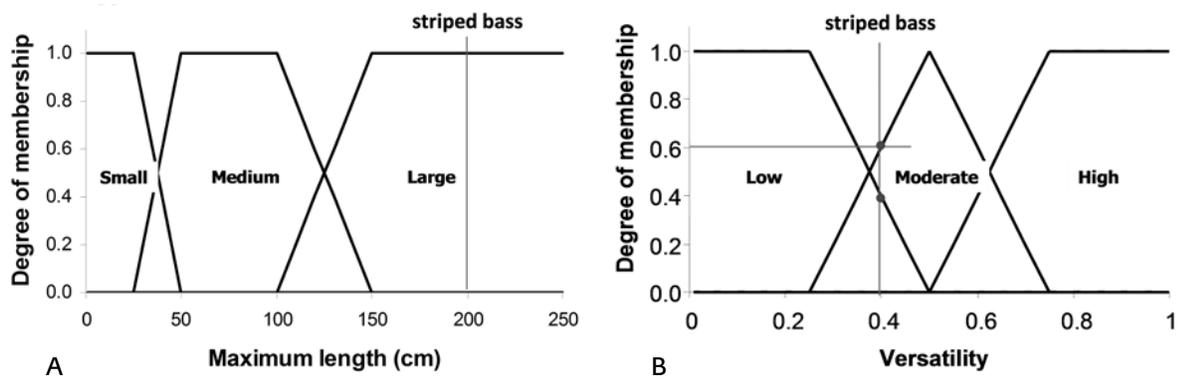
Note that because this mapping process deals only with commercially caught species, the distribution ranges for higher-level taxa (e.g., genera, families) were usually generated using the combination of range polygons from the lower-level taxa included in the higher-level taxon. Thus, the range polygons for genera were built using the range polygons of the commercial species that fall within them. Similarly, family-level polygons were generated from genus-level polygons, and so on. Latitude ranges, depth ranges, and habitat preferences were expanded in the same manner. Although this procedure will not produce the complete biological distribution of the genera and families in question, which usually consists of more species than are reported in catch statistics, it is likely that the generic names in catch statistics refer to the very commercial species that are used to generate the distribution ranges, because these taxa are often more abundant than the ones that are not reported in official catch statistics.

#### **FILTER 4: DEPTH RANGE**

Similar to the latitudinal range, the depth range (i.e., “[the] depth (in m) reported for juveniles and adults (but not larvae) from the most shallow to the deepest [waters]”) is available from FishBase for most fish species and SeaLifeBase for many commercial invertebrates, along with their common depth, defined as the “[the] depth range (in m) where juveniles and adults are most often found. This range may be calculated as the depth range within which approximately 95% of the biomass occurs” (Froese et al. 2000). Given this, and based on Alverson et al. (1964), Pauly and Chua (1988), and Zeller and Pauly (2001), among others, the abundance of a species within the water column is assumed to follow a scalene triangular distribution, where maximum abundance occurs at the top one third of its depth range.

#### **FILTER 5: HABITAT PREFERENCE**

Habitat preference is an important factor affecting the distribution of marine species.



**Figure 4.3.** Fuzzy membership functions for the three categories of (A) maximum length and (B) habitat versatility of a species. Habitat versatility is defined as the ratio of the number of habitat types with which a species is associated to the total number of defined habitat types in table 4.1. For example, the striped bass (*Morone saxatilis*) grows to a maximum total length of 200 cm (large body size; degree of membership = 1). It occurs in estuaries and “other habitats” (2 of 5 defined habitats, i.e., versatility = 0.4, low to moderate; degree of membership = 0.4–0.6). (Modified from Close et al. 2006.)

Thus, the aim of this filter is to enhance the prediction of the probability that a species occurs in an area, based on its association with different habitats. Two assumptions are made here:

- That, other things being equal, the relative abundance of a species in a spatial half-degree cell is determined by a fraction derived from the number of habitats that a species associates with in that same cell and by how far the association effect will extend from that habitat.
- That the extent of this association is assumed to be a function of a species’ maximum size (maximum length) and habitat versatility. Thus, a large species that inhabits a wide range of habitats is more likely to occur far from the habitats with which it is associated, whereas smaller species tend to have low habitat versatility (Kramer and Chapman 1999).

The maximum length and versatility of a species are classified into three categories, and it is assumed that a species can associate with one or more categories with different degrees of membership (0 to 1). A higher membership value means a higher probability that the species is associated with that particular category. The membership values are defined by a prespecified membership function for each of the length and versatility categories (figure 4.3). For example, the striped bass (*Morone sax-*

*atilis*) has a maximum length of 200 cm (total length). Based on the predefined membership function presented in figure 4.3A, the striped bass has a large body size with a membership of 1. Note that there are maximum length estimates for all the exploited species used by the *Sea Around Us*, derived from FishBase and SeaLifeBase.

The ability of a species to inhabit different habitat types, here referred to as “versatility,” is defined as the ratio between the number of habitats with which a species is associated to the total number of habitats as defined in table 4.1. These habitats are categorized as “biophysical” (i.e., coral reef, estuary, sea grass, seamount, other habitats), “depth-related” (shelf, slope, or abyssal), and “distance from coast” (inshore or offshore). Because species are generally specialized toward “biophysical” habitats, this filter takes only those five habitats into consideration. Taking our example again, FishBase lists the following for striped bass: “Inhabit coastal waters and are commonly found in bays but may enter rivers in the spring to spawn” (Eschmeyer et al. 1983). This associates striped bass with estuaries and “other habitats” (i.e., when it enters rivers to spawn). Given that the total number of defined biophysical habitats is five, and the striped bass is associated with two of them, then the versatility of striped bass is

**Table 4.1.** Habitat categories used here, with some of the terms typically associated with them (in FishBase, SeaLifeBase and other sources).

Categories	Specifications of global map	Terms often used
Estuary	Alder (2003)	Estuaries, mangroves, river mouth
Coral	UNEP-WCMC et al. (2010)	Coral reef, coral, atoll, reef slope
Sea grass	Not yet available	Sea grass bed
Seamounts	Kitchingman and Lai (2004)	Seamounts
Other habitats	—	Muddy, sandy, or rocky bottom
Continental shelf	NOAA (2004)	Continental shelf, shelf
Continental slope	NOAA (2004)	Continental slope, upper or lower slope
Abyssal	NOAA (2004)	Away from shelf and slope
Inshore	NOAA (2004)	Shore, inshore, coastal, along shoreline
Offshore	NOAA (2004)	Offshore, oceanic

estimated to be 0.4 (i.e., 2/5). Finally, based on the defined membership functions shown in figure 4.3B, the versatility of striped bass is classified as “low” to “moderate,” with a membership of approximately 0.4 and 0.6, respectively.

#### Determining Habitat Association

Qualitative descriptions relating the commonness of (or the preference of) a species to particular habitats (as defined in table 4.1) are given weighting factors as enumerated in table 4.2. Such descriptions are available from FishBase for most fishes and in SeaLifeBase for most commercially important invertebrates. Going back to our example, we thus know that striped bass occur in (and thus prefer) brackish water (i.e., estuaries) but enter freshwater (i.e., “other habitats”) to spawn. Given the weighting system in table 4.2, estuaries is assigned a weight of 0.75 (usually occurs in) and “other habitats” is given a weight of 0.5 (assuming a seasonal spawning period).

#### Maximum Distance of Habitat Effect

Maximum distance of habitat effect (maximum effective distance) is the maximum distance from the nearest perimeter of the habitat that attracts a species to a particular habitat. This is defined by the maximum length and habitat versatility of the species using the heuristic rule matrix in table 4.3. Taking our example for the striped bass, with a

“large” maximum length (membership = 1) and “low” to “moderate” versatility (membership values of 0.4 and 0.6), points to a “farthest” maximum effective distance in table 4.3. The degree of membership assigned to maximum effective distance is equal to the minimum membership value of the two predicates,<sup>2</sup> in this example, 1 vs. 0.4 = 0.4 and 1 vs. 0.6 = 0.6. When the same conclusion is reached from different rules, the final degree of membership equals the average membership value (in this example,  $[0.4 + 0.6]/2 = 0.50$ ).

The maximum effective distance from the associated habitat can be estimated from the centroid value of each conclusion category, weighted by the degree of membership. The centroid values for “near,” “far,” and “farthest” maximum effective distances were defined as 1 km, 50 km, and 100 km, respectively. In our

**Table 4.2.** Common descriptions of relative abundance of species in habitats where they occur and their assigned weighting factors. The weighting factor for “other habitats” is assumed to be 0.1 when no further information is available.

Description	Weighting factor
Absent or rare	0.00
Occasionally, sometimes	0.25
Often, regularly, seasonally <sup>a</sup>	0.50
Usually, abundant in, prefer	0.75
Always, mostly, only occurs	1.00

<sup>a</sup>If a species occurs in a habitat but no indication of relative abundance is available, a default score of 0.5 is assumed.

**Table 4.3.** Heuristic rules that define the maximum effective distance from the habitat in which a species occurs. The columns in bold characters represent the predicates (categories of maximum body size and versatility), and those in italics represent the resulting categories of maximum effective distance.

Versatility	Maximum body size		
	Small	Medium	Large
Low	Near	Near	Near
Moderate	Far	Far	Farthest
High	Far	Farthest	Farthest

example, we obtained membership values of 0.4 for near (1 km) and 0.6 for farthest (100 km) maximum effective distance, respectively. This gives an estimate of  $(0.4 * 1 + 0.6 * 100) / (0.4 + 0.6) = 60.4$  km (see figure 4.4).

### Estimating Relative Abundance in a Spatial Cell

Several assumptions are made to simplify the computations. First, it is assumed that the habitat always occurs in the center of a cell and is circular in shape. Second, species density (per unit area) is assumed to be the same across any habitat type, and that density declines linearly from the habitat perimeter to its maximum effective distance. Given these assumptions, the total relative abundance of a species in a cell equals the sum of abundance on and around its associated habitat, expressed as:

$$B'T = [\alpha_j + \alpha_{j+1} \dots (1 - \alpha_j)] \dots (1 - ed A), \quad (4.1)$$

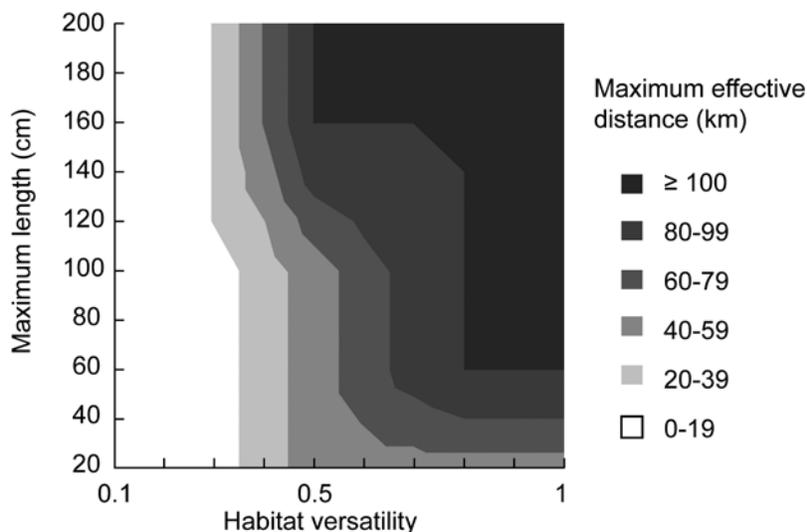
where  $B'T$  is the final abundance,  $\alpha_j$ , is the density away from the habitat from cell  $j$ , and

$A$  is the habitat area of the cell. The relative abundance resulting from the different habitat types is the sum of relative abundance and is weighted by their importance to the species.

Although these assumptions about the relationship between maximum length, habitat versatility, and maximum distance from the habitat may render predicted distributions uncertain at a fine spatial scale, this routine provides an explicit and consistent way to incorporate habitat considerations into distribution ranges.

### FILTER 6: EQUATORIAL SUBMERGENCE

The equatorial submergence phenomenon was well known to Charles Darwin, who wrote that “we hear from Sir J. Richardson, that Arctic forms of fishes disappear in the seas of Japan & of northern China, are replaced by other assemblages in the warmer latitudes & reappear on the coast of Tasmania, southern New Zealand & the Antarctic islands” (Pauly 2004, p. 198).



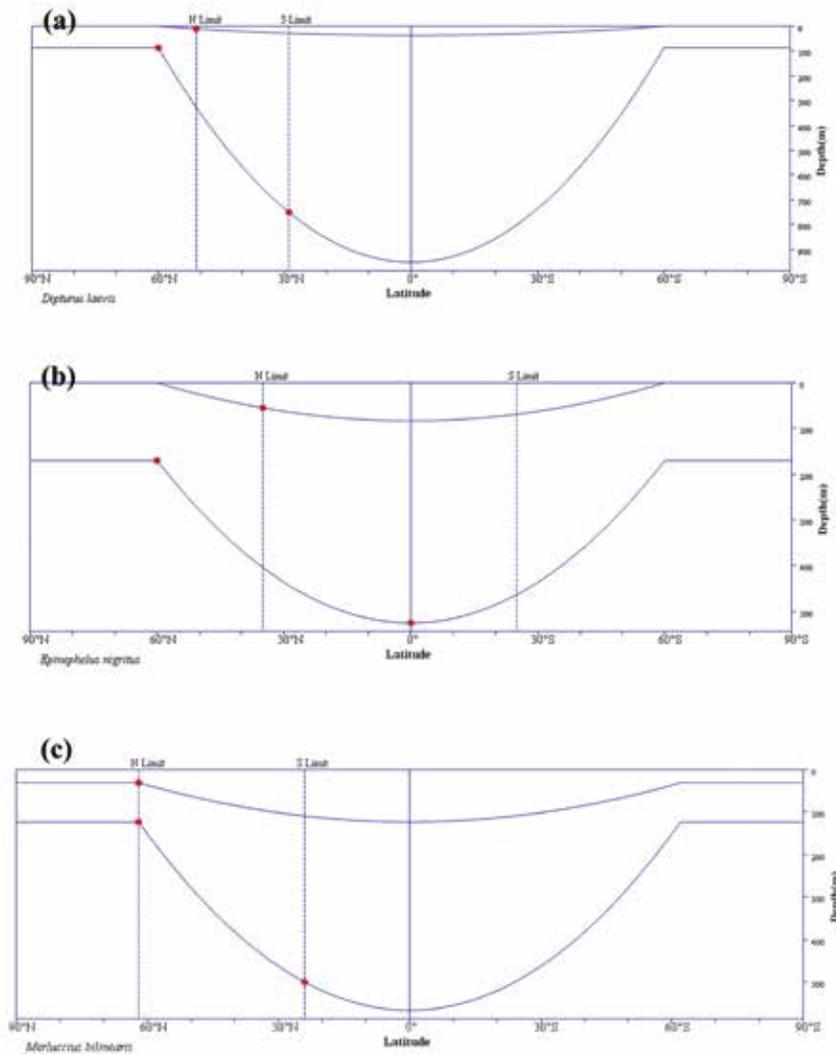
**Figure 4.4.** Maximum effective distance for striped bass (*Morone saxatilis*) estimated from the habitat versatility and maximum length of that species (see text). (Modified from Close et al. 2006.)

Eckman (1967) gives the current definition: *Animals which in higher latitudes live in shallow water seek in more southern regions archibenthal or purely abyssal waters. . . . This is a very common phenomenon and has been observed by several earlier investigators. We call it submergence after V. Haecker [1906–1908] who, in his studies on pelagic radiolarian, drew attention to it. In most cases, including those which interest us here, submergence increases towards the lower latitudes and therefore may be called equatorial submergence. Submergence is simply a consequence of the animal’s reaction to temperature. Cold-water animals must seek colder, deeper water layers in regions*

*with warm surface water if they are to inhabit such regions at all.*

Equatorial submergence, indeed, is caused by the same physiological constraints that also determine the “normal” latitudinal range of species, as described above, and its shift due to global warming (chapter 8), that is, respiratory constraints fish and aquatic invertebrates experience at temperatures higher than that which they have evolved to prefer (Pauly 1998, 2010).

Modifying the distribution ranges to account for equatorial submergence requires accounting for two constraints: data scarcity and



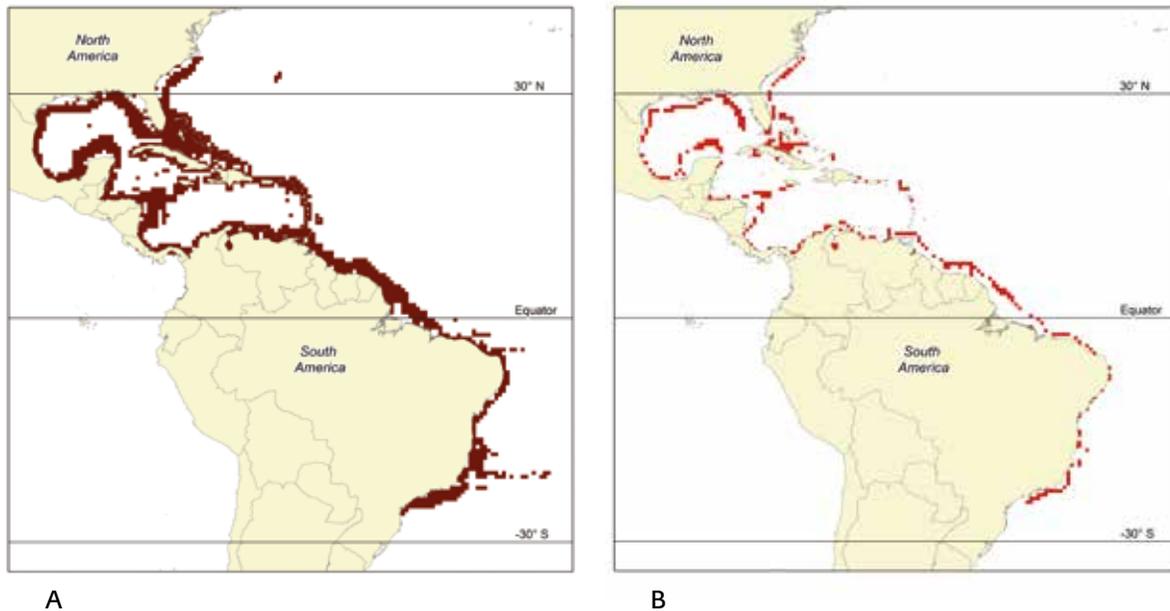
**Figure 4.5.** Shapes used to generate “equatorial submergence,” given different depth and latitude data. (A) Case 1: barndoor skate (*Dipturus laevis*). When the distribution range of the species is at latitudes lower than 60°N or 60°S, the shallow parabola ( $P_{\text{shallow}}$ ) is assumed to intercept zero at 60°N and 60°S. (B) Case 2: When the distribution range is spanning the northern and southern hemispheres, as in the case of the Warsaw grouper (*Epinephelus nigritus*), the deepest depth of the deep parabola ( $P_{\text{deep}}$ ) is at the Equator. (C) Case 3: Silver hake (*Merluccius bilinearis*). The poleward limit of the latitudinal range ( $L_{\text{high}}$ ) is at higher latitudes than 60°N or 60°S. (Modified from Pauly 2010.)

uneven distribution of environmental variables (e.g., temperature, light, food) with depth. FishBase and SeaLifeBase notwithstanding, there is little information on the depth distribution of most commercial species. However, in most cases, the following four data points are available for each species: the shallow end of the depth range ( $D_{\text{shallow}}$ ), its deep end ( $D_{\text{deep}}$ ), the poleward limit of the latitudinal range ( $L_{\text{high}}$ ), and its low-latitude limit ( $L_{\text{low}}$ ). If it is assumed that equatorial submergence is to occur, then it is logical to also assume that  $D_{\text{shallow}}$  corresponds to  $L_{\text{high}}$  and that  $D_{\text{deep}}$  corresponds to  $L_{\text{low}}$ .

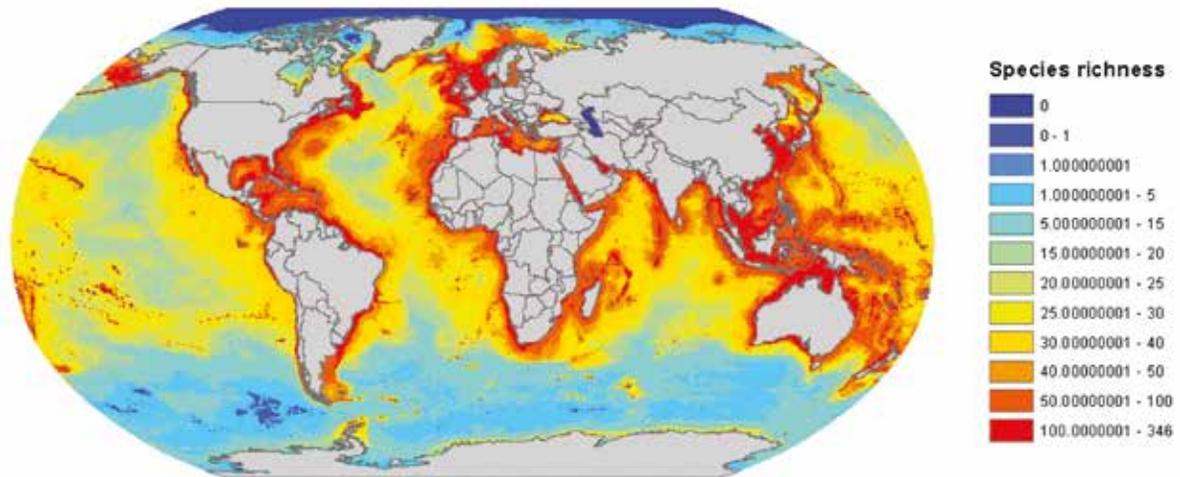
Also, we further mitigate data scarcity by assuming the shape of the function linking latitude and equatorial submergence. Here, two parabolas ( $P$ ) are used (figure 4.5), one for the shallow limit of the distribution ( $P_{\text{shallow}}$ ) and one for the deep limit ( $P_{\text{deep}}$ ), with the assumption that both  $P_{\text{shallow}}$  and  $P_{\text{deep}}$  are symmetrical about the Equator. In addition, maximum depths are assumed not to change poleward of  $60^\circ\text{N}$  and  $60^\circ\text{S}$ . The uneven distribution of the temperature gradient can be mimicked by constraining  $P_{\text{shallow}}$  to be less concave than  $P_{\text{deep}}$  by setting the geometric mean ( $D_{\text{gm}}$ ) of  $D_{\text{shallow}}$  and  $D_{\text{deep}}$  as the deepest

depth that  $P_{\text{shallow}}$  can attain. Three points draw the parabolas. In most cases,  $P_{\text{shallow}}$  is obtained with  $D_{60^\circ\text{N}} = 0$ ,  $D_{60^\circ\text{S}} = 0$ , and  $D_{L_{\text{high}}} = D_{\text{shallow}}$ , and  $P_{\text{deep}}$  with  $D_{60^\circ\text{N}} = D_{\text{gm}}$ ,  $D_{60^\circ\text{S}} = D_{\text{gm}}$ , and  $D_{L_{\text{low}}} = D_{\text{max}}$ . If  $L_{\text{high}}$  is in the northern hemisphere and  $L_{\text{low}}$  is in the south,  $P_{\text{deep}}$  is drawn with  $D_{\text{deep}}$  at the Equator and conversely for the southern hemisphere. Finally, it is assumed that if a computed  $P_{\text{shallow}}$  intercepts zero depth at latitudes higher than  $60^\circ\text{N}$  or lower than  $60^\circ\text{S}$ , then  $P_{\text{shallow}}$  is recomputed with  $D_{60^\circ\text{N}} = D_{\text{shallow}}$ ,  $D_{60^\circ\text{S}} = D_{\text{shallow}}$ , and  $D_{L_{\text{high}}} = 0$ .

Figure 4.5 illustrates three cases of submergence based on different constraints. When this process is applied to a distribution based on latitudinal range and depth that did not account for submergence, these have the effect of “shaving off” parts of the shallow end of that distribution at low latitudes and, similarly, shaving off part of the deep end of the distribution at high latitudes. Also, besides leading to narrower and more realistic distribution ranges, this leads to narrowing the temperature ranges inhabited by the species in question, which is important for the estimation of their preferred temperature, as used when modeling global warming effects on marine biodiversity and fisheries (chapter 8).



**Figure 4.6.** “Equatorial submergence” has the effect of “shaving off” areas from the distribution range of the Warsaw grouper, *Epinephelus nigritus*: (A) Original distribution; (B) Distribution adjusted for “equatorial submergence.”



**Figure 4.7.** Distribution of the richness of “commercial” species (836 fish and 230 invertebrate spp.) created by the *Sea Around Us* by the mid-2000s for mapping fisheries and studying distribution shifts caused by global warming. The number of species available for such a map has increased since then by about 50%, as more species are included in reconstructed data and thus become “commercial” (see text).

## CONCLUSION

The key outcome of the process described above consists of distribution ranges such as in figure 4.6 for more than 2,500 taxa, which can be viewed on the *Sea Around Us* website. They are also accessible via FishBase and SeaLifeBase (click “*Sea Around Us* distributions” under the “Internet sources” section of the species summary pages). These distribution ranges serve as basis for all spatial catch allocation done by the *Sea Around Us* (chapter 5).

The numbers of taxa used to spatialize fisheries catches in different regions of the globe (as described in chapter 5) are mapped in figure 4.7; these numbers, pertaining to the mid-2000s, have increased considerably since then, given the increasing taxonomic resolution of the reconstructed catch statistics used (chapter 2).

Predictions of distributions from the *Sea Around Us* algorithm are comparable in performance to other species modeling approaches that are commonly used for marine species (Jones et al. 2012). Specifically, AquaMaps (Kaschner et al. 2008), Maxent (Phillips et al. 2006), and the *Sea Around Us* algorithm are three approaches that have been applied to predict distributions of marine fishes and invertebrates. Jones et al. (2012) applied these three species distribution modeling

methods to commercial fish in the North Sea and North Atlantic using data from FishBase and the Ocean OBIS. Comparing test statistics of model predictions with occurrence records suggest that each modeling method produced plausible predictions of range maps for each species. However, the pattern of predicted relative habitat suitability can differ substantially between models (Jones et al. 2013). Incorporation of expert knowledge, as discussed above with reference to Filter 3, generally improves predictions and therefore was given here particular attention.

## ACKNOWLEDGMENTS

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# REFERENCES

- Alder, J. 2003. Putting the coast in the *Sea Around Us* project. *The Sea Around Us Newsletter* 15: 1–2.
- Alverson, D. L., A. L. Pruter, and L. L. Ronholt. 1964. *A Study of Demersal Fishes and Fisheries of the Northeastern Pacific Ocean*. Institute of Fisheries, The University of British Columbia, Vancouver.
- Cheung, W. W. L., V. W. Y. Lam, J. L. Sarmiento, K. Kearney, R. Watson, and D. Pauly. 2009. Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries* 10: 235–251.
- Close, C., W. W. L. Cheung, S. Hodgson, V. W. Y. Lam, R. Watson, and D. Pauly. 2006. Distribution ranges of commercial fishes and invertebrates. Pp. 27–37 in M. L. D. Palomares, K. I. Stergiou, and D. Pauly (eds.), *Fishes in databases and ecosystems*. Fisheries Centre Research Reports 14(4). University of British Columbia, Vancouver.
- Ekman, S. 1967. *Zoogeography of the Sea*. Sidgwick & Jackson, London.
- Eschmeyer, W. N., E. S. Herald, and H. Hammann. 1983. *A Field Guide to Pacific Coast Fishes of North America*. Houghton Mifflin, Boston, MA.
- FAO-FIGIS. 2001. *A world overview of species of interest to fisheries*. Chapter: *Merluccius bilinearis*. Retrieved June 15, 2005, from [www.fao.org/figis/servlet/species?fid=3026](http://www.fao.org/figis/servlet/species?fid=3026). 2p. FIGIS Species Fact Sheets. Species Identification and Data Programme-SIDP, FAO-FIGIS.
- Froese, R., E. Capuli, C. Garilao, and D. Pauly. 2000. The SPECIES table. Pp. 76–85 in R. Froese and D. Pauly (eds.), *FishBase 2000: Concept, Design and Data Sources*. ICLARM, Los Baños, Laguna, Philippines.
- Haecker, V. 1906–1908. *Tiefsee-Radiolarien. Wissenschaftliche Ergebnisse der Deutschen Tiefsee-Expedition auf dem Dampfer "Valdivia" 1898–1899* 14. Fischer, Jena, Germany.
- Jones, M., S. Dye, J. Pinnegar, R. Warren, and W. W. L. Cheung. 2012. Modelling commercial fish distributions: prediction and assessment using different approaches. *Ecological Modelling* 225: 133–145.
- Jones, M. C., S. R. Dye, J. K. Pinnegar, R. Warren, W. W. L. Cheung. 2013. Applying distribution model projections in the present for an uncertain future. *Aquatic Conservation: Marine and Freshwater Research* 23(5): 710–722.
- Kaschner, K., J. S. Ready, E. Agbayani, J. Rius, K. Kesner-Reyes, P. D. Eastwood, A. B. South, S. O. Kullander, T. Rees, C. H. Close, R. Watson, D. Pauly, and R. Froese (eds.). 2008. AquaMaps Environmental Dataset: Half-Degree Cells Authority File (HCAF). [www.aquamaps.org](http://www.aquamaps.org).
- Kitchingman, A., and L. Lai. 2004. Inferences of potential seamount locations from mid-resolution bathymetric data. Pp. 7–12 in T. Morato and D. Pauly (eds.), *Seamounts: biodiversity and fisheries*. Fisheries Centre Research Reports 12(5), Fisheries Centre, University of British Columbia, Vancouver.
- Kramer, D. L., and M. R. Chapman. 1999. Implications of fish home range size and relocation for marine reserve function. *Environmental Biology of Fishes* 55: 65–79.
- Longhurst, A., and D. Pauly. 1987. *Ecology of Tropical Oceans*. Academic Press, San Diego, CA.
- MacCall, A. 1990. *Dynamic Geography of Marine Fish Populations*. University of Washington Press, Seattle.
- NOAA. 2004. ETOPO2: 2-Minute Gridded Global Relief Data. <http://www.ngdc.noaa.gov/mgg/fliers/01moggio4.html>.
- Pauly, D. 1998. Tropical fishes: patterns and propensities. Pp. 1–17 in T. E. Langford, J. Langford, and J. E. Thorpe (eds.), *Tropical fish biology*. *Journal of Fish Biology* 53 (Supplement A).
- Pauly, D. 2004. *Darwin's Fishes: An Encyclopedia of Ichthyology, Ecology and Evolution*. Cambridge University Press, Cambridge, England.
- Pauly, D. 2010. *Gaspung fish and panting squids: oxygen, temperature and the growth of water-breathing animals*. Excellence in Ecology (22), International Ecology Institute, Oldendorf/Luhe, Germany.

- Pauly, D., and T.-E. Chua. 1988. The overfishing of marine resources: socioeconomic background in Southeast Asia. *AMBIO: A Journal of the Human Environment* 17(3): 200–206.
- Phillips, S. J., R. P. Anderson, and R. E. Schapire. 2006. Maximum entropy modelling of species geographic distributions. *Ecological Modelling* 190: 231–259.
- Pikitch, E. K., C. Santora, E. A. Babcock, A. Bakun, R. Bonfil, D. O. Conover, P. Dayton, P. Doukakis, D. L. Fluharty, B. Heneman, E. D. Houde, J. Link, P. A. Livingston, M. Mangel, M. K. McAllister, J. Pope, and K. J. Sainsbury. 2004. Ecosystem-based fishery management. *Science* 305: 346–347.
- Sherman, K., M. C. Aquarone, and S. Adams. 2007. *Global applications of the Large Marine Ecosystem concept*. NOAA Technical Memorandum NMFS NE, 208.
- Smith, C. L. 1997. *National Audubon Society Field Guide to Tropical Marine Fishes of the Caribbean, the Gulf of Mexico, Florida, the Bahamas, and Bermuda*. Alfred A. Knopf, Inc., New York.
- UNEP-WCMC et al. 2010. *Global distribution of coral reefs, compiled from multiple sources*. UNEP World Conservation Monitoring Centre. <http://data.unep-wcmc.org/datasets/1>.
- Zeller, D., and D. Pauly. 2001. Visualisation of standardized life history patterns. *Fish and Fisheries* 2(4): 344–355.

## NOTES

1. Cite as Palomares, M. L. D., W. W. L. Cheung, V. W. Y. Lam, and D. Pauly. 2016. The distribution of exploited marine biodiversity. Pp. 46–58 in D. Pauly and D. Zeller (eds.), *Global Atlas of Marine Fisheries: A Critical Appraisal of Catches and Ecosystem Impacts*. Island Press, Washington, DC.
2. Predicate logic is a generic term for systems of abstract thought applied in fuzzy logic. In this example, the first-order logic predicate is “IF maximum weight is large,” and the second-order logic predicate is “AND versatility is moderate.” The resulting function, i.e., the conclusion category based on the predefined rules matrix in table 4.3, is “THEN maximum effective distance is farthest.”