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Mapping global fisheries: sharpening our focus

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Abstract

Mapping global landings is an important prerequisite for examining causal relationships between fishing and ecological change. Landing statistics, typically provided with poor spatial precision, can be disaggregated into a grid system of spatial cells (30 min ×30 min) using a rule-based approach and ancillary data about distributions of fished taxa and fishing access of reporting countries. Presentation of time series catch composition is then possible for many types of marine areas including biogeochemical provinces, large marine ecosystems and exclusive economic zones.

Keywords fisheries landings, fisheries statistics, global fisheries, mapping

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Introduction

As global capture fishery landings falter under increasing demands (Pauly *et al.* 2002), many agencies are attempting to address growing concerns using a variety of management approaches. All these plans require one common element. They need insights into historical catch patterns so that fishing impacts on stocks and on the marine environment can be investigated, and mitigated where necessary . Historically, one of the most commonly maintained fisheries statistics, records of fisheries landings, allowed commercial transactions, industrial development and trade agreements to be documented. It may therefore surprise some readers that these records often prove inadequate for the purposes we most urgently require, that of managing the fisheries and their impacts on the marine environment.

Where fisheries landing records exist, and they do exist in some form for most of the fisheries of the world, these statistics usually suffer from a number of deficiencies. Ignoring typical problems of missing/incomplete data and inconsistent units of measure, one of their most common weaknesses is that they are often quite vague. They can be vague in two ways that frustrate attempts to use them in 'cause and effect' environmental analysis. They can be very uncertain as to the identity of the harvested taxa (i.e. what was it?). This is understandable given the difficulty and confusion in the identification of many marine species even by experts. Fishers are usually too busy to apply the finer points of fish taxonomy to their record keeping, and in any case, their taxonomy is based on characteristics of price, handling requirements and associated quotas/restrictions. Many national and international reporting systems for fisheries landings evolved to track the value of fisheries catches rather than to provide a breakdown by species. In statistics released by the Food and Agriculture Organization (FAO) of the United Nations, which is based on voluntary country reporting, approximately 20% of landings are reported as highly aggregated categories such as miscellaneous fishes, molluscs or crustaceans, or even entire orders or classes of animals. Without information on the taxonomic identity of the landed product it is not usually possible to use ancillary information such as species distributions or fisheries access agreements to refine the location of catch so that they are of use to most ecological analysis.

The second way in which landing statistics are too vague is that the catch location is not well defined (i.e. where was it?). Often the scale of the reporting areas used is many times larger than that required in ecological models or in most causal analysis. The spatial precision used in reporting systems varies greatly globally and often issues of confidentiality arise as the precision increases and threatens to reveal individual fishing grounds. Since 1950, FAO's global landing series has used reporting regions averaging more than 21 million km^2 in area. Locating where catch was taken with precision is not only difficult with moving or drifting gear such as trawl gear but reporting agreements with fishermen often preclude agencies from releasing fine-scale data. Nevertheless, there is a critical need for greater spatial precision than most fisheries data currently supplies if the impacts of fishing are to be investigated and managed.

There are a number of approaches that can provide better catch statistics. The most obvious is to improve current reporting systems. We need more than good recent data; however, analysis of spatial trends requires historical data. The release of currently confidential fine-scale data for analysis would assist investigations but this does not exist for most of the oceans of the world. The best hope is to make better use of existing, currently available data using novel methods as described here.

With our collaborators we have created a database of biological information pertaining to the global distribution of commercial taxa, and another of known fishing access arrangements. These are used in a rule-based approach to spatially distribute global landings statistics to a system of 30-min (latitude and longitude) spatial cells. Landings expressed in this finer scale grid system are used here to describe the catch taken from a range of spatial collections including biogeochemical provinces (Longhurst 1998), large marine ecosystems (LME) (Sherman and Duda 1999) and exclusive economic zones (EEZ) of individual counties. In addition, the raster-like nature and relatively small-scale of the statistics prepared in this way has facilitated the use of landing statistics in spatial ecological models such as Ecospace (Walters *et al.* 1998). This approach has already supported analyses that reveal worrying evidence of a global fisheries decline masked by systematic overreporting (Watson and Pauly 2001) and of basin-scale declines in the biomass of predatory fishes (Christensen *et al.* 2003).

Methods

Spatial cells and statistical areas

All databases, whether relating to species distribution or fishing access arrangements, were used to produce 'grid' files which represent values for spatial cells each covering 30 min of latitude and longitude. Of the more than 258 000 spatial cells so defined for the world as a whole, more than 180 000 contain some marine area. Because they are defined by latitude and longitude, and the distance between degrees of longitude varies with latitude, the area of the cells varies from only a few km^2 adjacent to the poles to a maximum of about 3000 km^2 at the equator. The size of the cells chosen was a compromise necessary to attempt to capture some details of coastal process, yet allow analysis of dataset representing global processes.

Data sources

The data used do not include catch discarded at sea but only that part of the catch that is landed and reported. The landings data used as input, including tuna landings, were downloaded from FAO and accessed via the FishStat software package (http://www.fao.org/fi/statist/statist.asp). This data represented global capture fisheries values from 1950 to 2000 inclusive. The smaller-scale FAO regional data (available for years after 1969) were not used (but plans exist). Therefore the data records employed represent entire FAO statistical areas (Fig. 1). Future versions will augment FAO's landings data with statistics obtained from the International Council for the Exploration of the Sea's (ICES) STATLANT database (http://www.ices.int/fish/statlant.htm), Northwest Atlantic Fisheries Organization (NAFO) (http://www.nafo.ca/), the Canadian, US and other governments to supply additional detail and finer initial spatial precision.

Some modifications were made to FAO's statistics, predominantly to correct for impossible combinations of taxonomic identifications and their landings from reporting areas as identified using FishBase (see below). Reductions (up to 63% in 1998) were also made to catch reported by mainland China since 1994 in keeping with over-reporting biases documented by Watson and Pauly (2001).

Taxonomy

The fish taxonomy used in our process, where possible, was based on that used by FishBase (http://www.fishbase.org/), and that of cephalopods based on Cephbase (http://www.cephbase.org/). It is common for landings data to be reported using a range of taxonomic precision ranging from species to order, or even groups using the International Standard Statistical Classification for Aquatic Animals and Plants (ISSCAAP) system. Our taxonomy had to accommodate landings as they were reported, but landings reported using more aggregated groups than those of families were disaggregated into species, genera or families were appropriate and possible (see below).

Species distributions and critical habitats

It is obvious that landings cannot occur where the reported species do not occur. The distribution of a

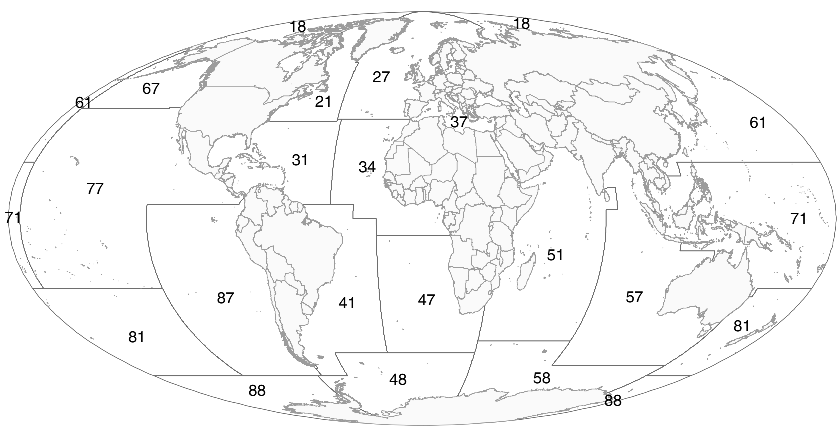

Figure 1 FAO statistical areas used since 1950 for reporting the global fisheries landings used in the analysis.

species (or higher taxa) therefore is a very useful tool to limit the possible area from where catches were made. We developed and used a database of the distributions of global commercial species in our process of assigning landings statistics to spatial cells. Information for this database was sourced in a variety of ways. For some of the world's major commercial species, such as Atlantic cod, there are published global distributions but for most the available distributions do not cover the entire global distribution and are often truncated by jurisdictional boundaries. In such cases other information can help restrict the range. These include water depth (for non-pelagic species) and latitudinal limits. For both depth and latitude we assumed a gradient of landings based on a triangular distribution defined by these limits, with a central point where maximum landings were assumed to occur. For water depth this maximum was taken to be at one-third of the depth range from the shallow limit (favouring shallower distributions). For distributions based on latitude we assumed the maxima was at the latitude at the midpoint of the range.

In addition to depth and latitude, species may be limited in their distribution by proximity to critical habitats. Several of these were identified and sources of mapped distributions found. These included coral reefs, mangrove and seagrass (World Conservation Monitoring Centre, Cambridge, UK), seamounts (NOAA National Geophysical Data Centre) and estuaries (Alder 2003). Conversely, it is highly unlikely that commercial quantities of fish will be landed from ocean areas permanently covered by ice. Ice coverage was received from the US National Snow and Ice Data Center, Boulder, Colorado (http://www.nsidc.org).

Many commercial species have been recorded and collected by scientific expeditions for centuries, and have been well documented by museum records. FishBase (Froese and Pauly 2000 , http://www.fishbase.org) is an excellent on-line database, and records the presence or absence of taxa by country and by FAO statistical area. Cephbase (http://www.cephbase.org) has records for cephalopods. Using these sources we can further restrict the possible locations of catches to those known to be within the range of recorded specimens.

In addition to gradients in distribution introduced by limits to depth and/or latitude we used global representative primary productivity data (Space Applications Institute Marine Environment Unit Joint Research Centre of the European Commission, Ispra, Italy) to produce a density gradient based on long-term production differences in which areas of higher productivity can be assumed to support denser populations (and subsequently landings).

The distributions of commercial taxa used are available on-line (http://www.saup.fisheries.ubc.ca/saupmap/distribution/search.aspx) and facilities are available to experts for comment, correction and receive accreditation for information contributed.

Agreements and fishing access

Fishing fleets do not fish in all coastal waters of the world. This is not only a logistical impossibility and an economic improbability – it would also be illegal. With the declaration of territorial seas, and more recently the 200-nautical mile EEZ, it became necessary for fishing nations to negotiate access to the coastal waters of other nations. There is great incentive to do this as coastal waters produce most of the ocean's commercial landings. Furthermore, many countries with rich marine resources have developed some enforcement capability necessitating other countries to negotiate fishing access. Whether these agreements are bilateral agreements between countries or between companies and countries, or even between international associations such as the European Union and non-European countries, the contents of these agreements may remain private and the information is often considered to have some strategic commercial value. Nevertheless, many of these negotiated agreements are reported in the press or in government notices. The FAO created a database of these agreements called Farisis (FAO 1998). We have further developed and widely expanded the contents of this database so that it could be used in the spatial allocation process to restrict, where possible, the locations of catches in coastal waters. This additional information includes all reports we could locate documenting fishing by one nation in another nation's coastal waters. It is also necessary to include two other types of records in such a database. One that records the likelihood that unauthorized or illegal fishing has occurred leading to illegal, unreported and unregulated (IUU) catches, and another that there is likely that some arrangement existed but that this has not yet been properly documented. It is not simply enough to record that fishing did occur or could occur; it is much more useful to know what types of animals were targeted, for example, was it fishing for tuna or for shrimp. Thus our database includes records of which countries were fishing (or could have been fishing) for each of a broad range of target species for each spatial cell on the year in question.

This is a challenging area of research as in recent times the re-flagging of vessels and the growth in direct and private commercial arrangements between large companies and governments frustrate attempts to document who is fishing at which place and for what purpose. In 2000 there were at least 392 EU fishing vessels with flags of convenience (European Parliament 2001). We have made our database of fishing access records available online by country (http://www.saup.fisheries.ubc.ca/eez/eez.asp) and facilities are available to experts for comment, correction and to receive accreditation of information used.

Spatial disaggregation

We will refer to the process of allocating landing statistics from extensive reporting areas to our system of 30-min spatial cells as spatial disaggregation. The process used landings data records, and using a rule-based approach and databases, assigned the landings to an appropriate collection of spatial cells (Fig. 2). The database records used represented the distribution of the taxa nominated, the fishing access of the reporting country for the nominated taxa and the geographical extent of the statistical reporting area. The cells among which the reported landing tonnage is divided are those that are within the range of the taxa distribution, in areas where the reporting area is allowed and/or is known to fish for the group of taxa involved, and within the extent of the original reporting area.

In order to facilitate the spatial disaggregation process it is important that the taxonomic identity of the reported landings be as precise as possible. The use of highly aggregated or vague groups is problematic because they do not allow the best use of ancillary information (e.g. species distributions). The best clue to the identity of these aggregated groups is the taxonomic composition of landings provided for the same place and time by other records. Therefore, for each year, all landing records provided with identifications at 'precise' levels (species, genus or family) were processed first. In this way the recorded taxonomic composition of landings in each cell could be used to guide a process of taxonomic disaggregation, in which the landing records provided at aggregated levels (order, class or ISSCAAP group) could be prorated into the more precise taxonomic levels on a cell-by-cell basis. Thus, if for a given year landings from three different taxa, identified at precise levels, were allocated to a given spatial cell, then subsequent landings identified to a general taxonomic level, one

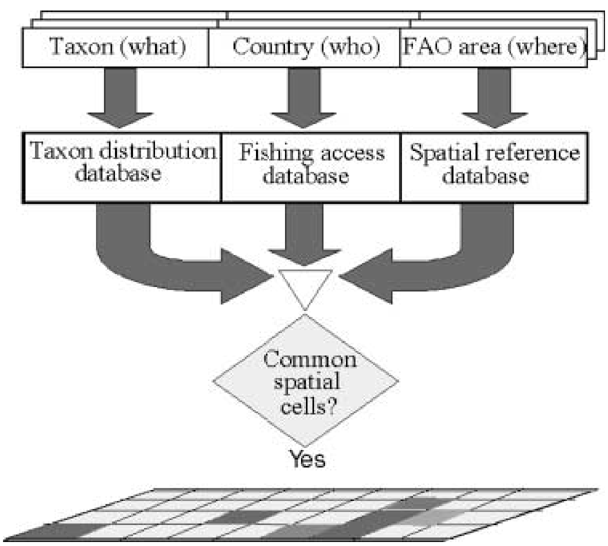

Figure 2 Flowchart showing the spatial disaggregation process. Rule-based process uses reported taxa (what), reporting country (who) and reported FAO area (where) data fields from FAO landing statistics, in conjunction with databases of the distribution of commercial taxa, access by fishing countries and spatial reference by area to divide large-scale fisheries landings into smaller (30-min latitude × 30-min longitude) spatial cells.

that includes these precise taxa, would be prorated into these taxa. We did this using ratios calculated from previous allocations to the cell for the same year. When information on the distribution of precise taxonomic levels was not available then aggregated landings are allocated at the original taxonomic level provided by the statistics.

Results

Global maps

When the process of spatial disaggregation was complete, it was possible to represent global landings on maps with a resolution of the 30-min spatial cells (Fig. 3). To allow comparisons across latitudes (which are different-sized spatial cells in absolute area) it was necessary to express the landings as a rate (tonnes per km^2 of ocean surface). In Fig. 3 global catches are represented for the 1970s and the 1990s. A glance will indicate that the highest density of landings, and in fact most of the world's landings came from the coastal shelf areas although these are only a fraction of the statistical areas used to report them. Insets of the North Atlantic and the Western Pacific are provided to allow inspections of the details. Note the reduction of landings around maritime Canada following the collapse of the cod fishery. Notice also the general movement of significant landings to offshore areas in both areas. Maps of global landings have been prepared for various taxonomic groupings and are available on-line (http://www.saup.fisheries.ubc.ca/Catchrate/map/viewer.htm).

Biogeochemical provinces

Once landing data were available on a 30-min spatial cell basis for the period 1950–2000 inclusive it became possible to create time-series views of important spatial subsets. These can be of any scale. One important large-scale spatial structure used in marine biology is the biogeochemical provinces that divide the oceans of the world into areas with similar primary productivity patterns (Longhurst 1995). For purposes of demonstration we have chosen a large offshore area in the Atlantic known as the North Atlantic Subtropical Western Gyral (NASW) (Fig. 4). Figure 5 shows a time series of landings from this area broken down by the individual taxa reported in FAO records. Information for this specific area of the Atlantic would not be possible without the preceding spatial disaggregation process.

Large marine ecosystems

Another spatial system of the world's oceans, this time exclusively for coastal areas are the LME

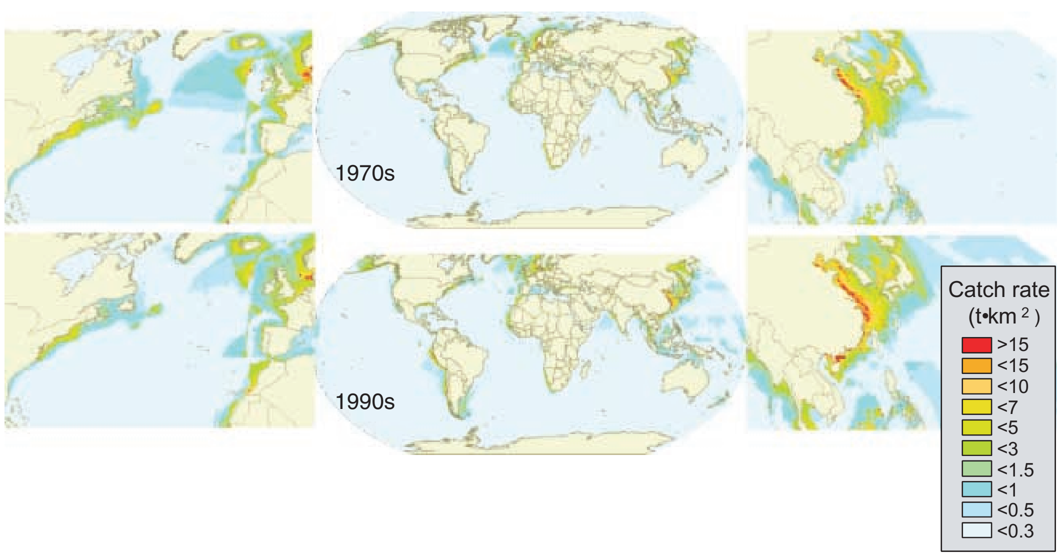

Figure 3 Global landings (t km^{-2}) average for the 1970s and 1990s expressed in spatial cells (30-min latitude × 30-min longitude) following spatial disaggregation process. Insets show details of the North Atlantic and the Western Pacific.

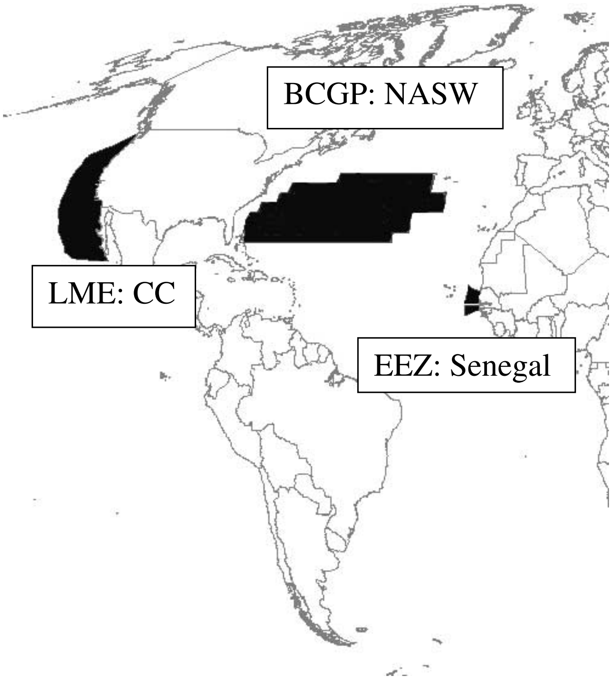

Figure 4 Location of biogeochemical province North Atlantic subtropical western gyral (BGCP: NASW), large marine ecosystem California current (LME: CC) and the exclusive economic zone of Senegal (EEZ: Senegal).

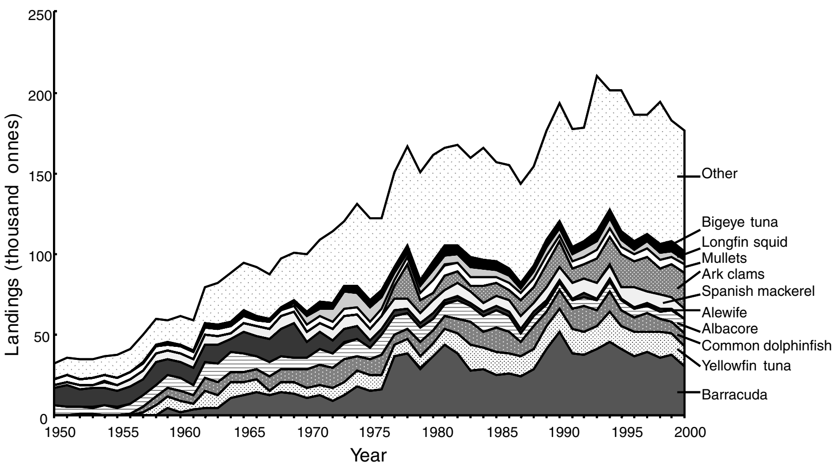

Figure 5 Catch comparison of the North Atlantic subtropical western gyral (NASW) biogeochemical province from 1950 to 2000 based on spatially disaggregated statistics from FAO.

areas. This system groups together large coastal areas with broad ecosystem similarities and is currently being used to direct many large-scale investigations of marine systems. We represent these by the California Current LME found along the west coast of the US (Fig. 4) extending out to about 1000 km offshore. In Fig. 6 a time series is presented for this area based on the results of spatial disaggregation. Similar and related data for all LMEs are available at http://www.saup.fisheries.ubc.ca/lme/lme.asp

Exclusive economic zones

The EEZ associated with coastal countries typically extend 200 nautical miles offshore, and represent an area where the country has jurisdiction over coastal resources including fishing. There is much interest in tracing the development of fishing in these areas including landings by foreign nations. Some countries have statistical systems in place to monitor landings within their EEZ boundaries but typically many do not. Even where these systems

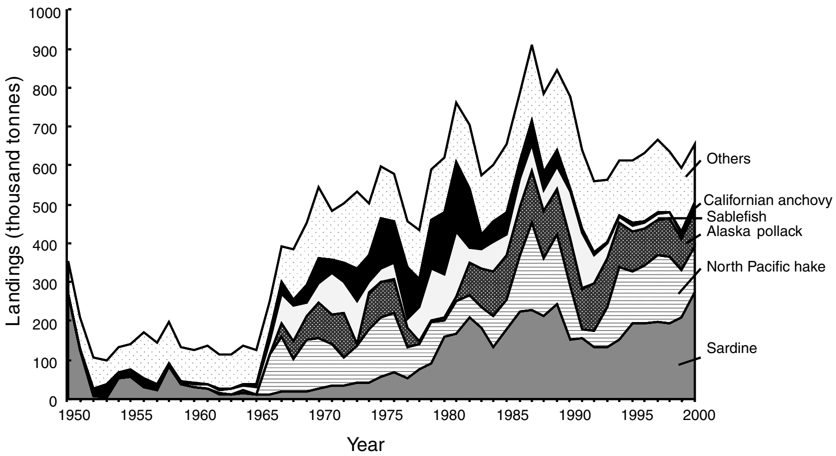

Figure 6 Catch comparison of the California current large marine ecosystem from 1950 to 2000 based on spatially disaggregated statistics from FAO.

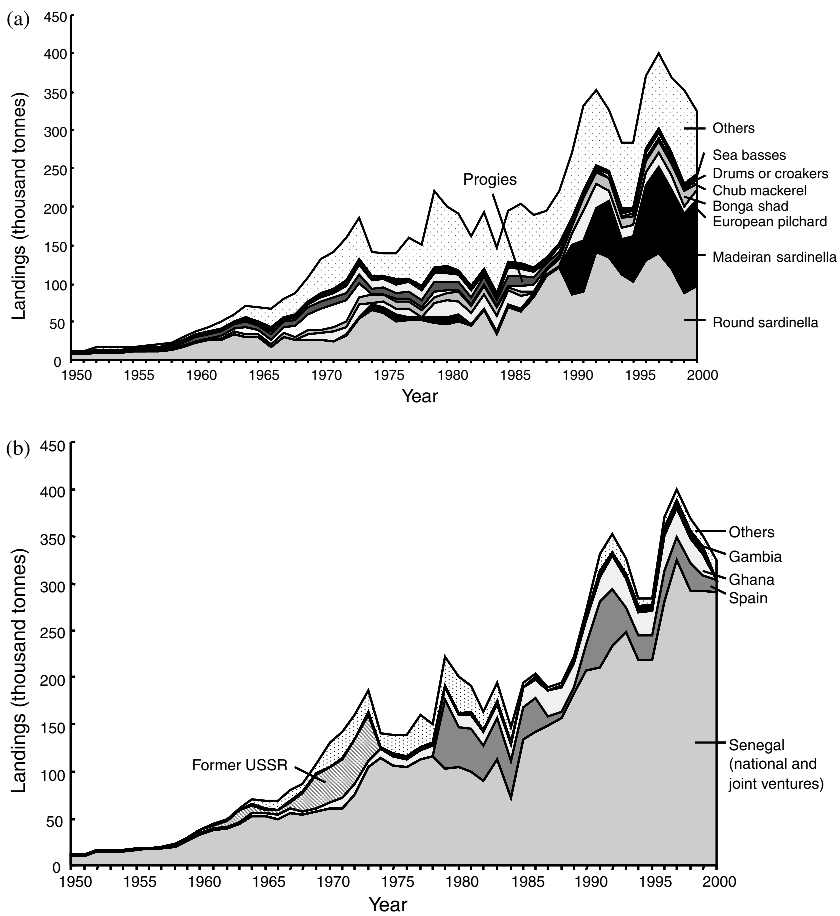

Figure 7 Landings taken within the exclusive economic zone of Senegal from 1950 to 2000 based on spatially disaggregated statistics from FAO (a) catch composition and (b) landings by fishing country.

are in place they were often initiated in the late 1970s or later, after these EEZ areas were declared. By using landings from our spatial cells it is possible to provide a time series of landings within these areas that is consistent with species distributions, access arrangements and reported statistics. The EEZ of Senegal (Fig. 4) is represented by the landing time series in Fig. 7a showing among other changes a marked increase in landings of Madeiran sardinella (*Sardinella maderensis*, Clupeidae) in the late 1980s. It is also possible for EEZs (as with other areas) to examine the pattern of fishing by country. Within current limits of Senegal's EEZ there have been a number of foreign fleets fishing (Fig. 7b). Mapped records indicate that fleets from the former USSR were not replaced as might be expected by those from the Russian Federation, but by Spain, which took larger landings in this area starting in the late 1970s. Similar data is available on-line for all the EEZs and major disputed areas of the world's oceans (http://saup.fisheries.ubc.ca/eez/eez.asp) based on the methods presented here.

Discussion

This publication presents several examples of maps and charts of fisheries landing information that could not be constructed directly from landings data as supplied by the FAO (or other sources) but are possible through the process of spatial disaggregation. The examples demonstrate the feasibility of examining spatial patterns and aggregations in landings data from any area larger than the 30-min cell size used in the process. Examples included the EEZ of Senegal (169 000 km^2), the California Current LME is (2.2 million km^2) and the NASW biogeochemical province (5.8 million km^2), a range of 34 times in area.

The disaggregation process maintains the detail of the original records allowing for a wide variety of analyses to be completed. For example, databases such as FishBase have many attributes available for fish taxa, which when combined with landings data disaggregated into spatial cells, allows examination of the spatial patterns of changes in characteristics such as trophic level. Similar changes can be examined for maximum size, year of maximum catch, etc. (see Pauly and Watson 2003).

Catch rates in spatial cells prepared using the methods outlined here have already been used in conjunction with Ecospace spatial ecosystem models (Walters *et al.* 1998; Pauly *et al.* 2000) to document basin-wide changes in the biomass of parts of the marine ecosystem and the concurrent rise in fishing intensity (Christensen *et al.* 2003). They have been used to look at the overlap in the diets of marine mammals and commercial fishing in the North Atlantic (Kaschner *et al.* 2001; Pauly and MacClean 2003).

Separating landings into a collection of spatial cells also allows anomalies to be examined. Although some areas of the ocean produce many times the landings of other areas with similar latitudes and depths, there are usually documented oceanographic factors such as nutrient upwelling that support this. In other cases we must conclude that the reported landings are not accurate. Watson and Pauly (2001) used disaggregated landing data to show that fisheries statistics from China have been exaggerated through the late 1990s and have contributed to a false belief that global fisheries landings are stable whereas despite increases in fishing intensity these landings have in fact been falling for many years.

Validation is an essential part of any data modelling process. In our case the total weight of landings reported for each FAO statistical area were conserved, therefore it is spatial patterns at a smaller scale that should be examined. As most fisheries and their production are concentrated in coastal areas this basic pattern would be expected to be reproduced in credible maps. This pattern, however, evolves trivially as a consequence of the purely coastal distribution of many important commercial species because only coastal cells were assigned their landings. At a national scale there is still a close match with expectations as many countries extract most of their fisheries landings from their own waters. Our database of fishing access ensured that a nation had sole access to its own EEZ waters expect where documented use by other countries exists. Validation of fishing patterns by foreign fleets is usually a difficult process for those countries whose waters are fished largely by foreigners. Limited resources mean that these countries may have little knowledge of total extractions, let alone detailed spatial landing patterns with which we can compare our findings. Our country-scale results have been put on the world-wide web (http://www.seaaroundus.org) and we have begun to invite comments from fishery experts in the countries represented so that they can help us test the accuracy of the process. They are invited to review maps of landings, species ranges and records of fishing by other countries in their waters. This feedback process will allow better definition of species distributions and of coastal access by other countries, improving future allocations.

Plans are underway for taking similar approaches to those presented here to map a variety of related data including: the use of fuel by commercial fisheries (Tyedmers 2001), fisheries effort, illegal/unreported/unreported (IUU) catches (Pitcher *et al.* 2002), protein capture, fishmeal sourcing, *in situ* value, etc. As more global databases of critical habitats are available, the mapping of dependent species landings will become more precise and useful, leading to the ability to predict the impacts of habitat loss on fisheries landings especially in conjunction with climate change. Similarly efforts to trace the movement of seafood from its source (landings from spatial cells) to its eventual consumption by humans, industry, agriculture and aquaculture are underway. There is considerable interest in tracing the pathways for both protein and value. These are all important steps towards our understanding the effects of fishing on marine environments and the resultant impacts on food security and human enterprise. The key is to make better use of available spatial data – to wring the data not the hands.

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