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Seamounts: Biodiversity and Fisheries

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Seamounts: Biodiversity and Fisheries

Edited by

Telmo Morato and Daniel Pauly

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A Research Report from the *Sea Around Us* Project

Funded by the Pew Charitable Trusts, Philadelphia,

with additional support from the Natural Resources Defense Council, New York



DIRECTOR'S FOREWORD AND ACKNOWLEDGEMENT

This report illustrates nicely the collaborative theme highlighted in the just-released 2001-2003 report of the Fisheries Centre, in which our units and their various activities are presented.

Here, two groups within the Fisheries Centre, the *Sea Around Us* Project, which I lead, and the *Back to the Future* Project, led by T.J. Pitcher, joined forces with a partner in San Diego, Ms. Karen Stocks, and Dr. Rainer Froese at the Institut für Meereskunde in Kiel, Germany, to jointly study and document seamounts and the challenge they pose for management.

Their contributions range from the identification and distribution of seamounts in the world oceans, to a detailed documentation of their biodiversity and the potential and actual impact of fisheries thereon. The result is a report that should serve as a major source of information for all those interested in protecting seamount ecosystems.

On behalf of all authors, I wish to thank the Natural Resources Defense Council (NRDC), and particularly Sarah Chasis and Karen Garrison, for inspiring the work that led to this report, and for funding some of the encoding work that enabled *SeamountsOnline* and FishBase to improve their coverage of seamount invertebrates and seamount fishes, respectively. We also thank the Pew Charitable Trusts for their generous support of the *Sea Around Us* Project, Canada's National Scientific and Engineering Research Council (NSERC) for support to D. Pauly and T.J. Pitcher, the Fundação para a Ciência e Tecnologia (FCT, Portugal) and the European Social Fund for support to T. Morato, and the Sir Robert Black Trust Fund Scholarship for Overseas Studies for support to William W.L. Cheung.

The Fisheries Centre Research Reports series, which is covered by the major abstracting service in marine biology and fisheries (Aquatic Science and Fisheries Abstract), publishes original contributions by faculty and staff of the Fisheries Centre, UBC and their research partners, or the proceedings of workshops they organize. Hard copies are distributed to libraries of partner institutions, and are also available online at www.fisheries.ubc.ca/publications/reports/fcrr.php.

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FOREWORD

Accounts of overfishing have become so common that concerns about bottom fishing on seamounts—underwater mountains in the deep sea — and other vulnerable deep-sea habitats could easily be lost in the noise. That would be a tragedy of proportions surpassed only by the dramatic events now unfolding on seamounts themselves.

Scientists have sampled few of the world's many seamounts, but these explorations have revealed thrilling discoveries: new and endemic species on virtually every seamount, including the deepest dwelling known plants; tree-like corals and sponges as elaborate and diverse as anything in the tropics; centuries-old coral formations; and several living fossils—life forms thought extinct since the time of dinosaurs. Seamounts and other deep-sea features serve as magnets in the open ocean for migratory creatures that gather to feed on their bounty, and many support abundant populations of long-lived bottom-dwelling fish such as Orange roughy.

These extraordinarily rich environments are also being targeted for intensive fishing. Advanced technology allows bottom trawlers to go deeper, fish steeper slopes, and access even more remote locations in a discover-and-deplete syndrome that can exhaust whole populations in a few years. Few deep-sea fisheries have recovered from bottom trawling even two or three decades after fishing ceased and the impacts of trawling on rare and diverse species go unrecorded.

The motivation for this report is the urgent need to make sense of the incomplete but growing body of data on seamounts, extracting the kinds of insights and patterns that can help guide management decisions. The authors use innovative tools for that purpose, performing the most comprehensive assessment ever of seamounts and their species—including corals, sponges, other invertebrates and fish; estimating the temporal and spatial structure of fisheries landings; and examining conservation options in international law and policy.

They find that about half of the world's seamounts occur in international waters, underscoring the importance of international action to conserve their species. Analysis of seamount fishes reveals that they are far more vulnerable than marine fishes in general, so much so that even moderate levels of fishing deplete them. Explorations of a small percentage of seamounts have uncovered habitats so diverse, so fragile and so rich in unique species that it is clear we have only scratched the surface of what is there. Yet bottom trawling can destroy the creatures that make up these habitats before we have documented their existence, much less understood their ecological function or their possible uses for humanity. These varied lines of inquiry point to two conclusions: seamount ecosystems are a significant and highly vulnerable portion of the world's biodiversity, and they are being fished with little regard to sustainability or protection of the richness of life they support.

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and**

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EXECUTIVE SUMMARY

This report, assembled by a group of researchers at the Fisheries Centre, University of British Columbia, Vancouver, Canada, and colleagues in San Diego, USA and Kiel, Germany, reviews present knowledge on seamounts, the underwater mountains dotting the bottom of the world's oceans, and home to a rich, if fragile, diversity of organisms. One definition of seamounts identifies them as reaching at least a thousand meters (about 3000 ft) from the sea floor. Of volcanic origin, seamounts can be visualized as thin cones reaching up, but not fully breaching the sea surface, and supporting often isolated, but rich underwater ecosystems, now increasingly threatened by unregulated fishing.

Due to their narrow base, seamounts can be distinguished from other underwater structures only on high-resolution sea bottom maps. The first contribution in the report, by Adrian Kitchingman and Sherman Lai, identifies and discusses the distribution of over 14,000 seamounts in the world oceans. However, it can be assumed that they would have located more seamounts, had one of the presently classified, high-resolution global sea bottom maps been available to them. About half of the seamounts they identified occurred within the 200 mile economic zones (EEZs) of maritime countries, a theme to which we shall return.

Only a few dozen seamounts have been thoroughly investigated in terms of the animals they contain. Karen Stocks, based on the SeamountsOnline database, which she briefly presents, reviews the knowledge on the invertebrates, emphasizing the high fraction of endemic species occurring on seamounts, i.e., species with narrow ranges, occurring only on one, or a few closely packed seamounts. She also highlights the tendency for seamount invertebrates to take the bushy shape of plants, optimal for capturing drifting food items, but which renders them extremely vulnerable to trawl nets and other fishing implements. Rainer Froese and Arlene Sampang, based on FishBase, the global online fish database, lists and reviews the fishes of seamounts and, based on the typical properties (notably high longevity) of species that have been studied, infers a high potential vulnerability of seamount fish to fishing. These analyses are the most comprehensive reviews of seamount species to date.

The theme of fish vulnerability is expanded in the next two contributions, one by William W. L. Cheung, Tony Pitcher and Daniel Pauly, who developed a new, rigorous method for inferring vulnerabilities from a wide array of features of fish species, and compared this new method with existing approaches, to which it is superior. The second, by Telmo Morato, William W. L. Cheung and Tony Pitcher, applies this new approach to a comparison between seamount fishes and all other marine fishes in FishBase, and shows seamount fishes to be, indeed, far more vulnerable to overexploitation by fishing than representative species of other habitat types. That these considerations are not mere academic exercises is illustrated by the analysis of existing seamount fisheries catch data by Reg Watson and Telmo Morato, which confirms that seamount fisheries - most of which use bottom trawl gear - induce rapid depletions of their resource base, and generally lack sustainability. This puts on a global basis the previous, rather depressing case studies that had been extracted from well-studied and seemingly 'well-managed' seamount fisheries.

The high vulnerability of seamount organisms to fisheries indicates a strong need for seamounts to be protected, both in terms of the biodiversity they contain, and in terms of sustaining their quickly-depleted fisheries resource. Jackie Alder and Louisa Wood show, on the other hand, that very few seamounts are presently protected, even though, as mentioned above, many of them occur within the EEZ of maritime countries. With approximately half occurring in international waters, beyond these zones of national jurisdiction, the responsibility to conserve seamounts as part of the global common heritage belongs to all nations. Clearly, this represents a challenge for the international community and individual countries wishing to conserve the precious biodiversity of these islands of the deep.

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INFERENCES ON POTENTIAL SEAMOUNT LOCATIONS FROM MID-RESOLUTION BATHYMETRIC DATA

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ABSTRACT

Seamounts are underwater volcanoes that did not grow tall enough to break to the sea surface and turn into islands. Once formed, seamounts tend to gradually sink under their own weight and the subsidence of the lithosphere. The ocean floor is littered with these former seamounts, here called 'seamounts'. Seamounts occur throughout the world's oceans, but their number (which may surpass 50,000) is difficult to estimate, even roughly, because it depends on the resolution of the bathymetric map used and the specific definition of a seamount used, i.e., the limits used to distinguish between seamounts and seamounts. Here, the locations of a subset of the seamounts of the world were identified using two algorithms relying on the depth differences between adjacent cells of a digital global elevation map distributed by the U.S. National Oceanographic and Atmospheric Agency (NOAA). The overlap of both algorithms resulted in a set of about 14,000 seamounts, but a different number would have been found had we used different thresholds. Known seamount locations supplied by NOAA and SeamountsOnline (<http://seamounts.sdsc.edu>) were compared against the corresponding seamounts located by the study, which led to some degree of ground-truthing. The coordinates of the seamounts identified in this study are available on the CD-ROM attached to this report, and on <http://www.seararoundus.org>.

INTRODUCTION

Seamounts are undersea mountains (usually of volcanic origin) rising from the seafloor and peaking below sea level (Duxbury and Duxbury, 1989; Kennish, 2000). Typically, seamounts are formed by volcanic activity over hotspots in the earth's crust (Epp and Smoot, 1989). Spreading of the sea floor away from these hotspots via plate tectonic movements means that seamounts often form long chains or elongated clusters. There are many opinions on what defines a seamount, but one widespread definition states that a seamount should be steep-sided and rise 1,000 m or more from the sea floor (Duxbury and Duxbury, 1989; Epp and Smoot, 1989). The shape of seamounts is also an important factor, often crucial in the identification of seamounts from sea floor data. Most are circular or elliptical (Epp and Smoot, 1989), although very elongated seamounts do occur (Wessel and Lyons, 1997).

Though most people may be unaware of it, underwater seamounts are fairly common. However, global seamount datasets containing information on seamount positions are rare and often only contain data for single oceans (e.g. Fornari et al., 1987; Smith and Jordan, 1988; Epp and Smoot, 1989; Smith and Cann, 1990; Wessel and Lyons, 1997). In fact, Wessel and Lyons (1997) state that despite the post-World War II increase in oceanographic exploration, only a small fraction of seamounts have actually been mapped bathymetrically. Any detailed global seamount datasets that exist are usually maintained by governmental departments and are not available to the public. The *Sea Around Us* Project (<http://www.seararoundus.org>) has conducted a global analysis with the goal to generate a spatial dataset of points across the world's oceans that indicate large peaked bathymetric anomalies with a high probability of being seamounts, and we present its key results.

Obtaining data on seamounts has taken many forms over the years, ranging from visually scanning contour maps (Batzia, 1982) to extrapolating using remote sensing data (Wessel, 1997). The bathymetric data contained in the ETOPO2¹ raster dataset supplied by NOAA was chosen as the baseline data from which possible global seamount locations were inferred.

For the purpose of the *Sea Around Us* Project, a global database of seamount point locations was required. In this contribution, we attempt to infer potential seamount locations, and thus to generate, at least, a lower estimate of the number of seamount in the world's oceans.

¹ ETOPO2 Global 2' Elevations CD-ROM. 2001. National Geophysical Data Center, NOAA/NGDC. USA.
<<http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html>>

METHODS

The criteria we used to study seafloor anomalies across the globe were more general than the vertical gravity gradients used by Wessel (1997) and the slope and length to width ratios used by Batzia (1982). We assumed that a possible seamount should have a rise of 1,000 m or more from the seabed and should be roughly circular or elliptical in shape. Moreover, since the ETOPO2 data was the source for all analyses, the occurrence of volcanic activity was not a defining parameter.

The ETOPO2 dataset was constructed from a variety of sources, but mainly consists of data from satellite altimetry. The dataset was supplied at a 2-minute cell resolution (13.7 km² at the equator), which allowed a generalized, global analysis, but certainly caused us to miss many seamounts.

The ESRI ArcGIS² software flow direction and sink algorithms (ArcGIS) were used in combination with the ETOPO2 data to obtain the locations of all detectable peaks on the sea floor. The ETOPO2 data was used in an ESRI grid format for a cell-by-cell analysis.

The ETOPO2 elevation data was prepared by first eliminating all land cells (any elevation above 0 m) and then converting negative elevation values to absolute numbers. This allowed using the ESRI algorithms (see below), designed to detect downhill flow direction and sinks, to identify uphill flow direction and peaks.

The ESRI flow direction algorithm was first applied to the ETOPO2 data. This algorithm produces a grid in which each cell is allocated a flow direction value determined by the steepest descent from the immediate surrounding cells. There are eight valid flow direction values indicated in Figure 1. For example, if a focus cell's direction of steepest slope is to the right, the focus cell's value is 1.

Cells determined to have an undefined flow direction were given a value equal to the sum of the possible flow direction values. Undefined flow directions occur when all surrounding cells are higher than the focus cell or when two adjacent cells flow into each other. The ESRI sink algorithm was used on the resulting flow direction grid to identify all flow direction cells that have undefined flow directions. The resulting sink (seafloor peak) grid could then be overlaid with the ETOPO2 depth grid to indicate all identifiable peaks on the sea floor.

Using the detected peaks, two methods were used to identify possible seamounts. The first involved isolating peaks found associated with a significant rise from the ocean floor. The second method isolated peaks with a circular or elliptical base in an effort to eliminate small peaks found along steep ridges. The overlapping seamounts found by using both of these methodologies were used as the project's seamount dataset. To determine the overlap in the datasets generated from the two methods, points had to be within 2 minutes of each other.

Method 1

The initial part of the process involved producing a grid of standard deviation of depth across the ocean floor. The neighbourhood statistics function in ESRI's ArcGIS Spatial Analyst software was used to produce a grid giving a standard deviation in depth value for each ETOPO2 depth cell as compared to its immediate neighbourhood.

In order to enable the identification of possible seamounts, the standard deviation and seafloor peak grids were overlaid. Using ESRI's ArcGIS Spatial Analyst, each peak cell was then compared to a 5 x 5 kernel of its neighbourhood on the standard deviation grid. If any cells within the block were above a 300-metre standard deviation, the focal peak cell was considered a possible seamount (see Figure 2).

32	64	128
16	Focus Cell	1
8	4	2

Figure 1. Flow direction values indicate direction from focus cell.

² Environmental Systems Research Institute. ArcGIS: Release 8.3 [software]. Redlands, California: Environmental Systems Research Institute, 1999-2002.

Method 2

The second method used the peak grid dataset in comparison to the ETOPO2 depth data. An algorithm was developed that scanned ETOPO2 depths around each peak, along 8 radii of 90 km each, at 45° intervals (see Figure 3). The lowest and highest depths over the radii (10 cells per radii near the equator, more at higher latitudes) were then recorded. A raw peak was considered a seamount when the following conditions were met:

1. Each and all of the 8 radii included depths differing by at least 300 m. This helped eliminate insignificant seamounts;
2. If 2 radii included depths between 300 m and 1,000 m, with the shallowest point being closer to the peak than to the deepest point, and if the radii formed an angle of less than 135°. This condition was used to help eliminate ridges from seamounts.
3. At least 5 of the 8 radii around a peak included depths with a difference of a least 1,000 m, with the shallowest point being closer to the peak than to the deepest point.

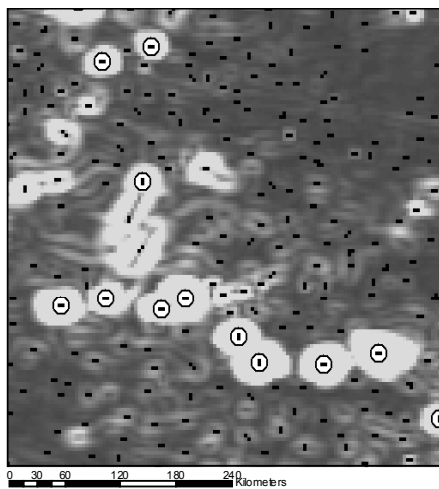


Figure 2. Potential seamounts detected from standard deviation of depth around detected seafloor peaks.

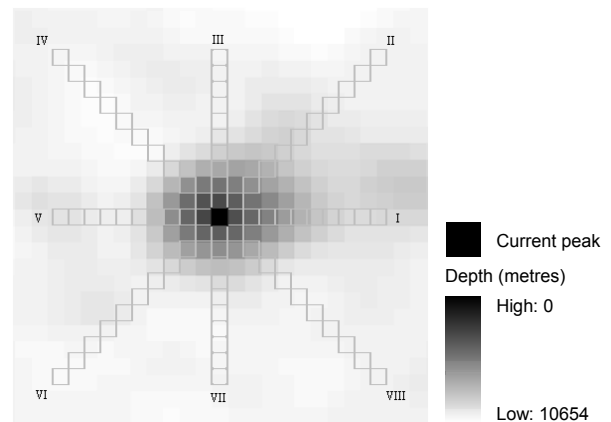


Figure 3. Location of each radius relative to the current peak pixel (depth in metres).

RESULTS

The two methods produced different numbers of potential seamount, with the first method producing almost double the amount (30,314) of the second method (15,962). The overlapping points resulting from the two methodologies identified 14,287 possible seamounts (Figure 4). The 300-metre standard deviation threshold, used in the first method, produced seamounts that were within the broad seamount definition. As expected, many of the predicted seamounts occurred along mid-ocean ridges.

The range of seamount numbers varied differently for the two methods and their set thresholds. Smaller potential seamounts were identified by method 1 when the standard deviation threshold was lowered, thus increasing the seamount count (see Table 1). Method 2 remained relatively constant, with estimates between 15,000 and 20,000 seamounts depending on depth change threshold set between 100 m and 500 m. The non-linear variation in seamount counts as the threshold is increased for method 2 is attributed to the fact that the proximity to the nearest seafloor rise and the depth of the valley between is taken into account as well as the change in surrounding depth (see Table 1).

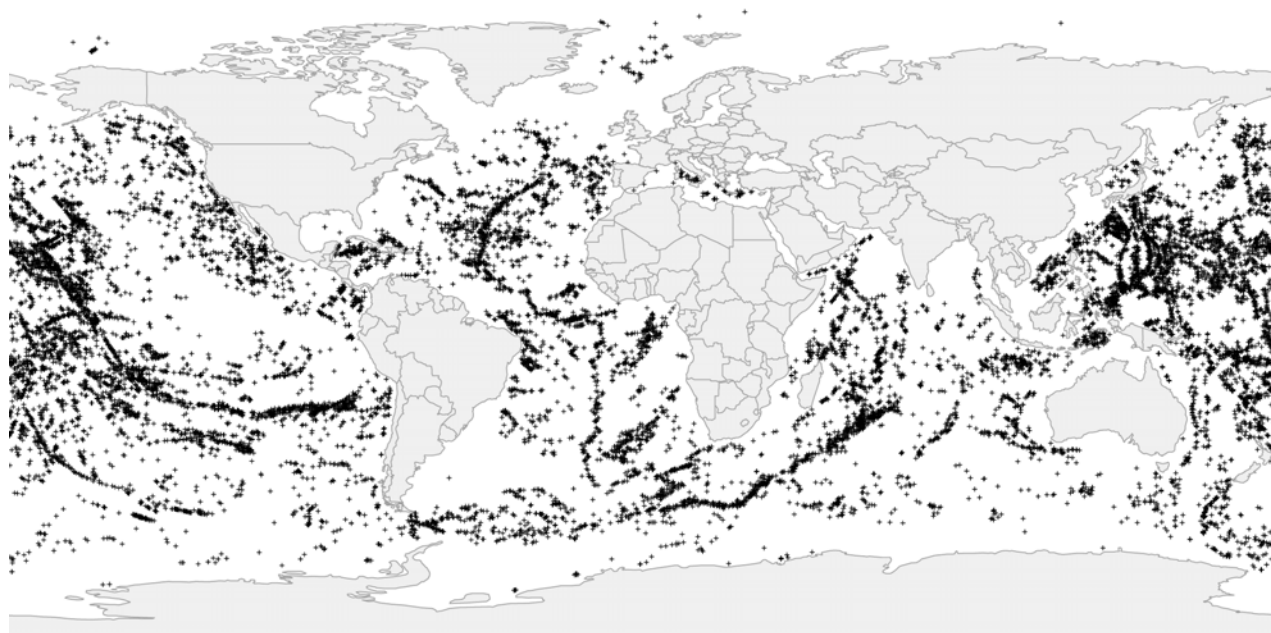


Figure 4. Global dataset of potential seamounts.

Ground truthing was performed on a dataset of known seamounts set at a 30-minute resolution and produced from a combination of data from the US Department of Defence Gazetteer of Undersea Features (1989)³ and SeamountsOnline (see Stocks, this vol.). It was found that approximately 60% of the known seamounts were within 30 minutes of predicted seamounts.

Since many studies are restricted to a particular ocean, an attempt to get an estimate of predicted seamounts per ocean was performed (see Table 2). The United Nations Food and Agriculture Organization (FAO; <http://www.fao.org>) statistical areas were used to identify oceans.

The seamount count for the Pacific Ocean falls within the bounds of Wessel’s (1997) estimate of 8,882. However, it is still below prediction of 12,000 by Batzia (1982), who also stated the probability of 22,000 to 55,000 seamounts in the Pacific Ocean.

Counts differ according to the boundary definitions of the Southern Ocean. The defining FAO areas would have underestimated the actual coverage of the Southern Ocean.

Table 1. Seamount prediction count at varied standard deviation (SD) thresholds.

S.D. threshold (m)	Potential seamount count	
	Method 1	Method 2
100	~ 142,000	~ 20,000
300	30,314	15,962
500	~ 8,500	~ 18,000

Table 2: Predicted seamount counts by ocean.

Ocean	FAO statistical areas	Number of potential seamounts
Pacific	61, 67, 71, 77, 81, 87	8952
Atlantic	21, 27, 31, 34, 41, 47	2763
Indian	51, 57	1651
Southern	48, 58, 88	883

³ Included in the 5-Minute Gridded Global Relief Data on CD-ROM (ETOPO5). 1993. National Geophysical Data Center, NOAA/NGDC. USA. <<http://www.ngdc.noaa.gov/mgg/fliers/93mgg01.html>>

DISCUSSION

Our study has found a relatively simple way of extrapolating potential seamounts from mid-resolution bathymetric data. Although there is no reference to volcanism, the requirement for finding large undersea peaked features (potential seamounts) was fulfilled. The criteria for the extrapolation was only sensitive to a broad level, with the definition of seamounts still very generalized. This sensitivity is also directly influenced by the depth standard deviation threshold and the scope of the neighbourhood cells examined (method 1) or length of radii (method 2). The sensitivity of the extrapolation is also directly influenced by the resolution of the underlying bathymetry data. Any features smaller than the cell size of the bathymetry data will have their dimensions blurred with surrounding features, which could bring them outside the bounds of extrapolation criteria.

The ranges in the number of the potential seamounts predicted by both methods are caused by the actual task performed by each method. Method 1 detects the degree of change in depth surrounding a detected peak. The wider the degree of change permitted, the smaller the potential seamounts that can be located. Method 2 was used to identify the peaks that had surrounding depth profiles conforming to the general shape of a seamount (circular or elliptical). Although the depth change ranges could be altered for method 2, only a limited number of seamounts conformed to our criteria, regardless of the depth change threshold. Our attempt to eliminate peaks along ridges could also eliminate actual seamounts. This leads to the conclusion that the criteria used by method 2 are too restrictive. It was decided to keep the results conservative (i.e., find only very obvious seamounts) in order to reduce error.

The results were also restricted by both methods in the scope of the area around each peak was tested for seamount characteristics. The kernel used by method 1 equates to an area of approximately 342 km² at the equator. It was hoped that a kernel of this size would allow the detection of large seamounts while eliminating large peaked banks. This kernel size could be further looked into in order to optimize the analysis sensitivity. Likewise the radii lengths in method 2 have a similar effect and could also be optimized.

Our methodology has provided a relatively simple way of generating a global seamount dataset directly from elevation data (see Figure 4). Although the current output is suitable for a generalized global analysis, tighter seamount predictions should be possible with some refinements to the methods used.

The set of location data generated here (see Appendix 1 on the CD-ROM, or <http://www.seaaroundus.org> for details) should be considered a subset of a much larger global set of seamount locations, as 50,000 or more seamounts could probably be identified, using bathymetric maps of higher resolution that are presently classified, combined with a broader definition of seamounts, which would take into account the true extent of their variety in shape and groupings.

APPENDICES

1. Location of > 14,000 likely seamounts

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SEAMOUNTSONLINE: AN ONLINE RESOURCE FOR DATA ON THE BIODIVERSITY OF SEAMOUNTS

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ABSTRACT

SeamountsOnline is an online resource for researchers and managers seeking data on the biodiversity of seamounts (undersea peaks in the ocean's floor). The goal is to bring together data on species that have been sampled or observed from seamounts and make these data freely available through a searchable website (<http://seamounts.sdsc.edu>). The data in SeamountOnline are being compiled from many literature publications and the holdings of researchers and institutions working on seamounts. The database covers seamounts globally and includes fishes, invertebrates, and plants; users can view a list of the species that have been found on a particular seamount, a list of all the seamounts from which a particular species has been found, find out what amount of research has been done on a particular seamounts, and search a bibliography of over 1200 literature references on seamounts. SeamountsOnline is currently serving data on 2700 species (or higher taxonomic groups) from almost 200 seamounts, and is expanding continually.

INTRODUCTION

Seamounts are submerged mountains on the ocean's floor. They are of interest to scientific research and biodiversity studies because they support unique communities of life. As described in Stocks (this vol.) and Froese and Sampang (this vol.), many seamounts have assemblages of species not found in other deep-sea habitats, high levels of endemic species (species found only on one seamount or seamount range and nowhere else in the oceans to date), certain extremely long-lived and slow-growing species, and a few examples of 'living fossils' – species thought long extinct. Why seamounts support such unusual ecosystems, and what they can tell us about the processes that create and maintain species in the oceans, are active areas of scientific research.

Seamounts are also of conservation, management, and policy concern. Major commercial fisheries target the dense schools of fishes that aggregate around some seamounts, and there is growing concern that these fisheries are not managed sustainably and are damaging fragile communities on seamounts (Stocks, this vol.; Froese and Sampang, this vol. Watson and Morato, this vol.). Countries are working to manage these fisheries and decide whether and where to site marine protected areas on seamounts within their national waters. Internationally, the need for marine protected areas or other fisheries controls for seamounts in the high seas is being considered within the United Nations (Alder and Wood, this vol.).

Both scientific and management interests in seamounts share the need for access to information on the biodiversity of seamounts. While a substantial amount of research has been conducted on seamounts, most studies have looked at a single seamount or small seamount chain. The data have been published in many sources, in many languages, and some cases remain in unpublished datasets held by researchers or institutions – they are not easily accessible. The purpose of SeamountsOnline (<http://seamounts.sdsc.edu>) is to aggregate and integrate the disparate sources of data on the biodiversity of seamounts and make them freely and openly available (for non-commercial uses) through a searchable web portal (Stocks, 2004b).

SeamountsOnline is also a data contributor to the Ocean Biogeographic Information System (Zhang and Grassle, 2003), an international portal for marine species distribution data. Data in SeamountsOnline can be accessed through the OBIS website at <http://www.iobis.org> as well as through the SeamountsOnline website.

DATA CONTENT

The core information that SeamountsOnline collects is a species distribution record: this is a record of the observation or collection of a particular species from a known seamount location. The project is compiling a database of these records, drawing them from the published literature and from the electronic data holdings of researchers and institutions. The spatial scope is global – data from seamounts the world over are being included. Biologically, the system covers only multicellular organisms: fishes, plants, and invertebrates. The focus is on species-level information, but because it is often difficult to identify organisms down to species the system also accommodates data on genera, families, and other less-precise groups.

Supporting each record is information on who provided the record and how and when the sample was collected or the observation made. SeamountsOnline strives to collect data from high-quality resources – peer-reviewed publications and datasets from reputable institutions and researchers are targeted – but cannot guarantee that these data resources are error-free. The system provides as much supporting information as possible to allow people to make an informed choice about using the data contents.

The system also gives information on the source of each record in order to credit the data providers. SeamountsOnline does not compensate people who contribute datasets – data are contributed by the dataset owners as a service to the community. In order to acknowledge this contribution, SeamountsOnline always attaches source information to every record served, and requires users to cite the original data source(s), not just SeamountsOnline, when using data in publications or presentations. In the spirit of facilitating free and open access to data, SeamountsOnline also makes all of its data available through the Ocean Biogeographic Information System (<http://www.iobis.org>), an international federation of marine data providers.

At the time of writing, SeamountsOnline held 10100 records that included 2700 species or higher taxonomic groups and 190 seamounts. This is by far the largest resource for seamount biology that exists. But it is a work in progress, and is not complete – there are existing seamount data that remain to be included. The SeamountsOnline project is actively seeking, and continually entering, new data. Certain regions and groups of organisms are better represented than others, and the reader is referred to the 'Database Content' link on the SeamountsOnline webpage for a current description of the holdings. In part the coverage represents the progress of SeamountsOnline in incorporating data, and in part it reflects the strengths and gaps in the sampling that has been done to date.

USING THE SYSTEM

There are three main avenues through which users can access the data in SeamountsOnline. Each is described below, and can be reached through a link on main menu of the SeamountsOnline homepage.

Search for Species

Through this search interface, the user can specify 1) a species or genus of interest and/or 2) either a particular seamount by name or a geographic area by latitude and longitude bounds. Figure 1 shows the interface for this option. From a search on a species or genus name the system will return a list of all seamount locations where that taxon has been found. From a search on a seamount name or region the system will return a list of all species that have been recorded from that location. The default return is a data table containing the taxonomic name (genus, species, and, where available, subspecies, and authority), seamount name, latitude and longitude with precision estimates, and the author(s) and publication year of the original data source (Figure 2). In the search interface, users can request the following additional fields: Family and Phylum name, depth of capture, date collected, number collected, and the full bibliographic citation of the source data. Each observation includes a sample number that is live-linked to the full sample information (see below). The results from a search can be downloaded either as a tab-separated text table or as a Microsoft Excel file. They can also choose to download the full sample information associated with each observation, either as one merged table or as separate species-observation and sample tables.

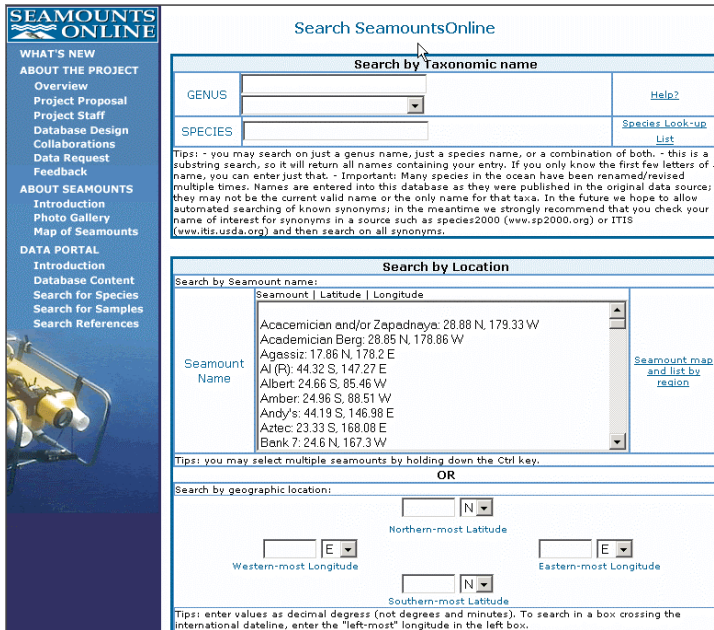


Figure 1. Interface for the “Search by Species” search option. The user can enter a genus or species of interest to retrieve a list of all the locations where that organism has been found, or can select a location of interest (by either clicking a seamount name or entering a latitude-longitude box) to see all the species recorded from that seamount. The searches can also be combined to ask for “all records of genus X in region Y.”

Search for samples

This interface describes the amount of sampling activity that has been conducted on a particular seamount. This information is important for evaluating whether species lists are complete and representative, and whether data are comparable between seamounts. For example, if a seamount of interest has only been sampled with a bottom trawl, then the absence of a particular midwater species from the observations does not necessarily mean that the species is not present there. To search for samples, the user selects a seamount of interest. The system returns a list of all the samples known from that seamount. The returned data for each sample includes, where available, the date(s) taken, the latitude and longitude location with precision, the depth, the depth zone (i.e., benthic or midwater), whether the sample was quantitative, the station or sample name/number given in the original data source, the gear used, the taxonomic groups recorded (e.g., “only fish were counted”), the cruise and vessel, and the individual or institution taking the sample (Figure 3). The results from a given seamount can be downloaded as either a tab-separated text file or as a Microsoft Excel file.

Results from your search in SeamountsOnline

Please cite both SeamountsOnline and the original data source when using these data.

Click on any field title to see a definition of that field.

Species Data (comma delimited text) [Download]

Back to Search for Species Page

Genus	Species	Subspecies	Authority	Seamount Name	Sample ID	Latitude	Longitude	Lat/Lon Precision	Data Source
Adelosebastes	latens		Abe and Nakabo	Multipeak	535481	+42.26	+170.45	0.5	Borets, L.A., 1986
Apristurus	sp.			Multipeak	535481	+42.26	+170.45	0.5	Borets, L.A., 1986
Barbourisia	rufa		Parr, 1945	Multipeak	535481	+42.26	+170.45	0.5	Borets, L.A., 1986
Chaceon	imperialis		Manning, 1992	Multipeak	130	+42.33	+170.83	0.01	Manning, R.B., 1992
Chionoecetes	japonicus	pacificus	Sakai, 1978	Multipeak	130	+42.33	+170.83	0.01	Sakai, T., 1978
Coryphaenoides	acrolepis		(Bean, 1884)	Multipeak	535481	+42.26	+170.45	0.5	Borets, L.A., 1986
Coryphaenoides	dineurus		(Gilbert, 1896)	Multipeak	535481	+42.26	+170.45	0.5	Borets, L.A., 1986
Coryphaenoides	longifilis		Gunther, 1877	Multipeak	535481	+42.26	+170.45	0.5	Borets, L.A., 1986
Coryphaenoides	pectoralis		(Gilbert)	Multipeak	535481	+42.26	+170.45	0.5	Borets, L.A., 1986
Geryon	affinis		A. Milne Edwards and Bouvier, 1894	Multipeak	130	+42.33	+170.83	0.01	Sakai, T., 1978
Holbyrnia	kulkovi		Fedorov and Sazonov	Multipeak	535481	+42.26	+170.45	0.5	Borets, L.A., 1986
Lithodes	longispina		Sakai	Multipeak	130	+42.33	+170.83	0.01	Sakai, T., 1978
Lithodes	nintokuae		Sakai, 1978	Multipeak	130	+42.33	+170.83	0.01	Sakai, T., 1978
Macroregonia	macrochira		Sakai, 1978	Multipeak	130	+42.33	+170.83	0.01	Sakai, T., 1978
Paralomis	pacifica		Sakai, 1978	Multipeak	130	+42.33	+170.83	0.01	Sakai, T., 1978
Progeron	guinotae		Crosnier	Multipeak	130	+42.33	+170.83	0.01	Sakai, T., 1978
Rondalelia	loricata		Abe and Hotta, 1963	Multipeak	535481	+42.26	+170.45	0.5	Borets, L.A., 1986
Sagamichthys	abei		Parr, 1953	Multipeak	535481	+42.26	+170.45	0.5	Borets, L.A., 1986
Symphysus	pacificus		Birley and Schroeder	Multipeak	535481	+42.26	+170.45	0.5	Borets, L.A., 1986

Figure 2. Example of the data returned from a “search for species” query. In this example, all species from Multipeak seamount were requested. Additional information on the depth and date of collection, number found, Phylum and Family of each species, the full data citation, etc., can also be selected for inclusion.

Search References

In the process of building the SeamountsOnline database, over 1200 bibliographic citations relating to seamounts were collected. Users can search this bibliographic database for authors, seamount names, or other terms of interest. The result of a search is a text list of references with the author, year, title and source given for each reference. This can be downloaded by copying from the screen and pasting to a local application. There is also a feature for downloading the entire bibliography as a text file in the same format as the screen return. The coverage is strongest for biological aspects of seamounts but also includes some references about seamount geology, hydrology, etc.

DATA REQUEST

SeamountsOnline is continually seeking new seamount data. Though data are being hand-entered from publications, this process is labour-intensive and often can access only summarized or condensed data. SeamountsOnline will grow most efficiently, and thus become most useful, if researchers and institutions are willing to provide electronic datasets for inclusion. These contributions are always fully acknowledged, and all intellectual property rights remain with the data provider. Please contact the author if you have data to contribute.

ACKNOWLEDGEMENTS

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The following samples have been recorded from the seamount(s) you selected
 Blank fields indicate missing information.
 Click on any field title to see a definition of that field.

Comma Text Delimited Download

Back to Search for Sample Page

Seamount Name	Sample ID	Sample Verbatim	Station Verbatim	Data Source	
Andy's	143		55	Koslow and Gowlett-Holmes, 1998	
Start Date (mm/dd/yyyy)	End Date (mm/dd/yyyy)	Latitude	Longitude	Lat/Lon Precision	
1/29/1997		-44.18	+146.94	0.01	
Min Depth (m)	Max Depth (m)	Seamount Zone	Water Zone	Quantitative?	Species Found
620	800	unknown	Benthic/Near Bottom	Yes	Click Here
Method/Effort	1 epibenthid sled haul, 25 mm mesh net, 0.72 sq m mouth opening				
Taxa Covered	Comprehensive for hydroids, decapod crustacea, ophiuroid echinoids, holothuroid echinoids, bivalve molluscs and cephalopod molluscs				
Cruise	SS 9701				
Vessel	Southern Surveyor				
Taken By	CSIRO				
Notes					

Figure 3. Example of the data returned from a "search by sample" query. This figure shows the data returned from one sampling event – if multiple sampling events had occurred on this seamount, then a series of these data boxes would be returned.

SEAMOUNT INVERTEBRATES: COMPOSITION AND VULNERABILITY TO FISHING

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ABSTRACT

To describe the invertebrate communities found on seamounts and their vulnerability to fishing, a global review of seamount data was conducted. Using data from SeamountsOnline (<http://seamounts.sdsc.edu>), data from 1771 kinds of organisms on 171 seamounts were evaluated, representing the largest global synthesis of seamount data to date. The data clearly indicate that seamount communities differ from those found in other deep-sea habitats. Filter-feeding corals, anemones, sponges, and feather stars are common on hard-bottomed seamounts, compared to the deposit-feeding species found most often in the muddy deep sea. The total abundance of life is generally high, leading to descriptions of seamounts as ‘underwater oases’. On almost every seamount that has been studied, new species have been found, leading to the conclusion that many species may be endemic to just one or a few seamounts. Extremely long-lived and slow-growing species have also been discovered on seamounts, representing some of the oldest animals known on earth. These same qualities also make seamount communities extremely vulnerable to fishing pressure. The tree-like and flower-like forms of the filter-feeders on seamounts are highly vulnerable to damage by bottom trawls, and the one existing study comparing fished and unfished seamounts indicates that trawling in that area reduced the overall biomass by a factor of seven and the species diversity by a factor of two. Endemic species, thought to be common on seamounts, are at greater risk for extinction. Also, impacts of trawling on very long-lived seamounts species may persist for centuries. Because of the fragility of these systems, and their potential importance to scientific research into ocean biodiversity, to future pharmaceutical discoveries, and to ocean communities as a whole, damage from trawling warrants serious attention.

INTRODUCTION

Seamounts are undersea peaks on the ocean’s floor – submerged mountains that do not break the water’s surface. As shown by Kitchingman and Lai (this vol.), they are common features on the floor of all oceans. Increasingly, seamounts have become targets for commercial fishing, raising concerns over the impacts that this activity may be having on seamount ecosystems. Here, we review what is known about the non-fish components of seamount communities, and discuss their vulnerability to fishing impacts.

HOW MUCH IS KNOWN ABOUT SEAMOUNT INVERTEBRATES?

For this review, we bring together data from 171 seamounts to undertake the largest global synthesis of seamount invertebrate ecology to date. While many seamount studies have been conducted, most focus on a restricted seamount or small seamount group. Not since a paper by Wilson and Kaufmann (1987) has a global review of the data been conducted. In the 1987 review, data was reported on 596 species from 59 seamounts. In the intervening time, many new seamounts have been sampled and new discoveries, such as the observation of centuries-old deep-coral beds, have been made.

Here, data on 1971 invertebrate taxa from 171 seamounts are reviewed, giving a much expanded perspective of these unique habitats (Figure 1). The data are drawn from SeamountsOnline (see details in Stocks, this vol.), a publicly-accessible resource of seamounts information. The data compilation is a recent project and the combined results are published here for the first time.

It is true that, like all deep-sea habitats, seamounts remain understudied: perhaps only 3-4% have been sampled for invertebrates. And what sampling has been done is not necessarily representative: seamounts that are nearer to the water’s surface and/or closer to land tend to be sampled more than others. Some, seamounts, such those under the Arctic ice cap, are virtually unknown. This review will not be limited to seamounts following the strict definition of being at least 1000 m in height – this is an arbitrary geological definition, and features less than 1000m can have similar biological properties as taller ones (Probert et al., 1997; Koslow et al., 2001). Therefore, data from hills less than 1000m tall are also included here.

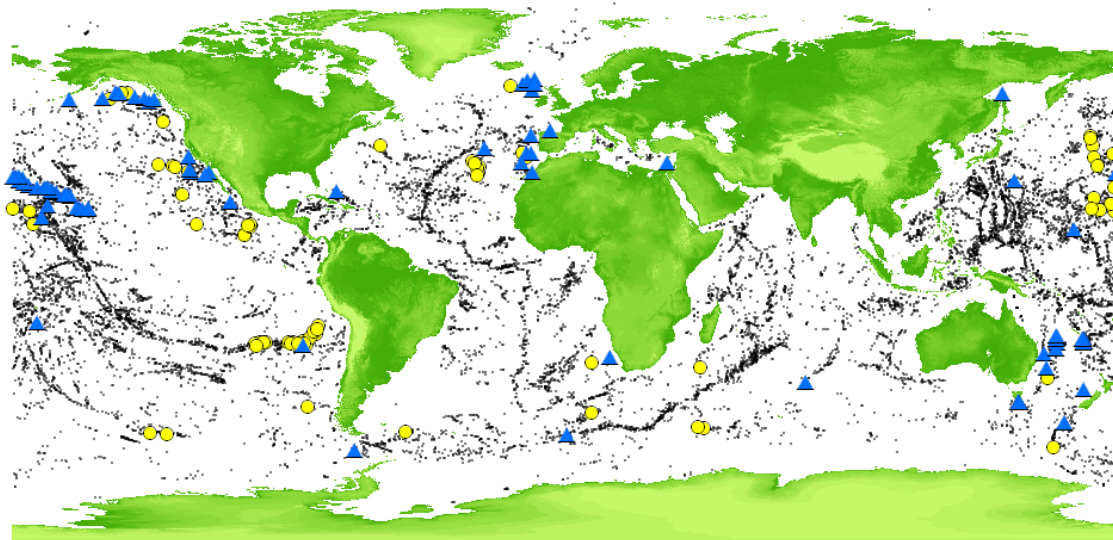


Figure 1. Locations of 171 seamounts for which SeamountsOnline has invertebrate data. Circles indicate seamounts outside any country's exclusive economic zone (EEZ). Triangles indicate seamounts within EEZs. Small dots indicate the predicted locations of the > 14,000 unsampled seamounts identified by Kitchingman and Lai (this vol.).

The data also have limitations because they were compiled from many different surveys with many different aims, instead of from a single, well-planned global sampling. Most importantly, these data should be considered 'presence only.' They indicate when a species has been recorded on a particular seamount, but the lack of a record does not necessarily indicate that the species does not occur on a seamount – the seamount may not have been sampled appropriately to find that species, even if present. Secondly, the majority of sampling done on seamount invertebrates has been through bottom trawls/dredges or visual/video observation by SCUBA diver, submersible, Remotely Operated Vehicle (ROVs), or towed video apparatus. These methods generally find the larger invertebrates, commonly called 'megafauna,' and those that live on or above the surface. Very small invertebrates, especially those that live buried in the sediment, and those that live in the water above seamounts are underrepresented and may be more common and widespread than this database indicates. This contribution is also restricted to multicellular invertebrates: fishes, other vertebrates, plants, and single-celled organisms are not considered. Finally, SeamountsOnline does not have data for every seamount that has been sampled – it is a work in progress, and much information remains to be entered.

Despite these cautions, the data in SeamountsOnline represents by far the most comprehensive summary of seamount invertebrate data that exists. Though this compilation of data, certain patterns have emerged from the sampling performed to date, and these are reported below. Care is taken to explain how sampling biases may have influenced results and which results are robust.

INVERTEBRATES ON SEAMOUNTS

Taxonomic Composition

To begin to understand the communities that live on seamounts, one can start by looking at the main groups of animals that are most common on seamounts. Table 1 summarizes the number of seamount from which each major taxonomic group has been recorded. The Crustacea is the group that has been recorded from the most seamounts (116). In part, their prevalence may be due to a sampling bias: crab and shrimp are of commercial importance and thus of particular interest in many surveys. Following the Crustacea are Anthozoa (corals and anemones), recorded from 84 seamounts. Also common (recorded on 30-45 seamounts) are gastropods, bivalves, echinoids (sea urchins), ophiuroids (brittle stars), asteroids (sea stars), polychaetes, and hexactinellids (glass and related sponges). Appendices 1a-d gives full lists of all the species recorded from each seamount. It is important to remember that these represent a minimal number of seamounts where these taxa occur, as some of the 171 seamounts have not been sampled appropriately to record a particular group even if it is present.

Table 1. Taxonomic groups recorded on seamounts. For each group, the number of seamounts from which it has been recorded is indicated. The database covers 171 seamounts: however not all seamounts have been sampled sufficiently to find every group. Therefore, the number of seamounts should be considered a minimal estimate. Note that the some records have been identified only to the phylum level, and so the number of seamounts for a given phylum (the ‘All’ category) can be larger than the sum of the groups within that phylum.

Phylum	Group	Seamounts #
Annelida	All	37
	Oligochaeta	2
	Polychaeta	37
Arthropoda	All	116
	Chelicerata	11
	Crustacea	116
	Malacostraca	2
Brachiopoda	All	20
	Articulata	17
	Inarticulata	4
Chaetognatha	All	3
Chordata	Tunicata (sea squirts)	7
Cnidaria	All	92
	Anthozoa (corals and anemones)	84
	Hydrozoa (hydroids)	23
	Scyphozoa (jellyfish)	8
Ctenophora	All	2
Echinodermata	All	74
	Asteroidea (sea stars)	38
	Crinoidea (feather stars)	22
	Echinoidea (sea urchins)	39
	Holothuroidea (sea cucumbers)	21
	Ophiuroidea (brittle stars)	38
Echiura	All	1
Ectoprocta	Bryozoa	14
Entoprocta	All	1
Loricifera	All	1
Mollusca	All	76
	Aplacophora	3
	Bivalvia	42
	Cephalopoda (squid and octopus)	26
	Gastropoda (snails)	43
	Polyplacophora (chitons)	12
	Scaphopoda (tusk shells)	12
Nemata (nematodes)	All	3
Porifera (sponges)	All	46
	Demospongiae	11
	Hexactinellida (glass sponges)	30
Sipuncula	All	6

This list is very different from what one would expect from a ‘normal’ deep sea habitat, such as the continental slopes and abyssal plains, highlighting even at a high taxonomic level the uniqueness of seamount communities. In general, species that feed on particles in the sediments (‘deposit feeders’) are most common in the deep sea (Gage and Tyler, 1991). Because these areas are far below the zone where light reaches and plants can grow, they feed on the gentle rain of particles, known as ‘marine snow,’ falling to the seafloor from shallower waters. Seamounts, in contrast, have many species that ‘filter feed’: they grab particles that are swept past them by currents. These include many of the corals, anemones, featherstars and sponges found on seamounts, as well as some of the sea stars and brittle stars that are

adapted to draping themselves on corals and sponges to filter-feed higher in the water. These species also make seamounts visually striking: seamounts have been likened to underwater gardens because of the branching, tree-like and flower-like corals and sponges that cover many of them.

The prevalence of these emergent filter-feeders is due to two related properties of seamounts. First, because of how water currents move around them, many seamounts are swept clean of sediment and have hard rocky or cobbled bottoms. This allows forms that need a firm anchor, such as sea fans and large corals, to settle and grow. In contrast, a large part of the deep sea is covered by fine sands, mud or clays, and is inhabited primarily by species that burrow in or crawl along the bottom (Gage and Tyler, 1991). Secondly, ocean currents sweep zooplankton-rich waters by many seamounts. Zooplanktons are small animals that live in the water column and are most dense at depths of ~1000m below the surface. Species that live on seamounts can feed off of this constantly-replenishing food resource, leading to a prevalence of filter-feeders. This phenomenon also produces extremely dense aggregations of life: supplemented by the 'conveyor belt' of zooplankton, many seamounts support a much larger total mass of life than other deep sea habitats. It is precisely this feature that leads to the high densities of commercial fishes on seamounts.

Endemism

One of the most exciting discoveries in biological oceanography in the last decade, and a cause of great scientific interest in seamounts, has been the documentation of high levels of endemism on some seamounts. Endemics are defined in this context as species that have been found on only one seamount or a restricted seamount chain and, to date, nowhere else in the oceans. Scientists say that seamounts have 'apparently' high rates of endemism because it is not possible to know the true rates of endemism until the full spatial range of every species is known. Logically, to know that a species is only found on one seamount, one would have to have looked for that species at all other locations in the oceans, which is clearly impossible. But while the true rates of endemism are not known, it is known that studies of many seamounts have found high proportions of species new to science and known from nowhere else. In 1987, a compilation of the accessible data from global seamounts found that 12-15% of all species recorded on seamounts were endemics. Since then, several major studies have found much higher rates. On the Norfolk Ridge and Lord Howe seamounts south of New Caledonia, 31-36% of species were endemic (Richer de Forges et al., 2000). On Tasmanian hills, rates of ~35% were found (Koslow et al., 2001). And in the Pacific off of Chile, the Nasca and Sala-y-Gomez seamount chains have endemism rates of 44% for fishes and 52% for bottom-living invertebrates – one out of every two invertebrate species found was new to science (Parin et al., 1997). These rates are higher, in fact, than those found at hydrothermal vents, one of the most isolated and unusual habitats in the ocean (Richer de Forges et al., 2000). These high rates are not universal, though. On the Great Meteor seamount in the North Atlantic, 9% of the fishes found were endemic (Fock et al., 2002), and on Hawaiian seamounts the rate is 'only' ~5% for fishes (Stocks, in press). However, taken together, recent work indicates that the 1987 estimate is likely too low. New species at some level have been found on almost every seamount sampled to date, and so most unsampled seamounts are likely to hold such discoveries. In some cases, these will be enormous pools of undiscovered diversity (over 250 new species were found on 5 seamounts of the Norfolk ridge alone – Richer de Forges et al., 2000), in other cases, more modest.

Growth Rates

Very recently, several researchers have independently discovered that some seamount species are among the longest-lived animals on earth. Beds of the deep coral *Lophelia* have been found on 7 seamounts in the North Atlantic. While *Lophelia* specimens from seamounts have not been aged, *Lophelia* colonies in other deep-sea habitats have been aged at 1000-6250 years old (Wilson, 1979). Individuals of *Primnoa*, a gorgonian found on a Northeast Atlantic seamount, have been aged in other areas at 300-500 years old (Risk et al., 2002). And on small seamounts off of New Caledonia, featherstars (crinoids) and bamboo corals that are several centuries old have been discovered (Richer de Forges, pers. comm.). Compared to these, land tortoises, often touted in the popular press and textbooks as the oldest living animals at ~170 years, remain youngsters.

To date, the growth rates or ages of only a few invertebrate species from seamounts are known, so it is not possible to say how prevalent extremely long life is. But, given the discoveries from a limited number of aging studies to date, it seems highly likely that there are other long-lived species yet to be discovered on seamounts.

Other Discoveries

While insufficient data exist to establish trends, several other biological oddities have been recorded on seamounts. The deepest known plant life, a macroalgae living below 200 m, was found on a seamount (Littler et al., 1985). ‘Living fossils’ – life forms thought extinct since the time of the dinosaurs, have been discovered on the seamounts off New Caledonia, raising the potential that seamounts act as refuges for species with shrinking ranges (Schlacher et al., 2003). Also, work on several seamounts has extended the known ranges of varying species, finding them far outside their previously described arenas. The fauna of the Nasca and Sala-y-Gomez seamounts chains close to Chile in the Southeast Pacific, for example, is far more closely related to the Indo-West Pacific fauna than to the Chilean coast species (Parin et al., 1997).

VULNERABILITY TO FISHING

Many of the ecological characteristics of seamount communities make them of high concern for careful management.

1. Taxa common on seamounts are especially vulnerable to trawling damage.

As discussed above, seamounts have a high proportion of ‘emergent’ epifauna – species such as corals, anemones, crinoids and sponges that grow up and out of the substrate. Studies in deep-sea habitats have consistently shown that these forms are likely to be heavily damaged by trawling. In one study led by Keith Probert, the invertebrate bycatch most often collected by commercial fishing gear on hills off New Zealand were corals – including horny corals (Gorgonacea), stony corals (Scleractinians) and black or thorny corals (Antipatharians) – followed by brittle stars (Ophiuroidea) and seastars (Asteroidea) (Probert et al., 1997). This is the only study that looked specifically at seamounts, but when trawls are conducted in other habitats with coral, coral pieces are common by-catch (Behnken, 1993a; 1993b; McAllister and Alfonso, 2001), indicating that the nets are causing heavy damage. A single pass of a trawl was found to damage 67% of vase sponges and 55% of sea whips in an experimental study off Alaska (Freese et al., 1999). A similar study by Van Dolah et al. (1987) found that trawling decreased the density of barrel sponges and caused visible damage to octocorals and hard corals. Trawl marks can be clearly seen in coral areas as parallel grooves of coral rubble (Roberts et al., 2000; Fosså et al., 2002), and the proportion of coral rubble is higher in trawled areas than untrawled areas (Hall-Spencer et al., 2002). On average, therefore, seamount communities are intrinsically more vulnerable to trawl damage than communities in the sand, mud and clay bottoms that cover the vast majority of the seafloor.

Damage to corals, sponges, anemones, etc., is of special concern because these species provide habitat for rich assemblages of other organisms. Studies have shown that gorgonians (sea fans) provide food, habitat, or shelter for a variety of crinoids, brittlestars, seastars, basketstars, anemones, molluscs, fishes, and crabs (Risk et al., 1998; Krieger and Wing, 2002). A study that examined stalks of glass sponges in one area found 139 associated species (Beaulieu, 2001) and 866 species have been recorded in association with *Lophelia pertusa* beds (Rogers, 1999). These structure-building species are the same species that are most damaged by trawling; damage to them will likely cause a cascade of disturbance effects throughout the associated communities.

2. Highly endemic species, which appear to be common on seamounts, will be at increased risk of extinction following disturbance.

From a population perspective, species with a small total number of individual, or a very localized spatial range, are expected to be at higher risk of extinction after a disturbance. Logically, taking 1000 individuals from a population of one million creates little risk of extinction, whereas taking 1000 individual from a population of 1200 may be devastating. As discussed earlier, the true ranges of most marine species are not known because the oceans are undersampled. But, within this uncertainty, rates of endemism appear to be high on seamounts. One study of seamounts off New Caledonia found that adjacent seamounts on a chain had only 21% of species in common, and that seamounts in chains separated by 1000 km shared just 4% of their species (Richer de Forges et al., 2000). This raises the concern that there are species whose entire range may be a single seamount, making them extremely vulnerable to extinction.

3. Slow growing seamount species will have very long recovery times.

Seamount species have been found that live for hundreds of years – there are invertebrates on seamounts that were alive during the American Revolution, probably during the Roman Empire, and perhaps when the great pyramids in Egypt were raised. A species that takes centuries to grow will take centuries to recover from damage, making trawling in these areas comparable to losing an old growth forest.

A direct study of trawling impacts on seamounts

Very little research has been done that directly assesses the impacts of fishing activities on seamount ecosystems – this information vacuum is the reality within which seamount management and policy must operate, and is the reason why we discuss above the characteristics of seamount species that make them more or less likely to be impacted. The author knows of only one study that examined the effects of fishing on seamounts by comparing fished and unfished seamounts. In 1997, Anthony Koslow led a team of researchers on an expedition to a cluster of hills off southern Tasmania (Koslow and Gowlett-Holmes, 1998; Koslow et al., 2001). This area is unique in the world in that it includes a marine protected area where trawling is banned and an adjacent unprotected fishing ground, so it offered the opportunity to compare fished and unfished seamounts. They found that, based on the fauna, the hills separated into three groups: fished (shallow) seamounts, unfished seamounts <1400m deep dominated by hard, ‘reef building’ corals, and unfished seamounts >1400 m deep where hard corals did not grow, likely because of natural limits to their depth range. Leaving aside the deepest hills without corals, Koslow et al. (2001) found that unfished hills, in comparison with fished hills, had:

- 7.2 times higher total biomass; and
- 106% more species.

The major limitation of this study is that the unfished seamounts had deeper summits than the fished seamounts. Can the observed differences still be attributed to fishing, or might they have been caused by different communities naturally occurring at different depths? Koslow et al. (2001) outline several reasons why they think it likely that the observed differences were due to fishing. First, there is no reason to assume that the hard corals could not live on the shallow seamounts. These hills are within the known depth range of the main hard coral species found, *Solenosmilia variabilis*, and supported other species that are often found in similar environments as hard corals (gorgonians, bryozoans, and solitary, non-reef-building corals). Second, fishers on the seamounts reported catching large amounts of coral in their nets in the early years of their fishery on the hills. Third, the bottoms of the fished seamounts were made up of coral rubble and coral sands, which may indicate the remains of past coral disturbance. Finally, one sample was recovered from near the base of a heavily-fished hill that had coral and other species similar to the unfished hills. It is difficult to trawl near the deep base of a seamount, so this may represent an unfished, ‘natural’ community, and indicate that these species used to live on this fished hill. In conclusion, the Koslow study presents evidence that is strongly suggestive of how severe trawling impacts on seamount communities are.

CONSERVATION PERSPECTIVES

It is well known that commercial fishing pressure on seamounts is high. The section above outlines the likelihood that trawling causes severe and long-lasting damage to seamount communities and potentially species extinctions. Why is this of concern? Why are seamount habitats worth conservation, and what would really be lost if these communities were lost or severely degraded?

Scientific progress

One of the reasons that scientists have devoted so much effort to studying seamounts is because of what they can teach us about the patterns of life in the oceans in general. Why do seamounts support so many endemic species – what is it about these areas that produce, or retain, more new species? The fundamental processes that promote and maintain diversity in the oceans are not well understood, and seamounts offer case studies for addressing questions with larger implications. Only on seamounts not heavily impacted by fishing can we attempt to relate the natural rates of endemism and speciation to natural characteristics of the seamount.

Pharmaceuticals

The overwhelming majority of medicines are found in nature, and many are now coming from the oceans. For example, sponges have produced more patented, medically-related compounds than any other terrestrial or marine phylum, and have been particularly important for the discovery of anti-tumor agents (Kerr and Kerr, 1999). Seamounts, which have high numbers of unique species in general and sponges in particular, are likely to house unusual compounds that may prove important to human medicine.

Importance to Oceanic Communities and Biodiversity

It has been suggested that seamounts act as centres of speciation in the oceans, as refugia for relict populations with shrinking ranges, or as stepping-stones for trans-oceanic dispersal. How important their role is in larger-scale patterns of biodiversity in the ocean is not currently understood, but there is the potential that impacts on seamounts may also impact connected ecosystems. Furthermore, we know that migratory species such as tuna, marine mammals and seabirds congregate over seamounts (Hui, 1985; Blaber, 1986; Haney et al., 1995), implying that they can have a particular importance for species with much larger ranges.

Tomorrow's discovery

Perhaps the factor that makes seamounts most valuable for conservation is what may be discovered tomorrow. Just 3-4% of the world's seamounts have been sampled, and we have already discovered living fossils, the deepest known plant, some of the oldest animal species on earth, and hundreds of new species. What discoveries await on the other 96%?

APPENDICES

Data on invertebrates collected from seamounts globally were compiled from literature publications and electronic datasets provided by researchers and institutions working on seamounts:

1. Data in invertebrates collected from seamounts globally:
 - 1a. List of species from seamounts - ordered by species;
 - 1b. List of species from seamounts - ordered by seamount;
 - 1c. Bibliography of data sources cited in appendices 1a and 1b;
 - 1d. Distribution maps for seamount invertebrates given in appendices 1a and 1b.

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TAXONOMY AND BIOLOGY OF SEAMOUNT FISHES

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ABSTRACT

This study presents a preliminary annotated checklist, a preliminary bibliography, and an analysis of current knowledge of seamount fishes. Based on surveys carried out on sixty seamounts 535 species in 130 Families, 29 Orders and 4 Classes are recognized as seamount fishes. Sufficient information for sustainable management such as growth, maturity, fecundity, and diet is available for only 12 (2%) of the species. Yet 151 (28%) of the species are known to be exploited commercially. Most of the species for which data are available are of low or very low productivity and resilience to exploitation. Fitness strategies of seamount fishes are discussed and compared. The number of species in each ecological niche is low on seamounts signifying vulnerability at the ecosystem level. Of the six seamount fishes evaluated for the purposes of the 2000 IUCN Red List, one was critically endangered, two were vulnerable and three were of lower risk, near-threatened, while other seamount fishes have not yet been assessed. In this study, 62 (12%) seamount fish species are reported from only one seamount, suggesting a high rate of endemism.

WHAT ARE SEAMOUNT FISHES?

Seamounts are typically defined as mountains that rise at least 1000 m from the abyssal floor of the ocean in about 4000 m depth but do not reach the surface (see Kitchingman and Lai, this vol.). Seamount fishes thus are mostly deep-sea fishes with occasional visitors from the epipelagic realm or from the continental shelf or slope. Several seamounts reach within less than 100 m off the surface and their tops are inhabited by coral reefs and associated species typical of coastal areas or oceanic islands. Distinguishing ‘true’ seamount fishes that depend on seamounts as preferred habitat or major feeding or spawning grounds from those that inhabit only the upper zone of shallow seamounts or are opportunistic visitors is the first problem that must be resolved when attempting to review our knowledge of seamount fishes. Here, we have taken a pragmatic approach, marking as ‘strays’ those fishes that have a depth range not exceeding 150 m or that typically close their life-cycles in coastal waters without apparent dependence on seamounts, such as butterfly fishes or surgeon fishes.

HOW MANY SEAMOUNT FISHES ARE THERE?

Deep-sea fishes are often considered to consist of species living below 1000 m, but Weitzman (1997) extended this definition to include species occurring between 500 and 1000 m. He also provided an account of deep-sea fish Orders and Families, albeit without an attempt to estimate their numbers. According to Helfman et al. (1997) "more than 1000 species inhabit the open waters of the deep sea and another 1000 species are benthic". FishBase (Froese and Pauly, 2004) lists 1276 fishes as bathypelagic and 2103 as bathydemersal. Also, only few seamounts have been sampled so far (Stocks, this vol.) and data from only 60 seamounts are used in this study. Thus, the attached preliminary annotated checklist of seamount fishes (Appendix 1) with currently 535 species—although it represents the most comprehensive checklist to-date—is incomplete. We expect the total number to be close to 1000 species. A preliminary list of seamount fishes with localities (Appendix 2), by seamount (Appendix 3), and a list of commercially important seamount fishes (Appendix 4) are also presented, along with a list of references supporting those lists (Appendix 5 and 6).

Of the currently recognized seamount fishes 365 demersal or benthopelagic species live and feed on or close to the bottom whereas 170 pelagic species live and feed in the water column above and around the seamounts.

HOW IMPORTANT IS BIODIVERSITY OF SEAMOUNT FISHES?

The current 535 species of seamount fishes represent only about 2% of the over 28,400 recent fish species on earth. However, seamount fishes belong to 130 (25%) of 515 Families and 29 (47%) of 62 Orders and thus are mostly not closely related to each other, i.e., their genetic diversity is higher than suggested by the low number of species. Many seamount Families are small, with 13 Families consisting only of seamount species and 12 Families with half or more of the members living on seamounts. According to Marshall (1979) and Haedrich (1997), deep-sea fishes tend to be representatives of groups that appeared rather early in the evolution of modern fishes. However, many of them are highly derived and adapted to the particular environment and ecological conditions of the deep sea, such as specialized eyes, highly complex bioluminescent organs, elaborate gas glands and swim bladder constructions, and often remarkable jaws and teeth. Some fish synthesize potentially interesting organic compounds: for example, the luminescent excretion of the Softhead grenadier *Malacocephalus laevis*, which has been used to enhance (= 'lighten') baits used for cod fishing (Cohen et al., 1990). The fauna has persisted over very long time spans and has resisted competitive invasion from more recently evolved and less adapted forms such as the spiny-rayed (perciform) fishes which usually dominate the fish fauna of shallower waters (Marshall, 1979): only 109 (20%) of the listed seamount fishes are perciforms, compared to 35% perciforms in all fishes. Thus, although the number of known seamount fishes is comparatively small, because they encompass a quarter of fish Families, about half of the Orders and many unique adaptations, they represent a relatively large and unique portion of fish biodiversity.

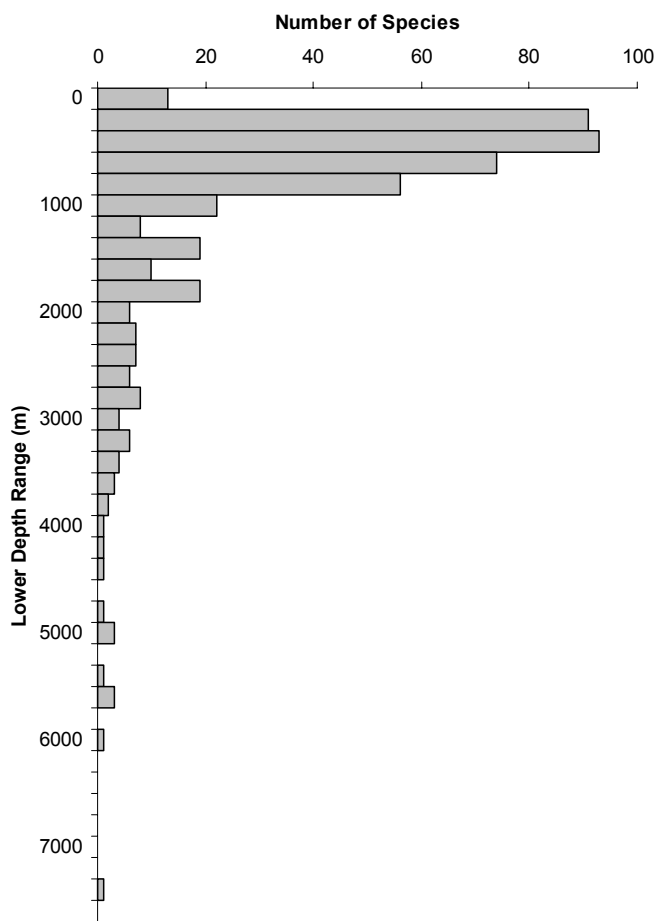


Figure 1. Number of seamount fishes (total = 470) by lower depth range.

HOW DEEP CAN YOU GO?

Depths reported for deep-sea organisms have to be treated as approximations. First of all, the sampling effort has mostly been inadequate and many species are likely to be found outside their current depth ranges in the future. Also, sampling is often done with open nets and thus an occurrence record with a depth range of 1000-3000 m does not mean that the species occupies this range, but rather that it has been captured somewhere in between, resulting in a maximum depth of 'at least 1000 m.' Figure 1 shows the number of species (with know depth distribution) by lower end of their depth range. Below 1000 m zooplankton and thus plankton feeders become scarce, leading to a marked drop in species numbers. Below 3000 m food in general becomes scarce and thus species numbers drop of again. Generally, numbers of species decline with depth and the shape of this decline is likely to be exponential as shown in Figure 1. Thus, the low and uneven shape of the curve below 1000 m is likely to be caused by under-sampling. Or to use a metaphor: the seamount fishes that we know, and thus much of our knowledge of seamount ecosystems, are only the tip of an iceberg.

KNOWLEDGE ABOUT SEAMOUNT FISHES

Many seamount fishes (26%) have been discovered and described only within the last 50 years, mostly by Russian workers such as N.V. Parin (first- or co-author of 39 recent descriptions). If taxonomic surveys of seamounts were to be increased, many new and undescribed species would likely be found.

The biology of most seamount fishes is poorly known, often only assumed from the morphology of the type specimens. Sustainable management of fish stocks requires information on how fast any extracted biomass is replenished. More particularly, data on body growth, length-weight relationships, mean age at maturity, fecundity and natural mortality are needed for stock assessment and management. In the context of ecosystem management additional data on trophic relationships, i.e., food items, diet composition and common predators are needed. Table 1 summarizes existing knowledge. A comprehensive suite is known for only twelve seamount fish species. Despite this lack of information needed for sustainable use, 151 seamount fishes are known to be exploited commercially.

HOW RESILIENT ARE SEAMOUNT FISHES TO EXPLOITATION?

Musick (1999) studied the vulnerability of fishes to extinction. He devised a scheme (Table 2) to assign species to productivity or resilience categories based on available knowledge. The first row in Table 2 gives the vulnerability threshold: if an observed decline measured in biomass or numbers of mature individuals over the longer of 10 years or three generations exceeds the indicated threshold value, the population or species is considered vulnerable to extinction unless explicitly shown otherwise. For example, if the biomass of a seamount fish with very low resilience has been reduced by 70% during the past 10 years, then it is considered vulnerable to extinction; unfortunately, biomass estimates are not available for most seamount fishes. The second row in Table 2 gives the maximum intrinsic rate of population increase (r_{max}), which is difficult to estimate and thus rarely available in fishes, and which is provided here as an output indicating the numerical range of the resilience categories. The minimum time (t_d) a population needs at low density to double in numbers is calculated as t_d (years) = $\ln(2) / r_{max}$ in the third row. The more familiar concept of the interest rate earned on capital is calculated as I (%) = $100 * (e^{r_{max}} - 1)$. Other parameters are defined in the caption of Table 2. The assignment is to the lowest resilience category fitting available data.

Table 2. Ranges of key traits of fishes used to assign species to resilience categories, where vulnerability threshold is as explained in the text, r_{max} is the maximum intrinsic rate of population increase, t_d is the minimum population doubling time in numbers corresponding to r_{max} ; interest rate is the maximum annual interest gained if the population were capital; K is the von Bertalanffy growth parameter; T_m is age at first maturity, and T_{max} is maximum age.

Parameter (unit)	High	Medium	Low	Very low
Vulnerability threshold	0.99	0.95	0.85	0.70
r_{max} (1/year)	> 0.5	0.16 – 0.50	0.05 – 0.15	< 0.05
t_d (years)	<1.4	1.4 – 4.4	4.5 – 14	> 14
Interest rate (%)	> 65	17 – 65	5 – 16	< 5
K (1/year)	> 0.3	0.16 – 0.30	0.05 – 0.15	< 0.05
Fecundity (1/year)	> 10,000	100 – 1000	10 – 100	< 10
T_m (years)	< 1	2 – 4	5 – 10	> 10
T_{max} (years)	1 – 3	4 – 10	11 – 30	> 30

Table 1. Knowledge about seamount fishes presented as number of records in FishBase (as of 03/2004) and number and percentage of species for which information is available.

Topic	Records	Species	Percent
Growth	328	70	13.1
Length Weight	286	109	20.4
Reproduction	126	126	23.6
Maturity	223	93	17.4
Fecundity	42	36	6.7
Natural mortality	51	46	8.6
Food items	1834	236	44.1
Diet composition	238	83	15.5
Predators	330	107	20.0
Commercial	-	151	28.2

Data for at least one of the parameters in Table 2 are available for only 76 seamount species, resulting in 5 (6.6%) species with High, 32 (42%) with Medium, 20 (26%) with Low and 19 (25%) with Very low resilience or productivity. This result may overestimate resilience of seamount fishes because usually it is the 'shallower' and thus 'warmer' species with presumably faster growth and life cycles, for which data are available. In other words, we can expect the percentage of species with low and very low resilience to increase with more knowledge about the 'deeper' seamount fishes because "biochemically, rates of enzymatic and metabolic activity and even levels of ATP-generating enzymes are lower in deep-sea fishes than in shallow-water relatives" (Helfman et al., 1997; p. 301). Also, annual fecundity is often not known and could reduce resilience to Low if < 100 and to Very low if < 10 , as can be assumed to be the case in all sharks, rays and chimaeras and all other live-bearers. Some of the few available growth studies on deep-sea fish suggest very fast growth based on the assumption that the few rings found in otoliths are annual; however, independent verification is lacking and this assumption could be erroneous. In contrast, some of the oldest known fishes occur on seamounts, such as the Yelloweye rockfish (*Sebastes ruberrimus*) with 118 years or the Sablefish (*Anoploma fimbria*) with 114 years.

It should be noted that sustainable exploitation of species with low or very low resilience makes little economic sense. Economically, it is more profitable to catch and sell all of the stock and then move on to exploit other resources, with devastating effects on seamount biodiversity. Unfortunately, this appears to be the pattern adopted by many seamount fisheries (See Watson and Morato, this vol.).

WHAT ARE THE FITNESS STRATEGIES OF SEAMOUNT FISHES?

Evolution favours the traits of those individuals, that under given circumstances, produce the highest number of reproductively successful individuals. To produce successful offspring individuals, have to avoid mortality, feed and grow to reach maturity, mate with best matching partners, and maximize chances of survival for their offspring. Fitness strategies thus have to balance various traits related to predator avoidance, position in the food web, mating success, number of offspring and parental care, if any. Individuals inherit a specific fitness strategy depending on the place of their species in the phylogenetic hierarchy of fishes. For the purpose of this study, we define fitness strategies as combinations of three traits that impact on the above themes and that are highly correlated with other traits and thus can serve as proxies. For these types of analyses to be conducted, information on these traits needs to be available for a high number of species across all phylogenetic groups. The traits selected here were size, trophic level and resilience. To include more species in this exercise we made assumptions about trophic level and productivity for species with no data, based on information available for other members of the same genus or family, resulting in 468 species included in Table 3. As discussed above, this procedure may be biased towards higher resilience categories, i.e., if more data become available a number of species that are now classified as Medium or High are likely to be transferred to lower categories.

The trophic levels utilized by seamount fishes are restricted to low-level predators which feed mostly on zooplankton or benthic invertebrates and to high level predators which feed mostly on other fish. No herbivore or omnivore fishes occur on seamounts. This confirms the observation by Helfman et al. (1997) that "All deep-sea fishes are carnivores...", as can be expected given that seamounts typically do not reach into the zone where plants can grow. Seamount fishes cover the whole range from very low to high resilience and from small to very large sizes.

There are 64 theoretically possible fitness strategies as combinations of the traits mentioned above. Seamount fishes make use of only 16 strategies (Table 3): hagfishes are large high-level predators of low resilience; chimaeras are large low- and high-level predators of low resilience; most (57%) sharks and rays are large high-level predators of low or very low resilience; ray-finned fishes are mostly (62%) medium-sized low- or high-level predators of medium or low resilience. The number of families per fitness strategy increases with the number of respective species, i.e., there is no evidence that species of a certain strategy tend to belong to the same Family.

Two Classes of recent fishes are missing from seamounts: Cephalaspidomorpha (lampreys) are mostly confined to freshwater or are anadromous; they are not known to occur in the deep-sea and thus are not expected to occur on seamounts. Of the Sarcopterygii (lobe-finned fishes), coelacanths occur in deep water and may be found on seamounts in the future.

Table 1. Fitness strategies of seamount fishes. Low-level predators have trophic levels between 2.75 and 3.75; High-level predators have trophic levels higher than 3.75; resilience scores were assigned according to Table 2; length groups were assigned in total length on a logarithmic scale, with Small < 7cm, Medium = 7-45 cm, Large >45 – 300 cm, and Very large > 300 cm; the number of species adopting a certain fitness strategy and the percentage within the respective Class is given, as well as the number of Families to which these species belong.

Class	Trophic group	Resilience	Length group	Species n (%)	Families n	
Myxini (hagfishes)	High-level pred.	Low	Large	2 (100.0)	1	
Holocephali (chimaeras)	Low-level pred.	Low	Large	3 (75.0)	1	
	High-level pred.	Low	Large	1 (25.0)	1	
Elasmobranchii (sharks and rays)	Low-level pred.	Low	Medium	1 (2.9)	1	
			Large	4 (11.4)	2	
	High-level pred.	Very low	Large	2 (5.7)	1	
			Medium	3 (8.6)	1	
			Large	10 (28.6)	4	
		Very low	Large	10 (28.6)	6	
			Very large	2 (5.7)	2	
			Very large	3 (8.6)	3	
	Actinopterygii (ray-finned fishes)	Low-level pred.	High	Small	5 (1.2)	3
				Medium	10 (2.3)	4
Medium				7 (1.6)	4	
Medium				160 (37.5)	45	
Low			Large	17 (4.0)	11	
			Small	1 (0.2)	1	
			Medium	49 (11.5)	17	
			Large	42 (9.8)	20	
High-level pred.		Very low	Large	7 (1.6)	5	
			Medium	43 (10.1)	24	
		Low	Large	26 (6.1)	15	
			Medium	10 (2.3)	7	
			Large	34 (8.0)	23	
			Very low	Large	16 (3.7)	10

If we consider the 16 fitness strategies as evolutionary responses to niches being available at the seamount ecosystem, then it is striking that, across seamounts 6 (38%) such niches are occupied by fewer than 10 species each, and probably less at any particular seamount. Given that we have no knowledge about relative niche importance for the overall functioning of the seamount ecosystem, such lack of redundancy in ecological roles should be taken as a sign of potential ecosystem vulnerability.

Table 4 provides a comparison of fitness strategies at the Class level. Ray-finned fishes are the most numerous group, making use of 14 out of 16 strategies, including 8 strategies without competition from other Classes. Sharks and rays make use of 8 strategies, including two strategies (very large high-level predators of low or very low resilience) without competition from ray-finned fishes. Chimaeras use only two strategies which they share with the other classes. The two species of hagfishes so far found in the upper region of seamounts use only one strategy. Thus, while the strategy of medium sized low-level predators of medium resilience has the highest diversity at the species level, large high-level predators of low resilience have the highest diversity at the Class level.

Table 2. Fitness strategies of seamount fishes by Class. Actino = ray-finned fishes, Elasm = sharks and rays, Holo = chimaeras, and Myxini = hagfishes.

Trophic group	Resilience	Length group	Actino	Elasmo	Holo	Myxini	Species
Low-level pred.	Very low	Large	7	2			9
		Small	1				1
	Medium	Medium	49	1			50
		Large	42	4	3		49
		Small	7				7
		Medium	160				160
		Large	17				17
		Small	5				5
	High	Medium	10				10
		Large	16	10			26
High-level pred.	Very low	Very large		3			3
		Medium	10	3			13
	Low	Large	34	10	1	2	47
		Very large		2			2
	Medium	Medium	43				43
		Large	26				26

DOES SIZE MATTER?

Maximum length of seamount fishes ranges from about 3.7 cm in Garrick (*Cyclothone braueri*) to about 480 cm in the Bluntnose sixgill shark (*Hexanchus griseus*). Most seamount fishes have total lengths between 10 and 100 cm (Figure 2). Interestingly, size ranges appear to decline with depth. Also, sharks, rays, chimaeras and hagfishes all of which are of low or very low resilience, appear to be restricted to depths above 2500 m, i.e., the area where most fishing occurs.

ENDEMISM OF SEAMOUNT FISHES

The data used in this study are ‘presence’ data in the sense that they provide evidence when and where a species has been found on seamounts. Absence of evidence for a species does not necessarily mean its absence, especially when only a few seamounts have been sampled and not all surveys are included in this study. With this restriction in mind, we refrained from classifying fishes as endemic to certain seamounts pending analysis of more data. Currently 62 (12%) species are reported from only one seamount in one subsection (FAO area) of the world ocean. This compares to reports in the literature of 44% endemic fishes on the Nasca and Sala-y-Gomez seamount chain (Parin et al., 1997), 9% on the Great Meteor seamount (Fock et al., 2002) and 5% on the Hawaiian seamounts (Stocks, in press).

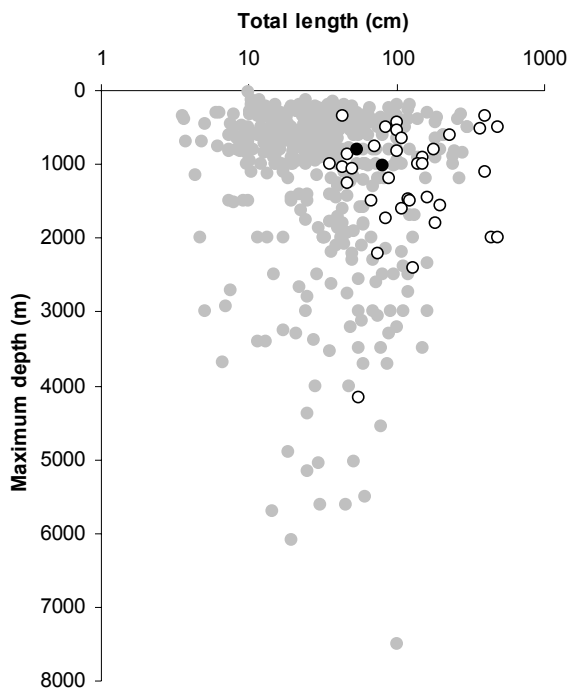


Figure 2. Size and depth distribution of seamount fishes. Grey dots are ray-finned fishes, black dots are hagfishes and circles are chimaeras, sharks and rays.

SEAMOUNT FISHES IN THE IUCN RED LIST

Only 6 seamount fishes are included in the 2000 IUCN Red List (Hilton-Taylor, 2000): *Sebastes paucipinis* is listed as 'critically endangered', *Sphoeroides pachygaster* and *Hexanchus griseus* are listed as 'vulnerable', and *Squalus acanthias*, *Dalatias licha* and *Prionace glauca* are listed as 'lower risk, near threatened.' Other seamount fishes have not been evaluated so far.

APPENDICES

The data and studies on which this analysis of seamount fishes is based are presented in the following Appendices:

1. Preliminary annotated checklist of seamount fishes;
2. Preliminary list of seamount fishes with reported seamounts;
3. Preliminary checklist of fishes by seamount;
4. Preliminary list of commercially important seamount fishes;
5. Reference numbers with citations;
6. Preliminary bibliography of seamount fishes.

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A FUZZY LOGIC EXPERT SYSTEM FOR ESTIMATING THE INTRINSIC EXTINCTION VULNERABILITIES OF SEAMOUNT FISHES TO FISHING

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ABSTRACT

Fishing has become a major conservation threat to marine fishes. Effective conservation of threatened species requires timely identification of vulnerable species. However, evaluation of extinction risk using conventional methods is difficult for the majority of fish species as the population data normally required by such methods are unavailable. This paper presents a fuzzy expert system that integrates life history and ecological characteristics of marine fishes to estimate vulnerability to fishing. We extract heuristic rules describing the known relationship between biological characteristics and vulnerability of marine fishes from published literature. The rules consist of the conclusions from one or more conditions connected by IF-THEN clauses. Input and output variables are defined by fuzzy sets which deals explicitly with the uncertainty associated with knowledge framed in qualitative terms. Conclusions inferred from input parameters are combined through fuzzy inference and defuzzification processes. Our fuzzy system provides vulnerability estimates that correlate with observed declines more closely than existing alternatives. The system has advantages in flexibility of input data requirements, in explicit representation of uncertainty and in high adaptability to new knowledge. This fuzzy expert system can be used as a decision support tool in fishery management and marine conservation planning.

INTRODUCTION

Increasing evidence indicates that marine species may be put under threat of local, and ultimately, global, extinction by the direct or indirect effects of fishing (Roberts and Hawkins, 1999; Reynolds et al., 2002; Dulvy et al., 2003). Commercially important species can be fished down to a vulnerable level because of their economic value, e.g. Chinese Bahaba (*Bahaba taipingensis*, Sciaenidae) (Sadovy and Cheung, 2003), Southern Bluefin tuna (*Thunnus maccoyii*, Scombridae) (Hayes, 1997). However, species with little or no commercial value are not safe from the threats of fishing. Non-targeted species may be threatened through bycatch (e.g. common skate, *Raja batis*, Rajiidae, Brander, 1981; barndoor skate, *Raja laevis*, Rajiidae, Casey and Myers, 1998). Moreover, fishing activities can create large disturbance and damages to benthic habitats (Jennings et al., 2001; Kaiser et al., 2002; 2003). Declines and extinctions can be associated with loss of essential habitat critical to complete the life cycle of the species (McDowall, 1992; Watling and Norse, 1998). Furthermore, experience from now extinct marine species suggests long delay in reporting marine extinction, also the ability to detect extinction is poor even on a local scale (Dulvy et al., 2003). Given the overexploited status of most fishery resources in the world (Pitcher, 2001a; Pauly et al., 2002; Hilborn et al., 2003), timely identification of species or populations that are vulnerable to extinction is urgently needed so that appropriate counter-measures can be formulated and implemented (Jennings et al., 1999a).

Owing to lack of data, conventional assessments of extinction vulnerability, which involve understanding of population dynamics, impose strong limitations to rapid assessment of marine fish species. Currently, the required population parameters can be estimated only for a small number of marine fishes, mainly commercially targeted species in developed countries. At the same time, quantitative data on fisheries and population status of exploited species are costly to collect (Reynolds et al., 2002; Dulvy et al., 2003). Moreover, the intrinsic rate of increase r , a population parameter that is key to conventional assessment, is particularly difficult to estimate reliably (Musick, 1999; Reynold et al., 2002; Dulvy et al., 2003).

LIFE HISTORY AND ECOLOGICAL CHARACTERISTICS AS A PROXY FOR EXTINCTION VULNERABILITY

Using life-history traits as ‘rule-of-thumb’ proxies to evaluate the intrinsic vulnerability of marine fishes to fishing has been suggested by Jennings et al. (1998, 1999a, 1999b) and Reynolds et al. (2002), given that responses of fish populations to exploitation are, at least in part, determined by life history characteristics (Adams, 1980; Roff, 1984; Kirkwood et al., 1994). Here, intrinsic vulnerability is defined as the relative extinction risk resulting from fishing, disregarding other factors, such as, e.g., pollution or coastal developments. Significant correlations have been empirically demonstrated between selected life history parameters and proxies for extinction vulnerabilities, e.g., historical population trends and recruits-per-spawner at low spawner abundance (Jennings et al., 1999a; 1999b; Denney et al., 2002). The American Fisheries Society (AFS) has adopted a scheme to identify the productivity (essentially the inverse of vulnerability) of fishes, incorporating life history characteristics such as intrinsic rate of population increase, longevity, age at first maturity, fecundity and the von Bertalanffy growth parameter K (Musick, 1999). The productivity estimates are then used to determine threshold population levels for extinction risk (Musick, 1999; Musick et al., 2000; Froese and Sampang, this vol.). Generally, species with larger body size (maximum body length or asymptotic length), higher longevity, higher age at maturity, and lower growth rate are suggested to have higher vulnerability to extinction (Smith et al., 1998; Jennings et al., 1999a; 1999b; Dulvy and Reynolds, 2002; Denney et al., 2002).

Certain ecological characteristics may also contribute to an increased vulnerability to fishing. Species forming large aggregations can be easily targeted by fishers and aggregative or shoaling behaviour often results in hyperstability of catch-per-unit-effort (CPUE), which masks the depletion of populations (Hilborn and Walters, 1992; Pitcher, 1995; 1997; Walters, 2003). Moreover, hyperstability of CPUE implies that economic incentives to fish can be sustained under low resource abundance (Hutchings, 1996) and as a result, bionomic equilibrium may not be reached until populations are depleted to a dangerously low level (Hilborn and Walters, 1992; Mackinson et al., 1997). In particular, species which form spatially and temporally predictable spawning aggregations are especially vulnerable. Depletion of these spawning aggregations may permanently prevent reproduction in these populations (Dulvy et al., 2003).

Assuming that specific life history and ecological traits can contribute concurrently to increasing vulnerability of marine fishes to exploitation, an indicator combining these traits should be useful in comparing vulnerability across species. Such indicator would be particularly useful for exploited fish assemblages where data are generally limited. For instance, knowledge on the biology and population dynamics of seamount fishes is generally limited (Froese and Sampang, this vol.) However, seamounts are being targeted by fishing (Watson and Morato, this vol.). Thus, an *a priori* understanding on the relative vulnerability of seamount-associated fishes would be useful when formulating conservation and management strategies. However, life history and ecological characteristics affect extinction vulnerability in complex, non-linear ways. Moreover, information for the majority of species is incomplete. Therefore, it is difficult to establish an index of extinction vulnerability from a wide range of life history and ecological characteristics using conventional parametric techniques such as linear regression.

FUZZY SET THEORY AND FUZZY LOGIC

We propose that the application of fuzzy set theory and fuzzy logic should be useful in deriving an index of extinction vulnerability that combines different life history and ecological characteristics. Fuzzy set theory was originally developed by Zadeh (1965) to represent how a domain can associate with a fuzzy set through a gradation of membership, instead of classifying them as either ‘true’ or ‘false’, as in conventional Boolean (‘crisp’) sets. At the same time, fuzzy logic also allows conclusions to be reached from premises with a gradation of truth. The memberships of a domain to one or more sets are defined by fuzzy membership functions (Figure 1).

The explicit use of vagueness in fuzzy sets is very useful for handling the uncertainty inherent to extinction vulnerability (Akçakaya et al., 2000). For example, we know that large fish tend to be associated with higher extinction vulnerability. However, it is difficult to provide a clear cut definition of what a ‘large fish’ is, i.e., to separate large and small body size, and thus high and low extinction vulnerability. Moreover, other characteristics may give the fish a low vulnerability, despite its size. On the other hand, fuzzy sets allow a fish to be defined as partly large and partly small, the parts being associated with a gradation of membership to each set, or category. They also allow a fish to be classified by multiple categories of vulnerability, with different degree of membership based on its different characteristics. Fuzzy logic been

used in fisheries science (Saila, 1996), with applications ranging from stock-recruitment relationships (Mackinson et al., 1999; Chen, 2001), to predicting fish shoaling behaviour (Mackinson, 2000) and identifying sub-stocks of fish (Zhang, 1994). It has also been used to assist the IUCN Red List's species assessment (Akcakaya et al., 2000). Tinch (2000) also proposed the use of fuzzy logic to assess extinction risks of different Pacific salmon stocks.

A fuzzy knowledge-based (= 'expert') system, designed to mimic how expert solve problems, is based on heuristic rules that describe the available expert knowledge, here on how different life history and ecological characteristics can be combined to estimate extinction vulnerability. The heuristic rules summarizing the available expert knowledge take the IF-THEN form:

IF A THEN B

where A is the premise while B is the conclusion which may lead to an object, events or other rules (Kasabov, 1996). In this study, the knowledge base consists of the various known relationships linking extinction vulnerability with life history and ecological characteristics of fishes. Following the above example on fish's body length, the rules would be:

IF fish's maximum body length is *large* THEN extinction vulnerability is *high*

IF fish's maximum body length is *medium* THEN extinction vulnerability is *moderate*

where *large* and *medium* are fuzzy sets of maximum body length and *high* and *moderate* are fuzzy sets of extinction vulnerability.

In some cases, the IF statement includes two premises connected by 'AND' or 'OR' operators. The 'AND' or 'OR' operators are defined mathematically by the MIN-MAX rule (Zadeh, 1965). When two or more conditions are connected by 'AND' operator, the membership of the combined premise is the minimum of the membership of all the conditions. On the other hand, when the premise is composed of conditions connected by 'OR' operator, the maximum membership among all the conditions is taken (Zadeh, 1965).

The actions defined by the rules are fired when the membership on the premises exceed certain trigger values. The trigger values are subjective criteria which define the minimum required membership assumed for an expert to require for that particular rule to be fired. Conflicting rules are allowed to fire jointly. For example, if a particular fish species is both large and medium with different memberships exceeding the trigger values, then both rules will be fired.

In this paper, we aim to develop an index of the intrinsic vulnerability of marine fishes based on published relationships between life history and ecological characteristics and extinction vulnerability of marine fishes, using a fuzzy expert system approach. We also aimed to determine whether the newly developed index would correlate with empirical data. Individual species is treated as the unit of assessment here, but the methodology can be applied to individual population or sub-stock. We further compared the pros and cons of the fuzzy expert system with other approaches in terms of its practical applications.

METHODS

Structure of the fuzzy expert system

We developed a fuzzy expert system (hereafter called fuzzy system) which aimed to evaluate the extinction vulnerability of marine fishes based on easily-obtainable life history and ecological characteristics i.e., features available through FishBase (Froese and Pauly, 2003; <http://www.fishbase.org>). We defined four linguistic categories referring to the levels of intrinsic vulnerability: (1) very high vulnerability to extinction, (2) high vulnerability, (3) moderate vulnerability and (4) low vulnerability. The domain

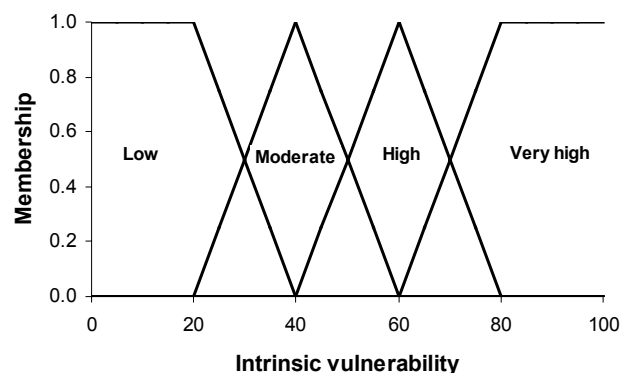


Figure 1. Output fuzzy sets for the intrinsic vulnerability of marine fishes. The "High" and "Very low" vulnerabilities are defined by trapezoid functions while the "Moderate" and "Low" vulnerabilities are defined by triangles. Intrinsic vulnerability was scaled arbitrary from 0 to 100. The dotted line present the supremums of the fuzzy sets (Degree of belief= membership).

for these fuzzy sets is an arbitrary ‘intrinsic vulnerability’ scale from 1 to 100, with 1 being the least vulnerable (Figure 1). Without prior knowledge on the best type of function to be used, we assumed the simplest form of fuzzy membership functions. Thus, trapezoids are used for ‘Very high vulnerability’ and ‘Very low vulnerability’ categories, and symmetric triangles for the other two categories (Figure 1). Thus, a species with an intrinsic vulnerability of 20 is ‘low’ with full membership, while a species with 70 would be both ‘high’ and ‘very high,’ with partial membership to each set.

We collated known relationships between life-history and ecological characteristics to intrinsic vulnerability from the published literature (Table 1), excluding those overwhelmingly disproved by empirical data. For example, high fecundity has been suggested to imply high productivity, and hence low vulnerability (Musick, 1999). However, empirical analyses do not support the inverse relationship between fecundity and vulnerability (see Sadovy, 2001). The published relationships were transformed into expert system (heuristic) rules. The rules are all in the IF-THEN format and relate the life history and ecological characteristics to the four vulnerability categories (Table 1).

We transformed the input biological attributes into linguistic categories defined by fuzzy sets (Figure 2), with trapezoid functions at the upper and lower limits, and triangular sets at intermediate position on the axis. We assumed the minimum membership in the premises (conditions) required to fire the rules (Alpha value) to be 0.2. Therefore, any premises with a membership below 0.2 would not trigger any rule to be fired. Without prior knowledge on the relative validity of each rule, we made an initial assumption of equal weighting with 0.5 confidence factor (CF) to all rules. The CF represents the uncertainty associated to the rule; thus, 0.5 means that we have only half certainty in the validity of the rule. That is:

$$Membership_{conclusion} = Membership_{premise} \bullet CF$$

We then tested the validity of the equal weighting assumption using a jackknife approach.

We obtained the membership to the fuzzy set of the final conclusion (four levels of intrinsic vulnerability) by combining the conclusions from each heuristic rule. Membership in the conclusion from each rule was combined using the knowledge accumulation method in Buchanan and Shortliffe (1984):

$$Membership_e = Membership_{e-1} + Membership_i \bullet (1 - Membership_{e-1})$$

where $Membership_e$ is the membership in the conclusion after accumulating memberships from e sets of rules, and $Membership_i$ is the membership of rule i . For instance, considering the following rules:

IF A THEN E (membership = 0.3)

IF B THEN E (membership = 0.4)

IF C THEN E (membership = 0.5)

$$Membership_2 = 0.3 + 0.4 \bullet (1 - 0.3) = 0.58$$

$$Membership_3 = 0.58 + 0.5 \bullet (1 - 0.58) = 0.79$$

Using this method, the order in which evidence appears has no effect on the final membership in the conclusion.

Operation of the fuzzy system

1. Determining fuzzy membership to input fuzzy sets (Fuzzifications)

We input the life history and ecological parameters into the fuzzy system. The input parameters were categorized into the different linguistic categories (e.g. large maximum size, low value of von Bertalanffy growth parameter K) with the corresponding membership based on the pre-defined fuzzy sets (Figure 2). Categories with membership exceeding the alpha values would trigger the firing of their corresponding rules. For example, for a fish species with maximum body length of 68 cm, the input parameters would correspond to “medium body size” and “large body size” with Membership of 70% and 30% respectively (Alpha value = 0.2) (Figure 3).

Table 1. Heuristic rules defined in the fuzzy system to assign relative vulnerabilities to fishes

Attribute	Rule	Conditions	Consequences	Supporting evidence ¹	Opposing evidence ²
1	1	IF Maximum length ³ is <i>very large</i>	THEN Vulnerability is <i>very high</i>	8, 11, 13, 14, 15, 16, 17,	
1	2	IF Maximum length ³ is <i>large</i>	THEN Vulnerability is <i>high</i>	21, 24, 27, 28, 29	
1	3	IF Maximum length ³ is <i>medium</i>	THEN Vulnerability is <i>moderate</i>		
1	4	IF Maximum length ³ is <i>small</i>	THEN Vulnerability is <i>low</i>		
2	5	IF Age at first maturity (t_m) is <i>very high</i>	THEN Vulnerability is <i>very high</i>	1, 2, 3, 4, 5, 11, 14, 15,	28
2	6	IF Age at first maturity (t_m) is <i>high</i>	THEN Vulnerability is <i>high</i>	19, 20, 24, 33	
2	7	IF Age at first maturity (t_m) is <i>medium</i>	THEN Vulnerability is <i>moderate</i>		
2	8	IF Age at first maturity (t_m) is <i>low</i>	THEN Vulnerability is <i>low</i>		
3	9	IF Maximum age (t_{max}) is <i>very high</i>	THEN Vulnerability is <i>very high</i>	13, 19, 33	14
3	10	IF Maximum age (t_{max}) is <i>high</i>	THEN Vulnerability is <i>high</i>		
3	11	IF Maximum age (t_{max}) is <i>medium</i>	THEN Vulnerability is <i>moderate</i>		
3	12	IF Maximum age (t_{max}) is <i>low</i>	THEN Vulnerability is <i>low</i>		
4	13	IF VBGF (K) is <i>very low</i>	OR	5, 6, 13, 19, 28, 33	11
		Natural mortality (M) is <i>very low</i>	THEN		
4	14	IF VBGF K is <i>low</i>	OR		
		Natural mortality (M) is <i>low</i>	THEN		
4	15	IF VBGF K is <i>medium</i>	OR		
		Natural mortality (M) is <i>medium</i>	THEN		
4	16	IF VBGF K is <i>high</i>	OR		
		Natural mortality (M) is <i>high</i>	THEN		
5	17	IF Geographic range is <i>restricted</i> ⁵	THEN	8, 19, 22	
5	18	IF Geographic range is <i>very restricted</i>	THEN		
6	19	IF Fecundity is <i>low</i> ⁶	THEN	1, 2, 3, 4, 5, 19, 20,	11, 14, 18, 23, 26,
6	20	IF Fecundity is <i>very low</i>	THEN	33	28, 31
7	20	IF Spatial behaviour strength is <i>low</i> ⁷	THEN	7, 9, 10, 12, 25, 32	
7	21	IF Spatial behaviour strength is <i>moderate</i>	THEN		
7	22	IF Spatial behaviour strength is <i>high</i>	THEN		
7	23	IF Spatial behaviour strength is <i>very high</i>	THEN		
8	24	IF Spatial behaviour is related to feeding aggregation	THEN	25	
8	25	IF Spatial behaviour is related to spawning aggregation	THEN	30, 32	

¹ Peer-reviewed literature supporting the assertions of the specific rules;

² Peer-reviewed literature opposing the assertions of the specific rules;

^{1, 2} References: 1. Holden (1973); 2. Holden (1974); 3. Holden (1977); 4. Brander (1981); 5. Hoening and Gruber (1990); 6. Pratt and Casey (1990); 7. Hilborn and Walters (1992); 8. Brown (1995); 9. Pitcher (1995); 10. Pitcher (1997); 11. Jennings et al. (1998); 12. Mackinson et al. (1999); 13. Russ and Alcala (1998); 14. Smith et al. (1998); 15. Walker and Hislop (1998); 16. Jennings et al. (1999a); 17. Jennings et al. (1999b); 18. Myers et al. (1999); 19. Musick (1999); 20. Stevens (1999); 21. Dulvy et al. (2000); 22. Hawkins et al. (2000); 23. Stevens et al. (2000); 24. Frisk et al. (2001); 25. Pitcher (2001b); 26. Sadovy (2001); 27. Dulvy and Reynolds (2002); 28. Denney et al. (2002); 29. Cardillo (2003); 30. Rowe and Hutchings (2003); 31. Sadovy and Cheung (2003); 32. Sadovy and Domeier (in press); 33. Rainer Froese (pers. comm.);

³ Asymptotic length (L_{∞}), a VBGF parameter, was used preferentially. However, if this was not available, we used maximum length (L_{max}) instead;

⁴ Growth of fish is represented by the von Bertalanffy growth function (VBGF) parameter K . Since natural mortality (M) and von Bertalanffy growth parameter K of fish are highly correlated (Pauly 1980), they were combined here, using an 'OR' operator;

⁵ Geographic range is roughly estimated from the known distribution of fish in Exclusive Economic Zones (EEZs) and Food and Agriculture Organization (FAO) statistical areas. For instance, if a fish species is known to occur in China and in FAO statistical area 61, its geographic range is represented by the area of the EEZ of China that falls within FAO statistical area 61;

⁶ Strong evidence is available suggesting that high fecundity does not reduce the extinction vulnerability of fishes. However, there is evidence suggesting that lower fecundity (less than 100) increases the vulnerability of fishes. Therefore, the rule relating low fecundity to increased extinction vulnerability is retained. Fecundity is expressed as the minimum number of eggs or pups produced per individual per year;

⁷ Spatial behaviour expresses how groups of fish aggregate together at varying time and spatial scale. Spatial behaviour may be related to spawning, feeding, migration, or defense (schooling and shoaling). The strength of the spatial behaviour is defined by an arbitrary scale ranging from 1 to 100. The method used to assign strength of spatial behaviour onto this scale is described in Appendix 1.

2. Rule firing and fuzzy reasoning

All premises (antecedents) with membership exceeding the alpha values ($membership_{ant}$) triggered the fuzzy system to fire their corresponding rules in the inference engine. Following the example used in the fuzzification sessions, the rules:

IF fish maximum body size is *medium*, THEN intrinsic vulnerability is *moderate*

IF fish maximum body size is *large*, THEN Intrinsic vulnerability is *high*

would be fired. The membership associated to each conclusion of rules i (precedent) ($membership_{pred,i}$) was calculated by:

$$Membership_{pred,i} = Membership_{ant,i} \bullet CF_i$$

When several rules with the same conclusion were fired, the conclusions (precedents) and their memberships were stored in the inference engine which were then combined and accumulated using the method of Buchanan and Shortliffe (1984).

3. Defuzzification

‘Defuzzification’ refers to the reduction of a range of conclusions being reached with different memberships to a single point output. The conclusions stored in the inference engine were defuzzified based on the output fuzzy sets (Figure 1). Defuzzification was based on the centroid weighted-average method (Cox, 1999), i.e., the output intrinsic vulnerability factor was calculated from the average of the supremums of each output fuzzy membership function, weighted by the membership associated with each conclusion (Figure 1). In a triangular fuzzy membership function, the supremum is equivalent to the intrinsic vulnerability factor with the highest membership. For trapezoid membership functions, the supremum was assumed to be the mid-point between the two ends of the plateau. Confidence limits were estimated by using the smallest and largest intrinsic vulnerability factors that fall within the particularly fuzzy membership function at the specified membership level, instead of using the supremums. Therefore,

$$Intrinsic\ vulnerability = \frac{1}{\sum_{i=1}^4 Membership_i} \bullet \left(\sum_{i=1}^4 Membership_i \bullet Sup_i \right)$$

$$Conf.\ Limits = \frac{1}{\sum_{i=1}^4 Membership_i} \bullet \left(\sum_{i=1}^4 Membership_i \bullet f_i(\phi) \right)$$

where Sup_i is the supremums of conclusion fuzzy membership functions i , and $f(\phi)$ is the estimated upper or lower limit of the conclusion fuzzy membership functions at the specified membership (ϕ).

System evaluations

We examined the distribution of the fuzzy system output generated from ranges of realistic life history and ecological characteristics input. We extracted from FishBase a list of all marine fishes which, at the time of the query (February 2004), had full records of the life history and ecological characteristic: asymptotic or maximum length, von Bertalanffy growth parameter K , age at first maturity, longevity, fecundity and geographic range (N=159). Using the life history and ecological information available for these fishes, we calculated their intrinsic vulnerability based on the fuzzy system.

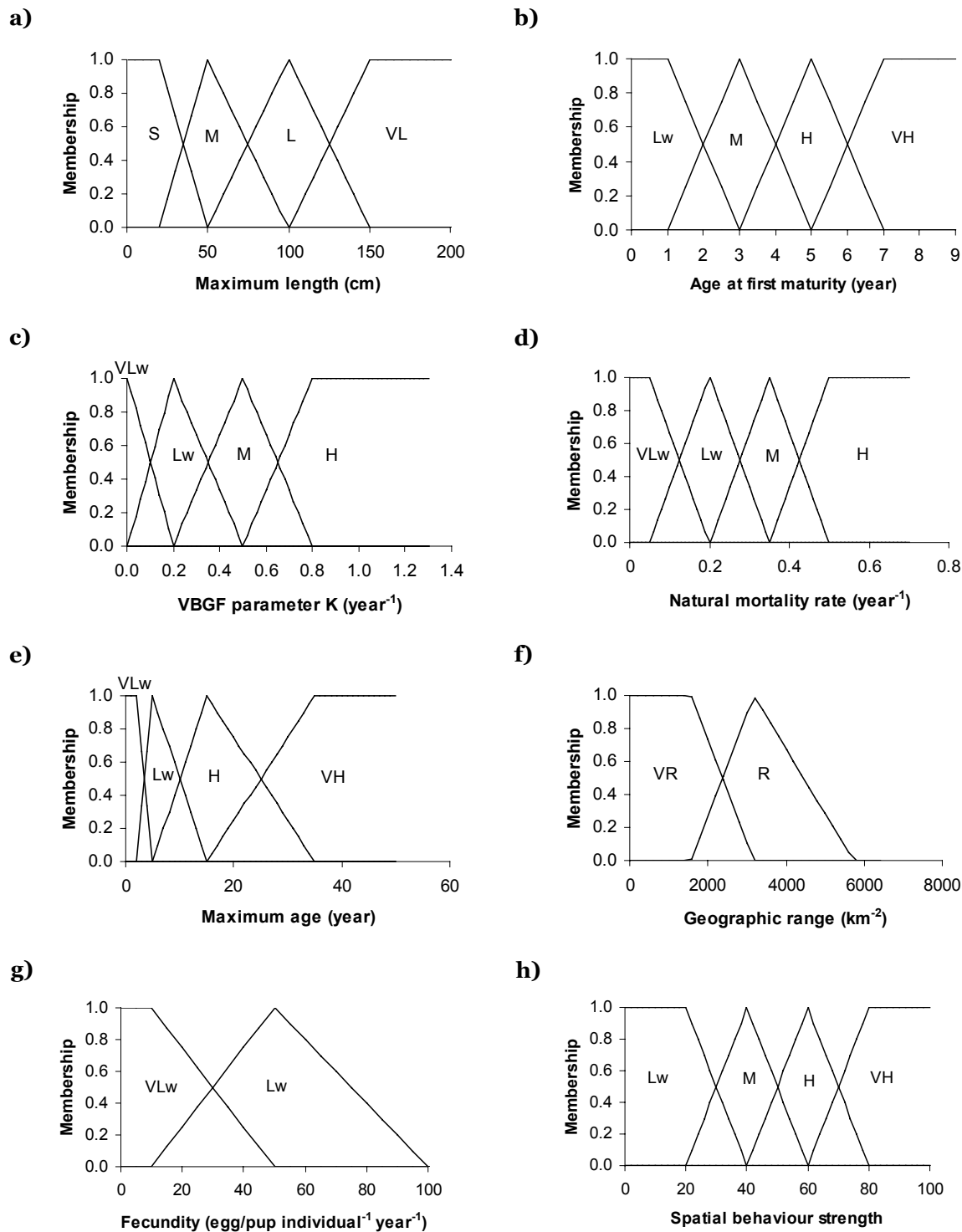


Figure 2. Fuzzy sets defining the input life history and ecological characteristics, with ‘Degree of belief’ = membership in a fuzzy membership function: (a) maximum body length, (b) age at first maturity (T_m), (c) von Bertalanffy growth parameter K , (d) natural mortality rate (M), (e) maximum age (T_{max}), (f) geographic range (km^2), (g) annual fecundity (egg or pup female⁻¹ year⁻¹), (h) strength of aggregation behaviour (see appendix 1). VLw – very low, Lw – low, M –medium/moderate, H – high, VH – very high, L – large, VL – very large, R – restricted, VR – very restricted..

We evaluated the impacts of individual attributes and rules to the output of the system using a jackknife approach (Sokal and Rohlf, 1995) whereas the calculations of the intrinsic vulnerability are repeated, while excluding one of the rules each time. A pseudo-value, which presented the degree of deviation from the output estimated with full sets of rules (Sokal and Rohlf, 1995), was calculated for each species i when rule j was removed from the system:

$$Pseudo\ value = nR_T - (n - 1) \cdot R_{-j}$$

where n is the total number of rules (25) and R is the estimated output from the system with full set of rules (T) and rule j being removed. We repeated the sensitivity analysis by jackknifing attributes instead of individual rules.

Validity tests on vulnerability estimates

We examined the validity of the intrinsic vulnerability estimated from the fuzzy system using empirical data. We conducted three tests that used three independent sets of data in which historical abundance trends of the marine fish species or populations in the datasets were known. Species included in the data sets represent examples from wide longitudinal and habitat ranges. The three tests included:

1. 40 species of marine fishes in the IUCN Red List (Hilton-Taylor, 2000);
2. 24 species of demersal fishes in the northern North Sea (Jennings et al., 1999a); and
3. 13 species of reef fishes (Scaridae, Serranidae and Lutjanidae) in Fiji (species in Jennings et al., 1999b with at least 15% of their observed population trends explainable by fishing).

For each test, the intrinsic vulnerabilities estimated by the fuzzy system were regressed against the observed historical abundance trends of the corresponding species. Whenever the required biological parameters for the species were unavailable in the original data sets, we obtained the data for the same species from FishBase (Froese and Pauly, 2003). We used the goodness-of-fit of the linear regression (R^2) between the vulnerability estimates and the observed population trends as an indicator of the goodness of the representation of extinction vulnerability.

We repeated the tests using two other selected proxies of extinction vulnerability: (1) whichever life history parameters (maximum or asymptotic length, age at first maturity, longevity or von Bertalanffy growth parameter K) which provided the best fit (highest R^2); (2) Productivity categories evaluated using the AFS scheme (Musick, 1999). We compared the intrinsic vulnerability from the fuzzy system with these two proxies using two attributes: (1) predictive ability - represented by the goodness-of-fit with the empirical data, (2) data requirement - the amount and flexibility of data required in the calculation of the proxies. We also conducted an additional test to evaluate the correlation between intrinsic vulnerability from the fuzzy system with an independent resilience indicator. The 'resilience' indicator was estimated by quantitative criteria of biological characteristics of the species and expert judgments (Rainer Froese, FishBase coordinator, pers. comm.). We tested the correlation between the two indicators using a Spearman non-parametric test.

RESULTS

Based on the input life history and ecological parameters, the fuzzy system estimated the intrinsic vulnerability of the fishes in both continuous and ordinal scale with an associated membership on the outputs. For instance, using the biological parameters available from FishBase, we estimated that Baird's smooth-head (*Alepocephalus bairdii*, Alepocephalidae) has an intrinsic vulnerability of 71 (100 being the most vulnerable) with a confidence limit ($\phi=0.5$) of 57 to 85. It was identified as being highly to very highly vulnerable, with a membership of 0.54 to 0.31, respectively on this statement.

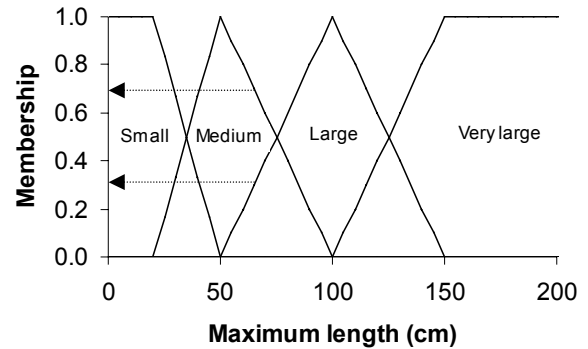


Figure 3. Example of a fuzzy membership function, used to classify fish lengths: small, medium, large and very large. The shapes and slopes of the FMF are pre-defined. For instance, a fish with a maximum length of 68 cm falls within the sets for medium and large, with degree of belief of 0.7 and 0.3 respectively. Degree of belief = membership.

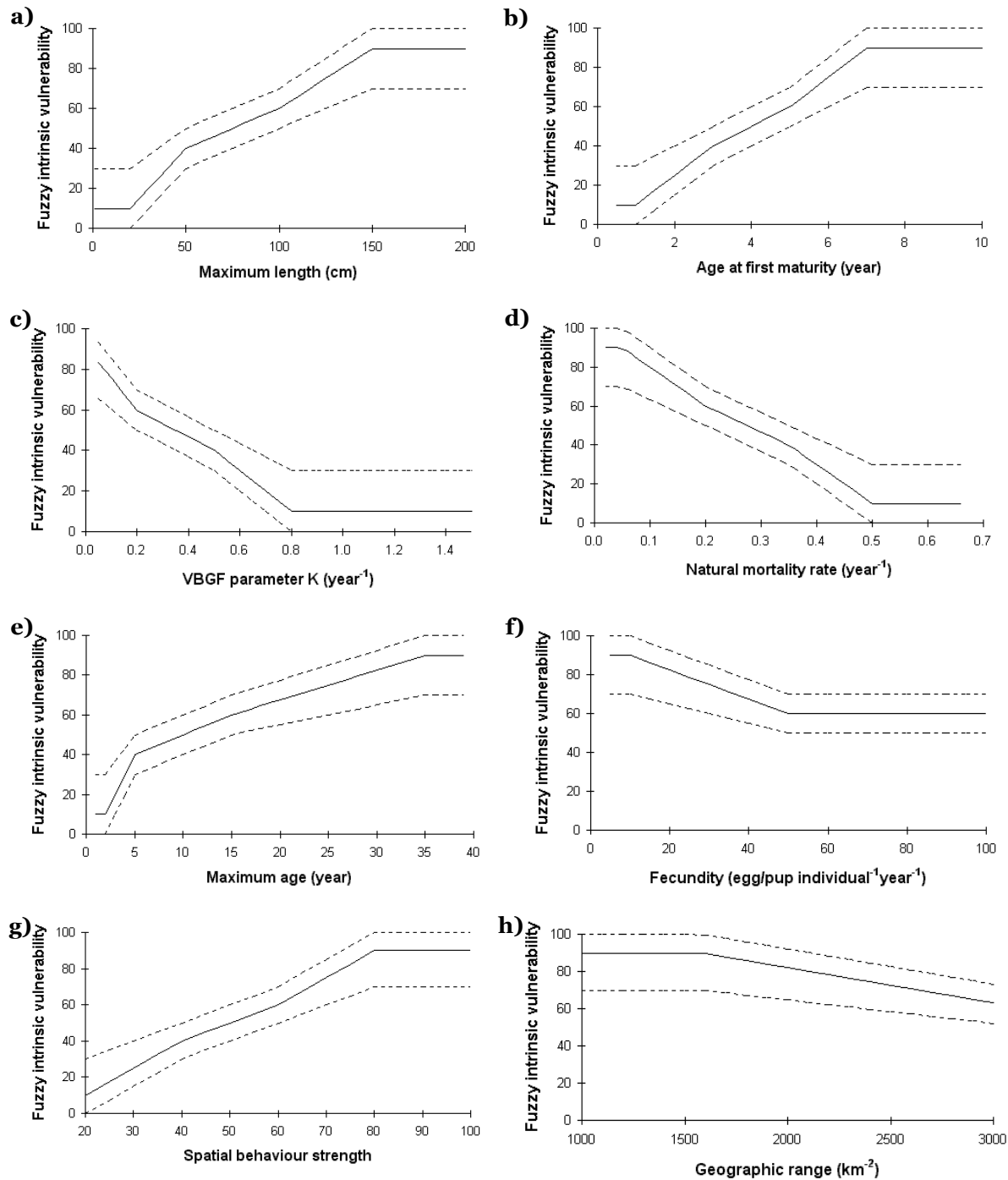


Figure 4. The output surface of the fuzzy system as we varied each individual input parameters: (a) maximum length (cm), (b) age at first maturity, (c) von Bertalanffy growth parameter K (year^{-1}), (d) natural mortality rate (year^{-1}), (e) maximum age (year), (f) fecundity ($\text{egg/pup individual}^{-1}\text{year}^{-1}$), (g) strength of aggregation behaviour (see Appendix 1), (h) geographic range (km^2). The dotted lines represent the confident limits based on an assumed acceptable degree of belief of 50%. We set the threshold level (Alpha value) to zero during system evaluation.

The response of the estimated intrinsic vulnerability to the input parameters is shown in Figure 4. In general, the intrinsic vulnerability estimated from the fuzzy system increases non-linearly with maximum length, age at first maturity, maximum age, and spatial behaviour strength. Conversely, vulnerability decreased with the increase in von Bertalanffy growth parameter K and natural mortality rate. Moreover, fecundity and geographic range, at low level, varies inversely with vulnerabilities.

Jackknifing showed that the deviations in the estimated intrinsic vulnerabilities were similar when individual attributes or rules have removed from the fuzzy system (Figure 5). Pseudovalues of individual rules were generally similar to the baseline, except for rules 6, 13, 17 and 20, which exerted slightly higher impacts on the outputs of the fuzzy system (high age at first maturity, very low von Bertalanffy growth parameter K or natural mortality rate, restricted geographic range and very low fecundity, respectively).

The intrinsic vulnerabilities estimated from the fuzzy system were significantly related to the population declines of marine fishes in the IUCN Red List with the highest goodness-of-fit relative to the two other vulnerability proxies (Figure 6). Musick's productivity and maximum length were significantly correlated to population declines ($R^2=0.16$: Spearman non-parametric test p -value=0.003, $R^2=0.228$: ANOVA p -value=0.002 respectively). However, intrinsic vulnerabilities performed best in explaining the variance in population trends ($R^2=0.35$: ANOVA p -value=0.0001).

The intrinsic vulnerabilities were also significantly related to the population trends of demersal species in the North Sea (Jennings et al., 1999a) with the highest goodness-of-fit (Figure 7). When we considered dragonet (*Callionymus lyra*) and spurdog (*Squalus acanthias*) as outliers, AFS productivity estimates (Musick's productivity; Musick, 1999) and individual life history parameters (age at first maturity) explained 34% and 28% of the variance respectively whereas our fuzzy system was able to explain over 36% of the variance. The relationship between the intrinsic vulnerability and the observed population trends was also significant when we included dragonet and spurdog in the analysis; however, its goodness-of-fit was higher than the other two vulnerability proxies by a smaller margin (Figure 7).

We did not obtain significant relationships between the three vulnerability proxies and the observed population trends of the Fiji reef fishes based on the information available from FishBase only (Figure 8). We could only estimate Musick's productivity for seven species as a result of lack of life history data. Based on these estimates, no significant correlation between Musick's productivity and the observed population trends could be obtained (Spearman non-parametric p -value=0.414). There was also no relationship between individual life history parameter (maximum length) and the fuzzy system intrinsic vulnerabilities with the observed population trends (ANOVA p -value=0.142 and 0.170 respectively).

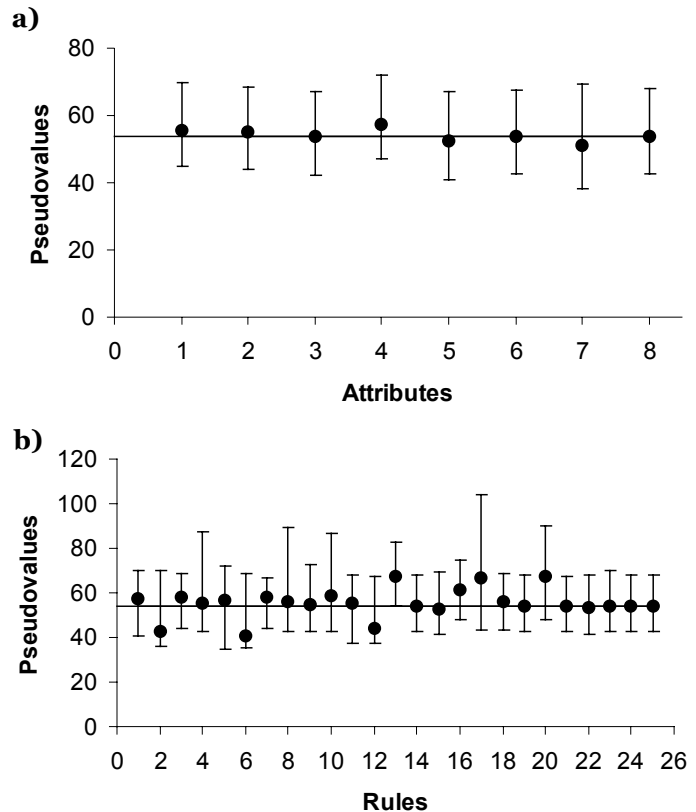


Figure 5. Sensitivity of the estimated intrinsic vulnerability to individual attributes and rules incorporated in the fuzzy system evaluated using the jackknife approach (Sokal and Rohlf, 1995). The black dots are the median of the pseudovalues of the 159 marine fishes from FishBase when individual (a) attributes and (b) rules were removed. The error bars are the 25% and 75% quartiles of the pseudovalues. The solid lines represent the baseline pseudovalues in which full sets of rules and attributes were included. Large deviation from the total averaged pseudovalues indicates that the estimated intrinsic vulnerabilities are sensitive to the individual attribute or rule.

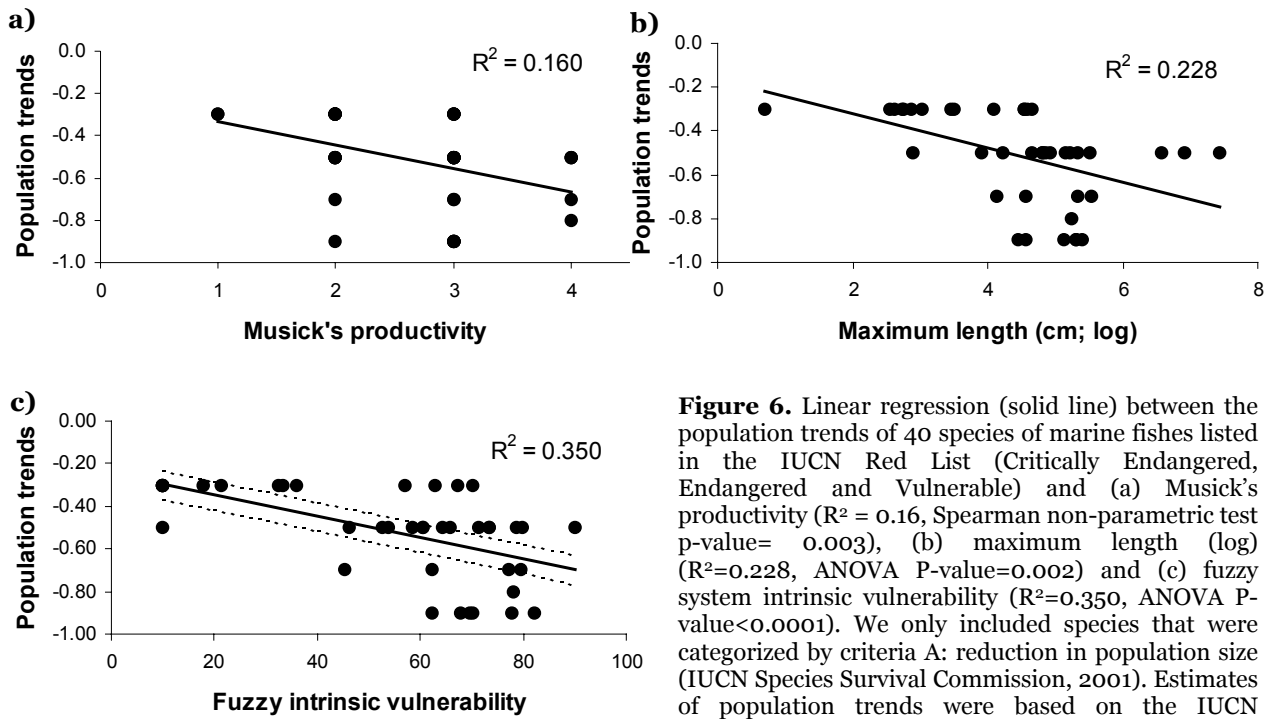


Figure 6. Linear regression (solid line) between the population trends of 40 species of marine fishes listed in the IUCN Red List (Critically Endangered, Endangered and Vulnerable) and (a) Musick's productivity ($R^2 = 0.16$, Spearman non-parametric test p -value= 0.003), (b) maximum length (log) ($R^2=0.228$, ANOVA P -value=0.002) and (c) fuzzy system intrinsic vulnerability ($R^2=0.350$, ANOVA P -value<0.0001). We only included species that were categorized by criteria A: reduction in population size (IUCN Species Survival Commission, 2001). Estimates of population trends were based on the IUCN categories and criteria (version 3.1). As such, the perceived population trends for different IUCN

categories were assumed to be: Critically Endangered (A1) = -90%, Critically Endangered (A2-4) = -80%, Endangered (A1) = -70%, Endangered (A2-4) = -50%, Vulnerable (A1) = -50%, Vulnerable (A2-4) = -30%. The dotted lines represent the CF from the fuzzy system based on an assumed acceptable membership of 50%.

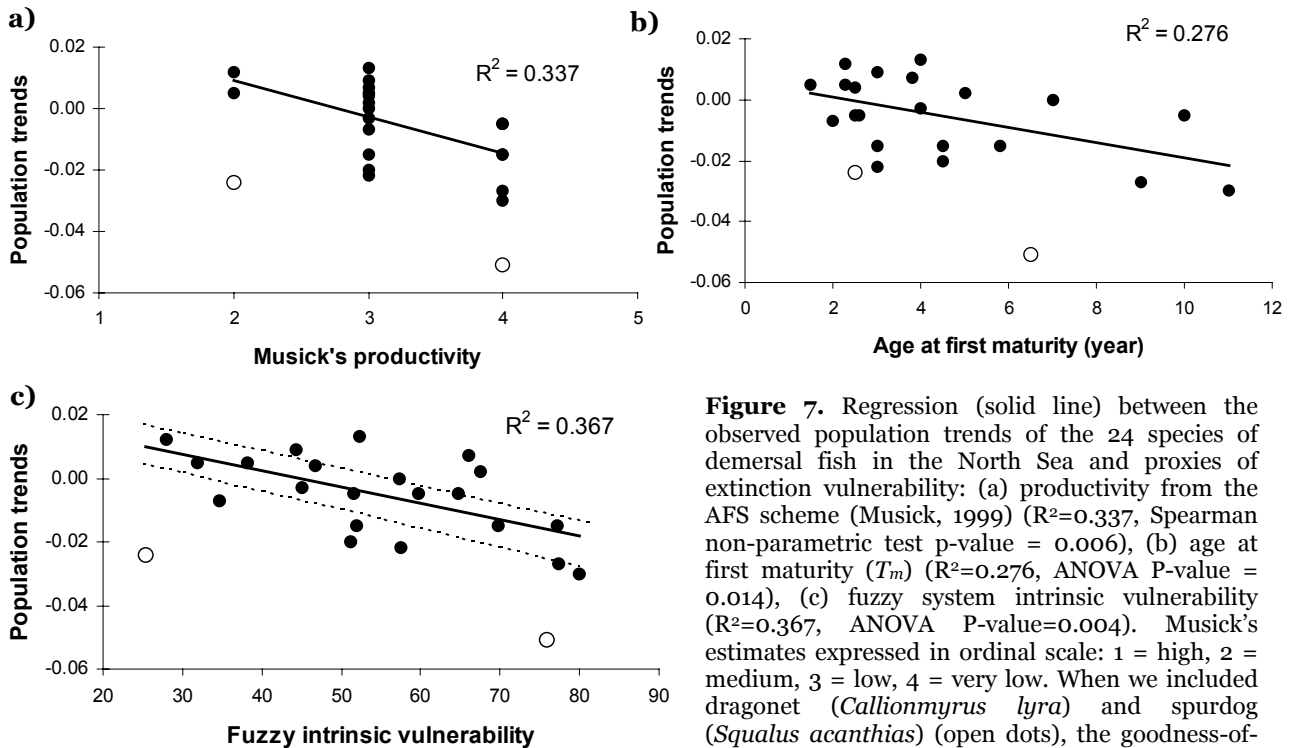


Figure 7. Regression (solid line) between the observed population trends of the 24 species of demersal fish in the North Sea and proxies of extinction vulnerability: (a) productivity from the AFS scheme (Musick, 1999) ($R^2=0.337$, Spearman non-parametric test p -value = 0.006), (b) age at first maturity (T_m) ($R^2=0.276$, ANOVA P -value = 0.014), (c) fuzzy system intrinsic vulnerability ($R^2=0.367$, ANOVA P -value=0.004). Musick's estimates expressed in ordinal scale: 1 = high, 2 = medium, 3 = low, 4 = very low. When we included dragonet (*Callionmyrus lyra*) and spurdog (*Squalus acanthias*) (open dots), the goodness-of-fits of the three proxies became: Musick's

productivity ($R^2=0.204$, Spearman non-parametric p -value=0.019), T_m ($R^2=0.207$, ANOVA p -value=0.029) and fuzzy system intrinsic vulnerability ($R^2=0.246$, ANOVA p -value=0.016). The dotted lines represent the confidence limits estimated from the fuzzy system based on an assumed acceptable membership of 50%.

Significant relationship between the fuzzy system intrinsic vulnerabilities and the population trends of Fiji reef fishes exists when we supplemented information on occurrence of spawning aggregation available from the global database of the Society for the Conservation of Reef Fish Spawning Aggregation (SCRFA Global Database, 2004) (Figure 8d). The fuzzy system is able to explain about 34% of the variance in population trends (ANOVA p-value=0.03).

The fuzzy system intrinsic vulnerabilities were significantly correlated with the resilience categories assigned by R. Froese to the selected species ('Froese's resilience') (Figure 9). The two estimates were significantly correlated (Spearman non-parametric test p-value=<0.0001) and had the expected negative sign. We summarize the comparisons between different approaches to estimation of extinction vulnerability in Table 2.

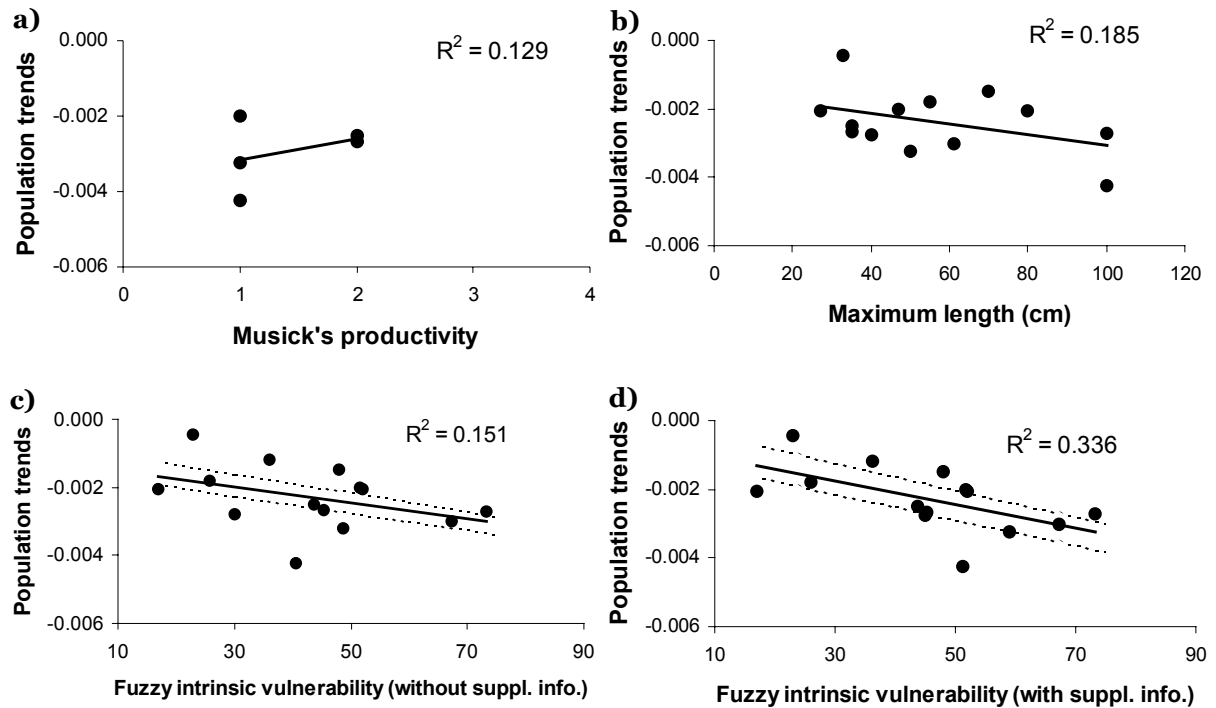


Figure 8. Linear regression (solid line) between the observed population trends of the 13 species of reef fish in Fiji and (a) Musick's productivity (Spearman non-parametric p-value=0.414), (b) maximum length ($R^2=0.185$, ANOVA P-value=0.142); (c) intrinsic vulnerability estimated by the fuzzy system based on information from FishBase only ($R^2=0.151$, ANOVA P-value=0.170). (d) intrinsic vulnerability estimated by the fuzzy system with supplementary information from SCRFA Global Database (2004) ($R^2=0.336$, ANOVA P-value=0.03). The dotted lines represent the confidence limits estimated from the fuzzy system based on an assumed acceptable membership of 50%.

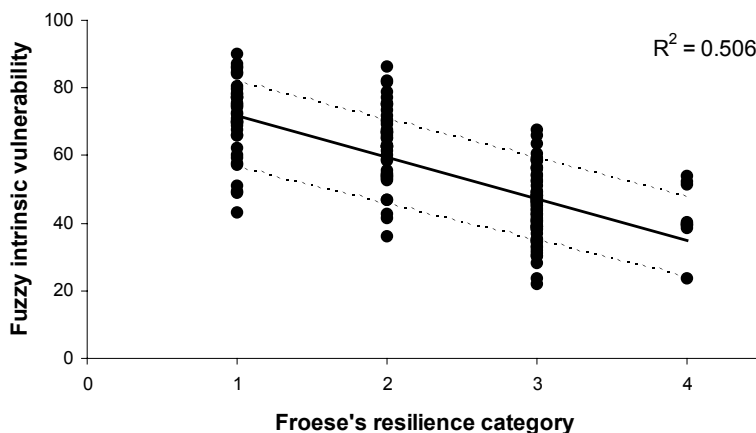


Figure 9. Comparisons between the fuzzy system intrinsic vulnerability and the resilience categories estimated in FishBase for the 159 species of marine fishes (Froese and Pauly, 2003). The resilience categories were assigned by quantitative life history criteria and subjective expert judgment (R. Froese pers. comm.), with 1 = very low, 2 = low, 3 = medium, 4 = high. The dotted lines represent the confident limits based on an assumed acceptable degree of belief to the output of 50%. The two indicators are significantly correlated (Spearman non-parametric test p-value<0.0001).

Table 2. Comparisons between approaches suggested to evaluate extinction vulnerability or resilience of marine fishes.

Attributes	Approaches				
	American Society	Fisheries Scheme	Individual life history parameters	FishBase Resilience Category	Fuzzy system intrinsic vulnerability
Data requirement ¹	One or more of the followings: r , T_m , T_{max} , K and <i>fecundity</i>		One of the life history parameters (L_{max} , T_m)	Expert judgments with one or more of the followings: r , T_m , T_{max} , K and <i>fecundity</i>	One or more of the followings: L_{max} , T_{max} , T_m , K , M , <i>fecundity</i> , <i>spatial behaviour</i> , <i>geographic range</i>
Outputs	Four ordinal categories		Continuous scale of the selected life history parameters	Four ordinal categories	(a) Arbitrary scale from 1 to 100 (b) Upper and lower confident limits (c) Four ordinal categories With estimated degrees of belief associated to each category
Goodness-of-fit with observed population trends (R^2) ²	Test 1 – 0.160		Test 1 – 0.228	N/A	Test 1 – 0.350
	Test 2 – 0.337		Test 2 – 0.276		Test 2 – 0.367
	Test 3 – 0.129*		Test 3 – 0.185		Test 3 – 0.151(0.336) ³

¹ L_{max} – maximum length, T_{max} – maximum age, T_m – age at first maturity, K – von Bertalanffy growth parameter, M – natural mortality rate, r – intrinsic rate of population increase, *aggregation strength* – see Appendix 1.

² Test 1 – 23 species of demersal fishes in North Sea (Jennings et al., 1999a); Test 2 – 13 species of reef fishes in Fiji (Jennings et al., 1999b); Test 3 – 41 species of marine fishes listed as Critically Endangered, Endangered or Vulnerability in the IUCN Red List (Hilton-Taylor, 2000). N/A – not available.

³ Values in parentheses represent the R^2 between the estimated vulnerabilities and the observed population trends when information from SCRFA Global Database (2004) was included.

* The direction of relationship between the Musick's productivity and the population trends was opposite to the expected direction.

DISCUSSION

The comparisons with empirical population abundance trends showed not only that a fuzzy system could be used to predict the intrinsic vulnerability of marine fishes, but also that its performance was superior to that of approaches proposed earlier. The population trends included in the analysis were confounded by factors other than fishing and differences in fishing intensities between species. Therefore, they could only be viewed as rough indicators of the vulnerability of the populations or the species to fishing. Thus, it was expected that the goodness-of-fit between intrinsic vulnerability and population trends would be low. However, the intrinsic vulnerabilities estimated from the fuzzy system still explained a considerable proportion of variance among species. Moreover, the proportions of variance explainable by the intrinsic vulnerability were higher than two suggested proxies of extinction vulnerability. Furthermore, the fuzzy system could be applied to species from a wide range of geographic locations, habitats and ecosystem types, and for which different levels of knowledge is available.

Fuzzy system allows incorporation of information from a wide range of sources (Mackinson and Nøttestad, 1998) through which the predictive ability of the system may be increased especially when information is limited. For example, reef fish spawning aggregations are generally poorly documented in formal scientific literature. On the other hand, occurrence of reef fish spawning aggregations identified from both scientific and local knowledge (e.g. fishers interview) are systematically documented in the SCRFA Global Database (2004). Incorporation of such information into the fuzzy system greatly increased the goodness-of-fit between the estimated vulnerabilities and the empirical population trends. This also implies the importance of spawning aggregation behaviour in the assessment of vulnerability of reef fishes (Sadovy and Domeier, in press).

Small variations of pseudovalues of the rules and attributes suggested that varying the weighting of individual rules and attributes does not measurably affect the performance of the fuzzy system. Conventional expert systems require individual rules to be weighted according to subjective expert judgment (Cox, 1999) or availability of evidence supporting the particular rules or attributes (Mackinson, 2000). Since we defined the attributes and rules incorporated in the fuzzy system from published literature, expert weighting of individual rules was not possible. Moreover, the amount of literature describing a rule (which has been suggested as a weighting factor) does not necessarily reflect the importance of this rule. Moreover, the intrinsic vulnerability estimated from the fuzzy system barely affected by the weights on individual attributes or rules. This supports the equal weight approach adopted here.

The fuzzy system can provide estimates of intrinsic vulnerability for species with different data availability. Despite the availability of FishBase, biological characteristics remain unavailable for a large number of marine fishes (Johannes, 1998), especially in the tropics. As the system inputs are connected in parallel to the outputs, intrinsic vulnerability can still be estimated by the rules fired from the inputs where data are available. Moreover, results from the analysis showed that the estimated intrinsic vulnerability was generally insensitive to individual attributes or rules. Thus, the output of the fuzzy system should not be greatly affected by incomplete data. In addition, the vagueness on the output, partly dependent on the amount of available data, can be explicitly measured by the estimated membership to the output values.

Fuzzy expert systems enable the integration of local and scientific knowledge (Mackinson and Nøttestad, 1998) and can be used to help improve our understanding about the extinction vulnerability of marine species. The fuzzy system can adapt to new information from either quantitative studies or qualitative experts' knowledge. The fuzzy expert system presented here was constructed from the best available, current knowledge. We inevitably made assumptions when particular knowledge was absent. However, new rules can be easily incorporated into the system as they become available. The choice of fuzzy memberships and weighting on the rules can also be adjusted when new evidence or experts' opinions are available. Therefore, a fuzzy expert system can be particularly useful in facilitating workshop or focus group discussion on the assessment of extinction vulnerability of marine species (see Hudson and Mace, 1996). In this case, the discussions and opinions from the experts can act as the knowledge base. The knowledge engineer who maintains the expert system can use the knowledge base to revise and update the expert system (Mackinson and Nøttestad, 1998; Cox 1999).

The approach described here can facilitate the identification of vulnerable species onto which management and conservation efforts can be focused. Current monitoring and management efforts mainly focus on commercially important species. However, commercially important species may not necessarily be the most vulnerable species. Bycatch and other indirect fishing impact may threaten non-commercial species (Dulvy et al., 2003). The near extinctions of the common and barndoor skates, both low-value bycatch species in bottom trawl fisheries are clear examples. A large reduction in the abundance of pelagic shark in the Gulf of Mexico was unnoticed previously because of their relatively low value compared to the tunas, despite life history characteristics which made them highly vulnerable (Baum and Myers, 2004). This is particularly true for tropical fisheries where diverse species are caught and resources for monitoring and management are low (Silvestre and Pauly, 1997; Johannes, 1998; Johannes et al., 2000). The intrinsic vulnerability estimated from the fuzzy system could provide a priori indicator on the vulnerability of the species. As such, prioritization of species according to their potential extinction vulnerabilities can help to allocate limited research and monitoring resources, and develop more effective fishery management and conservation policies. Development of fishing technology that minimizes the bycatch of vulnerable species could also be encouraged (Stobutzki et al., 2001; Kennelly and Broadhurst, 2002).

Intrinsic vulnerability may combine with the other external factors in estimating the total vulnerability of the species. Here, we narrowly defined vulnerability of fish as the risk of extinction associated with the life history and ecological characteristics of a species. However, external factors such as fishing intensity, degradation of essential habitat and climate change contributes significantly to the extinction risk associated with each species (Dulvy et al., 2003). These external factors, together with intrinsic vulnerability, should be integrated in assessing overall extinction risk. In fact, these external factors can be represented at a higher hierarchical level in the fuzzy system. Rules describing the effects of these external factors, and their synergistic effect with the intrinsic vulnerability, can be incorporated into the fuzzy system through which outputs representing the total vulnerability of the species can be obtained. This may provide a decision support tool on local or global extinction risk assessment and categorization such as the IUCN Red List of the World Conservation Union or the species listing under the Canada's Species At Risk Act.

APPENDICES

The method that assigns strength of spatial behaviour was described:

1. Assignment of strength of spatial behaviour of fish onto a 1 to 100 arbitrary scale.

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VULNERABILITY OF SEAMOUNT FISH TO FISHING: FUZZY ANALYSIS OF LIFE-HISTORY ATTRIBUTES

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ABSTRACT

Based on life history and ecological characteristics, several authors have placed seamount fishes at the extreme end of the vulnerability spectrum. However, it was still unclear if there is justification for the generalization that seamount fishes overall possess specific life-history characteristics that render them more vulnerable to fishing than other species. In this contribution, we test the hypothesis that seamount fishes generally have a high vulnerability to fishing, and that this is correlated with their life-history characteristics. Despite rather broad definitions, our global analysis shows that seamount fishes, particularly seamount-aggregating fishes, have higher intrinsic vulnerability than other groups of marine fishes. The pattern is similar when we considered only commercially exploited species. Biological characteristics leading to greater vulnerability of seamount fishes include a long lifespan, late sexual maturation, slow growth and low natural mortality. In light of our research, this experience supports that seamount fishes, especially those that aggregate on seamounts, are highly vulnerable to exploitation and that fishing on seamount will tend to be unsustainable, given current levels of exploitation and current fishing methods. A number of seamount populations have already been depleted. More will be depleted and some will go extinct if fishing on seamounts continues at current, or even more moderate levels.

INTRODUCTION

Seamounts are biologically distinctive habitats of the open ocean exhibiting a number of unique features (Rogers, 1994). Seamounts have received much attention mainly because of the presence of substantial aggregations of fishes in mid- and deep-water (Boehlert and Sasaki, 1988; Koslow, 1996; 1997; Koslow et al., 2000), which became the prime target of a highly technological fishery. Based on life history and ecological characteristics, several authors have placed seamount fishes at the extreme end of the vulnerability spectrum (Koslow, 1997; Branch, 2001; Boyer et al., 2001; Clark, 2001). However, with the exception of work by Koslow (1996) and Froese and Sampang (this vol.), few attempts have been made to review, summarize and compare the life-history of seamount species. Therefore, the generalization that seamount fishes overall possess specific life-history characteristics that render them more vulnerable than other species is still uncertain.

Responses of a fish species to exploitation may be partly determined by life history and ecological characteristics (Adams, 1980; Roff, 1984; Stokes et al., 1993; Kirkwood et al., 1994). Fish that mature late and have low growth and low mortality rates, likely have higher vulnerability to fishing (Jennings et al., 1998; 1999; Russ and Alcalá, 1998; Musick, 1999; Denney et al., 2002; Froese and Sampang, this vol.). In addition, species that display social aggregation behaviours such as shoaling, schooling (Pitcher and Parrish, 1993) or shoal spawning may have higher vulnerability because of increased catchability (Sadovy and Domeier, in press), leading to hyperstability of catch rates (Pitcher, 1995; 1997; Hilborn and Walters, 1992; Walters, 2003), and the possible disruption of group spawning behaviour by fishing (Johannes, 1998; Sala et al., 2001; Sadovy and Domeier, in press).

Even though the designation of 'seamount' species has been widely employed (e.g. Koslow, 1996; Probert et al., 1997; Probert, 1999; Koslow et al., 2000; Fock et al., 2002; Tracey et al., 2004), rigorous criteria used in identifying these taxa have not been clearly defined (see Froese and Sampang, this vol., and Watson and Morato, this vol.). Koslow (1996) categorized species that aggregate in association with seamounts and other topographic features as 'seamount-associated' fishes. Some of the most well known representatives of this group include the deep-water fishes: Orange roughy (*Hoplostethus atlanticus*), Alfosinos (*Beryx splendens* and *B. decadactylus*), Patagonian toothfish (*Dissostichus eleginoides*), Oreos (e.g. *Allocyttus niger*, *Pseudocyttus maculatus*), Pelagic armorhead (*Pseudopentaceros wheeleri*), several species of Rockfishes (*Sebastes* spp.) (Koslow 1996; Koslow et al., 2000) and probably Roundnose grenadier (*Coryphaenoides rupestris*) (Vinnichenko, 2002a). Vulnerability of 'seamount-associated' fishes is of particular concern from a management point of view because they are the prime targets of seamount fisheries.

Many other fish species, however, occur on seamounts or congregate over their summits to feed on the rich booty. This may be the case for some sharks (Klimley et al., 1988; Hazin et al., 1998), tunas (Holland et al., 1999; Itano and Holland, 2000; Sibert et al., 2000) and other large pelagic predators (Ward et al., 2000; Sedberry and Loefer, 2001). Some other fish species aggregate around shallow seamounts mainly for spawning, for instance, reef-associated fish such as groupers (*Mycteroperca rosacea*, *Paranthias colonus*) and jacks (*Caranx sexfasciatus*, *Seriola lalandi*) (Sala et al., 2003). Recently, Tsukamoto et al. (2003) found that the spawning site of the Japanese eel (*Anguilla japonica*) in the western North Pacific, appears to be near three seamounts, 2000-3000 km away from their freshwater adult feeding habitats. In this study 'seamount fishes' were considered as all fish species that have been reported for seamounts, and 'seamount-aggregating fishes' were those that fall into the category defined by Koslow (1996).

In this paper we attempt to test the hypothesis that seamount fishes generally have a high vulnerability to exploitation and that this is correlated with their life history characteristics. We build on previous studies that have found that vulnerability of fishes to exploitation is correlated with their life history characteristics (Froese and Sampang, this vol.; Cheung et al. this vol.). We estimate vulnerability quantitatively by analysis of life-history characteristics using a fuzzy-logic algorithm.

METHODS

Compilation of species list

Seamount fishes are defined as fish that have been reported as occurring on seamounts. In order to include some of the most important seamount fishes, a list of fish species occurring for seamounts worldwide (Froese and Sampang, this vol.) was augmented from additional sources (Appendix 1): Menezes (2003) and Melo and Menezes (2002) for fish species occurring on the Azorean seamounts; OASIS (2004) for species collected on Seine and Sedlo Seamounts (North-eastern Atlantic); Moore et al. (2001; 2002) for species from Bear seamount (North-western Atlantic); Kukuev (2002) for species at Mid Atlantic Ridge seamounts; Canessa et al. (2003) for Bowie seamount (North-eastern Pacific); Hughes (1981) for some Alaskan seamounts (North-eastern Pacific); and Tracey et al. (2004) for species occurring on New Zealand seamounts (South-western Pacific). A total of 794 species of marine fishes were classified as occurring on seamounts (even if rare). Additionally, we compiled a list (Table 1) of 23 seamount-aggregating fishes as defined by Koslow (1996). We acknowledge that this list (Table 1) is preliminary and its accuracy will improve as we gain more knowledge about the ecology of seamount and deepwater fish species.

Comparisons of biological characteristics and vulnerabilities

Using Fishbase (Froese and Pauly, 2003) and other sources, we compiled 6 life history attributes for over 14,000 marine fish species (Table 2: longevity, T_{Max} ; age at maturity, T_m ; asymptotic length, L_{∞} ; fecundity, Fec ; von-Bertalanffy growth parameter, K ; and natural mortality rate, M) together with information on preferred habitat (pelagic, demersal, reef-associated, benthopelagic, bathypelagic and bathydemersal). We used only those parameters directly estimated from empirical studies, while excluding those that were calculated from empirical relationships between life history parameters. If more than one estimate was available for a particular life history parameter of a particular species, we used the arithmetic mean.

The intrinsic vulnerability (Vul) was estimated for over 14,000 species of marine fishes based on their life history and ecological characteristics using a fuzzy¹ expert system (Cheung et al., this vol.). Cheung et al. (this vol.) defined two categories of extinction risk: (1) Intrinsic vulnerability, i.e., vulnerability to exploitation inherent to a species, as determined by its life history and ecology, and independent of external factors such as fishing intensity and environment; and (2) Total vulnerability, i.e., the risk of extinction resulting from both intrinsic and external factors. Only 1600 vulnerability estimates (Table 2) were included in comparative analyses because those species for which total length was the only available parameter were excluded from further analyses.

¹ Fuzzy logic was originally developed to represent gradation of truth, instead of classifying objects as either 'true' or 'false', thus allowing vagueness, while based on rigorous mathematic. The explicit use of vagueness in fuzzy logic is very useful for handling the uncertainty inherent to extinction vulnerability (see Cheung et al., this vol.).

Table 1. List of species considered as seamount-associated fishes (*sensu* Koslow, 1996).

Species	Aggregation	Reference
<i>Alepocephalus bairdii</i>	Maybe	6, 11
<i>Allocyttus niger</i> ^c	True	3, 4
<i>Allocyttus verrucosus</i> ^a	Maybe	12
<i>Aphanopus carbo</i> ^b	True	10
<i>Beryx decadactylus</i>	True	4, 9
<i>Beryx splendens</i>	True	3, 4, 7, 9
<i>Coryphaenoides rupestris</i>	True	8, 5
<i>Dissostichus eleginoides</i>	True	4
<i>Epigonus telescopus</i> [*]	True	10, 5
<i>Hoplostethus atlanticus</i>	True	3, 4, 8, 5
<i>Hoplostethus mediterraneus</i>	Maybe	6
<i>Lepidion eques</i> [*]	Maybe	6
<i>Mora moro</i>	Maybe	6
<i>Neocyttus rhomboidalis</i> ^{*, a}	Maybe	11
<i>Pseudocyttus maculatus</i> ^a	True	3, 4
<i>Pseudopentaceros richardsoni</i>	True	9
<i>Pseudopentaceros wheeleri</i> [*]	True	2, 3, 4
<i>Sebastes entomelas</i> ^{*, c}	Maybe	1
<i>Sebastes helvomaculatus</i> ^{*, c}	Maybe	1
<i>Sebastes marinus</i>	True	5
<i>Sebastes mentella</i>	True	8
<i>Sebastes paucispinis</i> ^c	Maybe	1
<i>Sebastes ruberrimus</i> ^c	Maybe	1

* intrinsic vulnerability index not estimated due to insufficient parameters; a) forming large shoals over rough ground near pinnacles and canyons; b) not a typical seamount-associated fishes (*sensu* Koslow, 1996); c) juveniles form large schools. References: 1) Parker and Tunnicliffe, 1994; 2) Rogers, 1994; 3) Koslow, 1996; 4) Koslow et al., 2000; 5) Hareide and Garnes, 2001; 6) Piñeiro et al., 2001; 7) Ramos et al., 2001; 8) Shibanov et al., 2002; 9) Vinnichenko, 2002a; 10) Vinnichenko, 2002b.; 11) Allain et al., 2003; 12) Fishbase: Froese and Pauly (2003).

We compared biological characteristics and the estimated fuzzy intrinsic vulnerabilities between non-seamount fishes, seamount fishes and seamount-aggregating fishes. Intrinsic vulnerability was also estimated for those species reported in the Food and Agriculture Organization (FAO) official landing statistics, to test if commercially targeted seamount fish species were also more vulnerable than other fish species. To explore what fish groups may be responsible for differences in vulnerabilities between seamount and non-seamount fishes, we estimate vulnerabilities for different fish groups occurring and non-occurring on seamounts. Additionally, we addressed the question whether seamount fishes are more vulnerable than deep-sea fishes in general by comparing intrinsic vulnerability of bathydemersal fishes not occurring on seamounts (our 'deep-sea' control fish group) with seamount fishes and seamount-aggregating fishes. Differences between the biological characteristics and intrinsic vulnerability estimates of the two groups were tested with Mann-Whitney (U) non-parametric statistics (see Zar, 1999).

Responses to fishing

We evaluated the relationship between vulnerability estimates and biomass change over time caused by fishing using a simulation model. We used a mass-balanced ecosystem model (Ecopath with Ecosim, see Christensen and Walters, 2004 for details) developed for a theoretical, isolated North Atlantic seamount (Morato and Pitcher, 2002). This model included 37 functional groups, of which twenty were fish groups assembled according to environment preference (i.e., depth and habitat: e.g. benthic, pelagic or benthopelagic), body size, energetics and life-history characteristics (see Morato and Pitcher, 2002 for a complete description of the model). The seamount fisheries were loosely based on those operating at the Azores / Mid Atlantic Ridge, and thus divided in 6 fleets (see Morato and Pitcher, 2002). We simulated biomass changes over 20 years by assuming a fishing mortality rate of 0.3 for one fish group at a time.

Table 2. Occurrence of fish species on seamounts, and number of species for which specific parameters are available. Data for those species that form aggregations on seamounts is also shown*.

Species group	Number of spp	T_{max}	T_m	M	K	L_{∞}	Fec	Vul^*
Non-Seamounts	14927	432	462	177	1089	11903	483	1409
Seamounts	795	90	83	37	148	723	76	191
Seamount-aggregating	23	19	16	10	18	22	11	18

*Here T_{max} is the longevity; T_m the mean age at first maturity; M is the natural mortality, K is a parameter of the von-Bertalanffy Growth Function (VBGF) of dimension 1/time; L_{∞} is another VBGF parameter, closely related to maximum observed length (L_{max}); Fec is total fecundity, and Vul is the intrinsic vulnerability. Even though vulnerability was estimated for almost all fish species (n= 14148), this table only shows the number of species included in further analysis, i.e. excluding those species for which only L_{∞} was available.

Additionally, we compared the relative extinction risk between each seamount fish group in the simulation model using a quantitative index. The index takes into account the fuzzy intrinsic vulnerabilities of the composite species of each functional group, and the simulated changes in biomass of the group (Cheung et al., this vol.). Essentially, a functional group with a higher index (scaled between 1 to 100) implies a higher risk of extinction for the species it contains.

RESULTS

We found significant differences in longevity and age at maturity among seamount, non-seamount and seamount-aggregating fishes (Figure 1). The longevity (Figure 1a) of seamount fishes was significantly higher than non-seamount fishes (median = 25 years and 12 years respectively; U ; $p < 0.001$). Seamount-aggregating fishes have the highest longevity among the three categories (median T_{Max} = 52 years), although the difference is significant only the comparison is with non-seamount fishes (U ; $p < 0.001$). Non-outliers' ranges of longevity of seamount-aggregating fishes (11.6-149 years) are also larger than both the seamount fishes (1-118 years) and non-seamount fishes (0.5-48 years). Accordingly, the age at maturity (Figure 1b) of both seamount and seamount-aggregation fishes were significantly higher (median T_m = 4.3 years and 9.9 years respectively) than the non-seamount fishes (median T_m = 3.0 y) (all U ; $p < 0.001$). Seamount-aggregating fishes also have a significantly higher age at maturity than seamounts fishes (U ; $p < 0.001$).

Comparisons of natural mortality rate (Figure 1c) and the von Bertalanffy growth parameter K (Figure 1d) among the three categories of fishes show similar, but reciprocal, trends as longevity and age at maturity. Seamount-aggregating fishes have the lowest natural mortality and lowest K values (median M = 0.16 and median K = 0.09), while non-seamount fishes have the highest values among the three fish categories (median M = 0.60 and median K = 0.34). All paired comparisons were significantly different at the 1% confidence level (U ; $p < 0.001$), with the exception of the comparison of natural mortality for seamount fishes and seamount-aggregating fishes, which was significant different at the 5% confidence level (U ; $p = 0.037$).

We observed a significant difference between the estimated intrinsic vulnerabilities of seamount, non-seamount and seamount-aggregating fishes. Median intrinsic vulnerabilities (Figure 2a) for non-seamount fishes, seamount and seamount-aggregating fishes were estimated to be 45.0, 51.8 and 68.2 respectively. The differences in intrinsic vulnerabilities are significant both comparing non-seamount and seamounts fishes (U ; $p < 0.001$) and comparing seamount fishes and seamount-aggregating fishes (U ; $p < 0.007$).

Vulnerabilities of fish reported as catches in the FAO landings statistics were also higher for seamount fishes, and significantly different from the median for non-seamount fishes (U ; $p < 0.001$). However, there were no significant differences between the vulnerabilities of seamount fishes and seamount-aggregating species (U ; $p < 0.111$), even though the median was higher for the later. Additionally, we estimated the mean of vulnerability weighted by the logarithm of the catch (Table 3). Similarly, vulnerability was higher for seamount-aggregation species and lower for non-seamount fishes.

Table 3. Intrinsic vulnerability weighted by log(catch) for seamount and seamount-aggregating species reported explicitly in FAO catches.

	Non-seamounts	Seamounts	Seamount-aggregating
Number of Species	508	102	13
Vulnerability	39.9	47.9	64.5

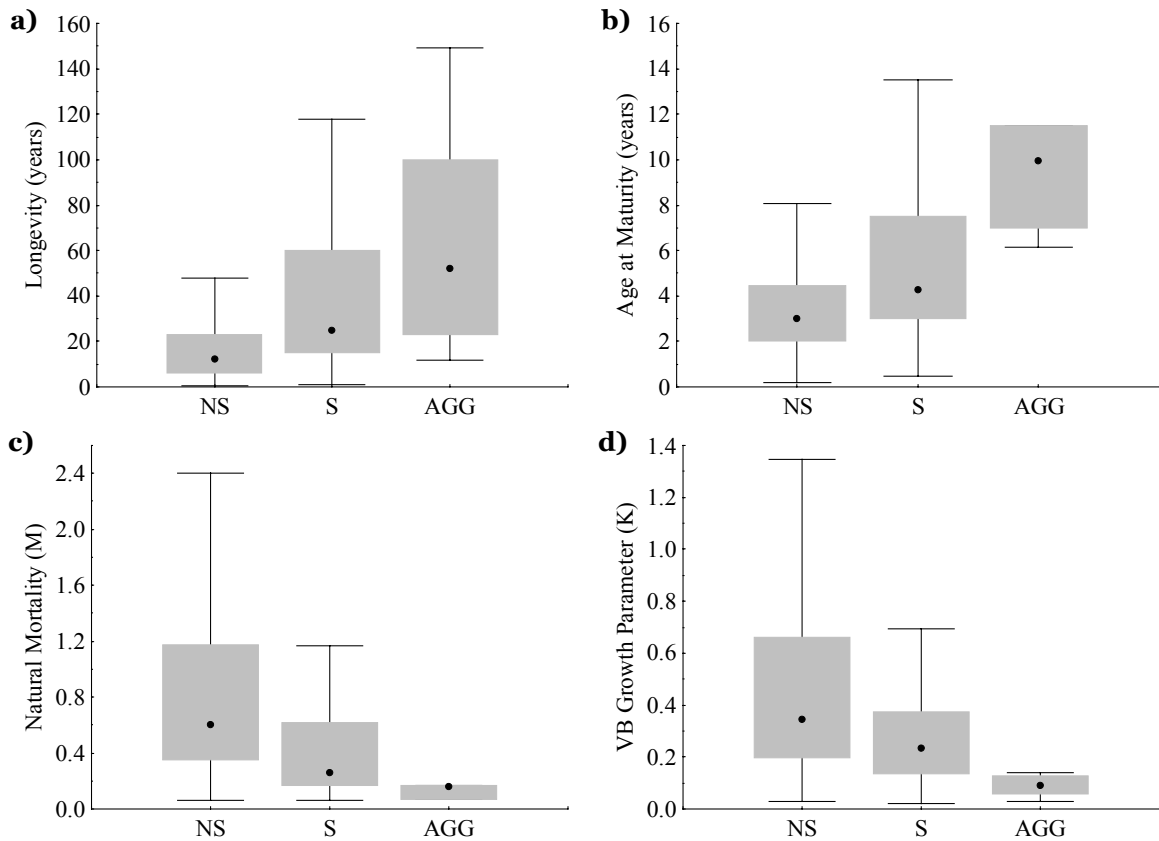


Figure 1. Comparison of some life-history characteristics of non-seamount fish species (NS), fish occurring on seamounts (S), and seamount-aggregating species (AGG); a) longevity (T_{Max}); b) age at maturity (T_m); c) natural mortality (M); d) von Bertalanffy growth parameter (K). In the graphs, the middle point is the median, the box represents the 25%-75% percentiles, and the whisker the range, excluding outliers.

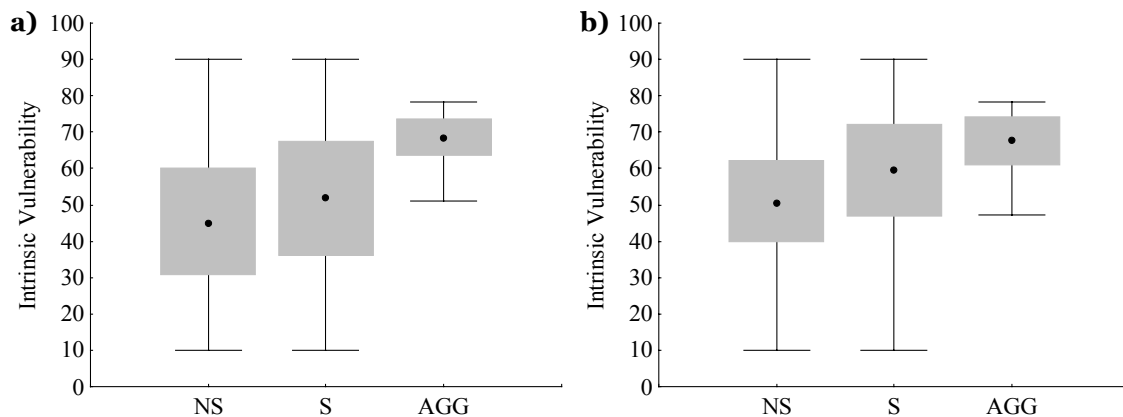


Figure 2. Intrinsic vulnerability index for fish species no-occurring on seamounts (NS), occurring on seamounts (S), and seamount-aggregating species (AGG); a) including all fish species; b) for species reported in FAO official landing statistics. In the graphs the middle point is the median, while the box represents the 25%-75% percentiles, and the whisker the range, excluding outliers.

The differences in vulnerability between seamount and non-seamount fishes were mainly due to benthopelagic and demersal fishes (Figure 3), which were found to have significant different medians of intrinsic vulnerability (U ; Demersal $p= 0.003$; Benthopelagic $p= 0.001$). For all other fish groups, the paired comparisons of medians were not significantly different. We also found that the bathydemersal fishes, benthopelagic and demersal fishes were among the most vulnerable fish groups, with seamount-aggregating fishes having the highest intrinsic vulnerability.

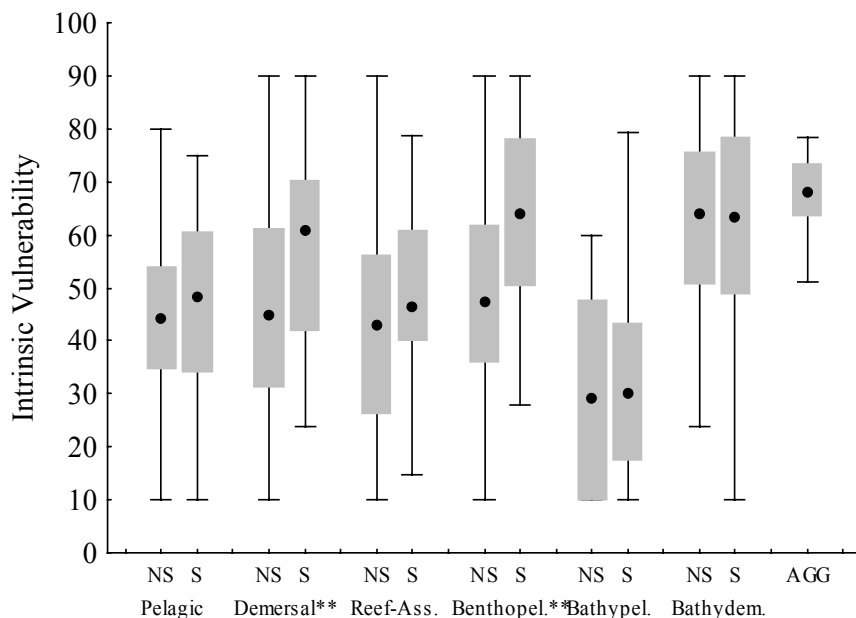


Figure 3. Intrinsic vulnerability index for fish species of different habitats: not-occurring on seamounts (NS), occurring on seamounts (S). The vulnerability for seamount-aggregating species (AGG) is also presented. In the graphs the middle point is the median, the box the 25%-75% percentiles, and the whisker is the range. ** indicates significant differences between medians (Mann-Whitney test; Pelagic: $p= 0.471$; Demersal: $p= 0.003$; Reef-Associated: $p= 0.076$; Benthopelagic: $p= 0.001$; Bathypelagic: $p= 0.806$; Bathydemersal: $p= 0.833$).

Vulnerabilities of the ‘deep-sea fish’ group (bathydemersal fishes not occurring on seamounts) (median $Vul= 64.0$) were not significantly different from seamount demersal fishes (median $Vul= 61.0$; $U, p= 0.194$), seamount benthopelagic fishes (median $Vul= 64.0$; $U, p= 0.819$) and seamount bathydemersal fishes (median $Vul= 63.5$; $U, p= 0.833$). Seamount-aggregating fishes (median $Vul= 68.2$) were the only group having higher vulnerability estimates than the ‘deep-sea fish’ group, but this difference were not significant ($U, p= 0.335$).

We found that vulnerabilities estimates for bathydemersal fishes non-occurring on seamounts, the ‘deep-sea fish’ group, (median $Vul= 64.0$) were similar and not significantly different from the vulnerabilities estimated for seamount demersal fishes (median $Vul= 61.0$; $U, p= 0.194$), seamount benthopelagic fishes (median $Vul= 64.0$; $U, p= 0.819$) and seamount bathydemersal fishes (median $Vul= 63.5$; $U, p= 0.833$). Seamount-aggregating fishes (median $Vul= 68.2$) was the only group having higher vulnerability estimates than the ‘deep-sea fish’ group, but this difference were not significant ($U, p= 0.335$).

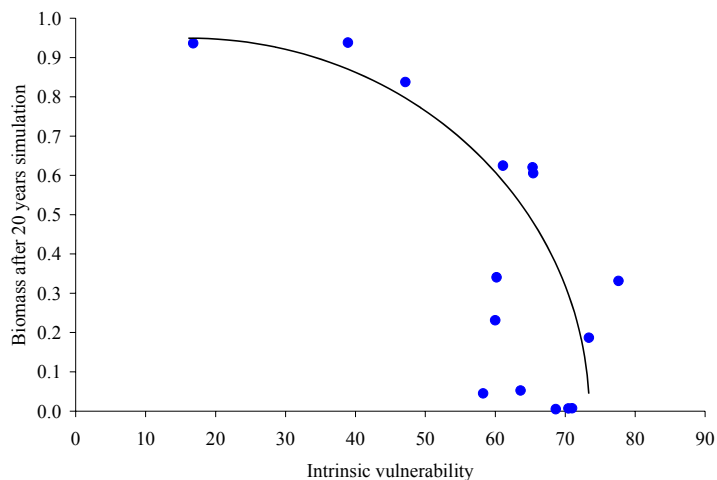


Figure 4. Biomass decline over time for fish groups with different intrinsic vulnerabilities. Biomass change was estimated by a generic seamount ecosystem model (Morato and Pitcher, 2002) and simulating the effect of a 0.3 fishing mortality rate for each group over a 20 years period.

We found that the intrinsic vulnerabilities estimated from the fuzzy system were significantly related ($R^2= 0.645, p= 0.007$) to the simulated population declines of marine fish groups (Figure 4) caused by fishing. Groups of species with higher vulnerabilities had larger biomass declines than species with lower vulnerabilities. Moreover, our simulation showed that even at modest levels of fishing, seamount species were depleted, not sustained.

Our estimates of relative risk of extinction (Figure 5) showed that seamount fishes (Orange roughy, Alfonsinos and seamount-aggregating fish) have the highest indices, followed by deepwater bottom fish (bathydemersal and bathybenthic) and elasmobranchs (rays, skates and sharks).

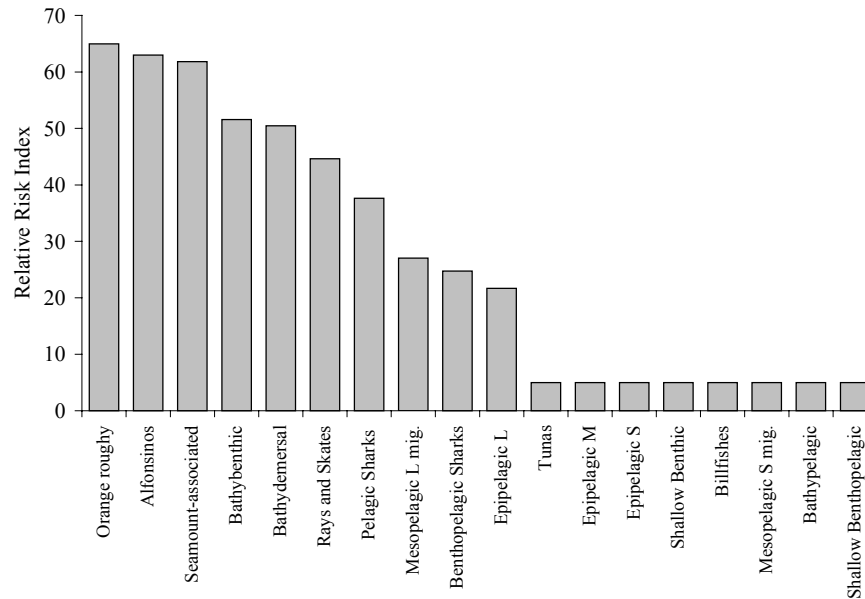


Figure 5. Relative risk of extinction for fish groups used in a generic seamounts ecosystem model (Morato and Pitcher, 2002).

DISCUSSION

Despite our rather broad definitions, our global analysis of over 14,000 species shows that seamount fishes, particularly seamount-aggregating fishes, have higher intrinsic vulnerability than other groups of fishes. The pattern is similar when we considered commercially-exploited species only. Biological characteristics leading to greater vulnerability include a longer lifespan, later sexual maturation, slower growth and lower natural mortality. These findings are in agreement with the life-history features of seamount fishes proposed by Koslow (1996; 1997), although very few complete case studies are available.

The high vulnerability raises serious conservation concerns about the exploitation of seamount fishes. Our simulation model confirmed that the biomass of fish with higher vulnerabilities declined more rapidly under exploitation. Although data limitations prevents us from validating the modelling results using empirical data, evidence from other species assemblages suggests a significant positive correlation between vulnerability and population decline (Cheung et al., this vol.). Considering that seamount fishes are increasingly being targeted by fishing (Watson and Morato, this vol.), highly vulnerable seamount species such as Orange roughy, Alfonsinos and other seamount-aggregating fishes may be under considerable risk of local extinction under only moderate fishing intensity ($F=0.3 \text{ year}^{-1}$ in our simulation model).

In the light of this analysis, we may ask whether seamount fisheries may be sustainable in the long term (Clark, 2001); our simulations suggest that exploitation rates of more than 5% are not sustainable. Examples from all over the world have shown the 'boom and bust' characteristic of seamount trawling fisheries, with rapid stock reduction and serial depletion of successively exploited new seamounts. The case of the Orange roughy, a seamount-aggregating fish, is well known. In Namibian waters, Orange roughy has been fished down to 10% of its pre-exploitation biomass in six years (Branch, 2001), while in Australia, biomass levels dropped to 7-13% in about 15 years (Lack, 2003). The Orange roughy stock in New Zealand was fished down to 15-20% of pre-exploitation level in less than 15 years (Clark, 2001), while annual sustainable levels of fishing have been estimated to be less than 2% of pre-exploitation level (Francis et al., 1995), which may not be economically viable. Another example is Russian fishing on seamounts at the Mid Atlantic Ridge. Vinnichenko (2002a) showed that the total catch (mainly of Alfonsino, *Beryx splendens* and Scabbardfish *Lepidopus caudatus*) at nine seamounts in the South Azores area and in three seamounts at the Corner Rising area declined, in each area, from 12,000 t to below 2,000 t in just two years. In a larger area of the ridge that included 34 seamounts, catches declined from 30,000 t to below 2,000 t in about 15 years (mainly Roundnose grenadier, *Coryphaenoides rupestris*, and Orange roughy).

Deep-water species have also been considered sensitive to exploitation owing to their biological parameters (Merrett and Haedrich, 1997; Roberts, 2002). Our analysis supports this theory by showing that bathydemersal fishes were far more vulnerable than any other non-seamount group of fish; only seamount aggregating fish had higher vulnerabilities.

The high vulnerability of seamount fishes should be a strong reason for more precaution in managing seamount resources. Collapse of seamount fisheries have often been attributed to lack of management. However, even in places where detailed research programmes were implemented at the same time that trawl fisheries exploitation started, and where scientific recommendation for management were followed and fisheries controlled, catches have declined unexpectedly fast and stocks have been depressed well below the biomass generating maximum sustainable yield (Boyer et al., 2001). In light of our research, this experience supports the conclusion that fishing on seamount is not sustainable, at current levels and with current methods. A number of seamount populations have already been depleted. More will be depleted and some will go extinct if fishing on seamounts continues at the current, high, or even at more moderate levels.

Our fuzzy-logic, life-history attributes method of estimating intrinsic vulnerability to biomass depletion by fishing (based on Cheung et al. this vol.), followed by evaluation of sensitivity and local extinction risk using simulation, is a relatively new technique, but it may be more informative and robust than previous methods. It provides a quantitative basis for more conservatively management of fisheries for seamount and seamount-aggregating fish in the future.

APPENDICES

The list of fish species occurring for seamounts worldwide prepared by Froese and Sampang (this vol.) was augmented from additional sources:

1. Additions to Froese and Sampang's checklist of seamount fishes.

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EXPLOITATION PATTERNS IN SEAMOUNT FISHERIES: A PRELIMINARY ANALYSIS

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ABSTRACT

Serious stock depletion on continental shelves helped create new pressure for alternative fishing grounds. In particular, seamounts were among those 'newly' targeted ecosystems that have been intensively fished since the second half of the 20th century. But what are the seamount fisheries? How have their catches changed in recent years? Can we map where these catches are taken? This paper describes the progress of this work. Most seamount species are also found on the continental slope, making the allocation of reported catches to specific seamounts difficult. Thus, future mapping of landings will require species distributions that allow proportioning of catches between slope areas and those taken on seamounts. Catches of fishes identified as mostly occurring on seamounts only began in 1967, initially with the Orange roughy fishery. The catches of these species have only continued because new seamounts with harvestable stocks were discovered as fisheries collapsed, and because new stocks or species were targeted. A pattern of successive rapid development and decline is evident. While the percent of fisheries that collapsed is somewhat similar for seamount species and those not associated with seamounts, it is obvious that those fisheries that are based on species found only on seamounts have collapsed with greater frequency and had poorer recovery. This points towards the conclusion that not only seamount fisheries, but deep-water trawling in general, may not be sustainable in the long term.

INTRODUCTION

Arguably, the expansion of commercial fisheries into deepwater areas, especially those outside the jurisdiction of current management agencies, is one of the most worrying developments in recent years. The life-history of many of the species exploited in these environments makes them particularly susceptible to overfishing and serial depletion (Morato et al., this volume). Already there is considerable evidence that many of these fisheries are more similar to 'mining' operations than to sustainable fisheries (Hopper, 1995; Merret and Haedrich, 1997), with targeted fish stocks showing signs of overexploitation within a short period from the beginning of the fishery. This has been the case for the Orange roughy (*Hoplostethus atlanticus*) fishery off the waters of New Zealand (Clark, 1999; Clack et al., 2000), Australia (Lack, 2003), Namibia (Boyer et al., 2001; Branch, 2001), and the North Atlantic (Branch, 2001), the pelagic armorhead (*Pseudopentaceros wheeleri*) fishery over seamounts in international waters off Hawaii (Sasaki, 1986; Humphreys and Moffitt, 1999), the blue ling (*Molva dipterygia*) fishery in the North Atlantic (Bergstad et al., 2003) and Alfonsino (*Beryx splendens*), Roundnose grenadier (*Coryphaenoides rupestris*) fisheries in the Mid Atlantic Ridge (Vinnichenko, 2002) and Giant redfish (*Sebastes marinus*) fishery in international waters close to Iceland (Hareide et al., 2001). To those investing in these fisheries, the low productivity of stocks, the high logistic costs, and their unregulated, 'gold rush' performance must represent a considerable risk. However, the high prices obtained for species such as 'Chilean seabass', i.e., the Patagonian toothfish (*Dissostichus eleginoides*), especially in the restaurant markets of America, offset losses. Over recent years more and more of the deep ocean bottom has been fished and these include areas with seamounts (Pauly et al., 2003).

Seamount fisheries have recently deserved much attention mainly because of their increased importance and recognized impact on these ecosystems. Information on seamount fisheries, however, is very sparse, and it is difficult to make a distinction between deep-water fishing activities in general and those occurring on seamounts. Moreover, fish species living on seamounts are also known to occur on other habitats, such as continental slope, and landings statistics are not spatially allocated, making it difficult to make an estimate of the total fisheries occurring on seamounts worldwide. Nevertheless, seamount fisheries are usually assumed to be economically important.

But what are seamount fisheries? How have their catches changed in recent years? Can we map where these catches are taken? To complete these tasks requires that we identify which species are associated with seamounts (see Stocks, this vol.; Froese and Sampang, this vol.), either exclusively or otherwise so that we can then examine their landings to date. Once we describe their global distributions with regard to the locations of seamounts (see Kitchingman and Lai, this vol.) we can construct maps of where they were taken. This report will describe the progress of this work.

METHODS

Identifying seamount associated fishes

An analysis of the published works describing the association of fish species with seamounts (Froese and Sampang, this vol.; Morato et al., this vol.) and continental slopes was used to construct a list of fish species with commercial value that occur on seamounts (Appendix 1). It must be recognized that in most cases species, associated with seamounts are or, at least were, associated with the continental slopes of many countries and not exclusively with seamounts (e.g. Tracey et al., 2004). In several cases the abundance of these species on the slope has diminished with fishing such that today they are recognized as predominantly 'seamount' species. It would, however, appear that there are comparatively few commercial fish species that are found almost exclusively on seamounts.

Global Catch Data Sources

The *Sea Around Us* project (SAUP) has constructed a global database of fisheries catches sourced from a number of agencies, regional and national, in addition to data made available by FAO (Watson et al., 2004). Using rule-based methods, and databases of the global distribution of species, as well as the fishing patterns of reporting countries, this project has mapped otherwise vaguely described catch data on a system of 180,000 spatial cells measuring 30 minutes of longitude by 30 minutes of latitude.

Analyzing Patterns of Collapse and Recovery

We examined the catch trajectories for each reported species and other taxonomic units in the SAUP catch database (<http://www.seararoundus.org/>). Fisheries were defined as any reported taxa within a large marine ecosystem (Sherman et al., 1990) for which a cumulative catch of at least 100 tonnes was reported since 1950. Most reached their maximum annual catch before the end of the time series that extends from 1950 to 2001 inclusive. In all series where a maximum occurred, it was examined to find out whether the catch had collapsed, which we defined, following Froese and Pauly (2003), as reduction in any one year to 10% or less than the maximum. The number of years between the year of the maximum and that of the collapse was calculated, as were the percent annual catches of the maximum that was reached 5 years, 10 years and 15 years following the collapse. The latter were used as an estimate of fishery recovery.

RESULTS AND DISCUSSION

Seamount associated fishes and their catches

The list of commercial fish species occurring on seamounts is surprisingly long (Appendix 1). Most species are also found on the continental slope, making the allocation of reported catches to specific seamounts difficult. Though there is some documented harvest of invertebrates, e.g., corals (Anon., 1999), associated with seamounts, it is very difficult at present to distinguish the dependence of commercial invertebrates on seamounts. Therefore we have limited our analyses to fishes. Future mapping of landings will require species distributions that allow proportioning of catches between slope areas and those taken on seamounts. Given the rapid depletion of some coastal stocks this partitioning will have to make some assumptions of the relative abundance in both areas through time. This work is underway but will need to be revised by experts with specific knowledge of seamount areas.

Based on FAO data, we infer that present landings of the slope and seamount-associated fishes in Appendix 1 presently stagnate at around 15 million t. Our examination of the distribution of species contributing to these catches suggests that species with a strong presence on continental slope, in relative close proximity to the fishing ports of industrialized countries, notably in the North Atlantic and North Pacific, would have supplied the overwhelming bulk of the earliest catches. Those catches reported in more

recent years, however, appear to consist to an increasing extent of species taken from seamounts (including those shown in Figure 1). Unfortunately there is a significant illegal catch of some species, notably Chilean seabass (i.e., Patagonian toothfish, *Dissostichus eleginoides*), so that the true landings, in recent years, would likely be higher than what has been reported to FAO from member countries. In fact, the illegal, 'pirate', catch of this species may be as much as four times the officially reported catch. (<http://www.traffic.org/toothfish>), and most of this is consumed in North America and Asia. Overall, we assume that the fraction of landings taken from remote seamounts compared to continental slope areas will continue to increase for some species (as also suggested in Pauly et al. 2003), at least until their stocks collapse.

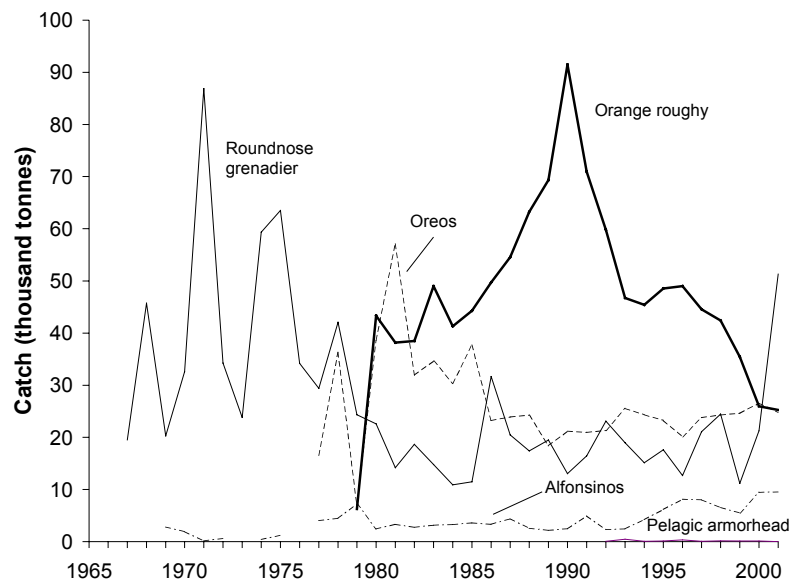


Figure 1. Sequence of catches in five seamount species, with the high variability documenting their lack of sustainability (see text).

Composition of seamount associated fish catches (1950-2001)

Figure 1 shows the catch composition from 1950 to 2001 of fishes identified as mostly occurring on seamounts (as subset of seamount associated species listed in Appendix 1). Catches of these species only began in 1967, initially with the Orange roughy fishery. The graph shows that the catches of these species has only been maintained because new seamounts with unexploited stocks were being discovered and because new species became targeted. A pattern of successive rapid development and decline is evident.

Collapse and Recovery of seamount associated fisheries

Table 1 compares the collapse and recover of non-seamount fisheries (Non-SM) with those of seamount associated (SM) and seamount only (SM Only, i.e., those species usually associated only with seamounts). While the percentage of fisheries that collapsed is somewhat similar for seamount associated species and those not associated with seamounts, it is obvious that those fisheries that rely on species found only on seamounts have collapsed with greater frequency. In addition, the latter fisheries took less than half the time between the year the maximum landings were reported until they collapsed (dropped to <10% of the maximum). This took less than four years on average for directed seamount fisheries. Following collapse the recovery of the fishery, as indicated by the percent of the maximum catch that was obtained 5, 10 and 15 years after the collapse, was also worse for directed seamount fisheries.

This points towards the question whether non-only seamount fisheries, but also deep-water trawling in general, may or may not be sustainable in the long term (Clark, 2001). Recently, several scientific studies (e.g. Hopper, 1995; Merrett and Haedrich, 1997; Moore, 1999; Moore and Mace, 1999; Probert, 1999; Roberts, 2002), and environmental NGOs (WWF and TRAFFIC, Lack et al., 2003; IUCN), and governments (New Zealand, Australia, Canada) have strongly advocated an urgent need for implementation of fishing regulations for deepwater fisheries, the establishment of marine reserves, and/or ban of deepwater trawl in what have been considered a very sensitive habitat, the seamounts (see also Alder and Wood, this vol.).

Table 1. Comparison of the collapse and recovery of non-seamount fisheries (Non-SM), those based on seamount associated fisheries (SM), and those based on species usually only found on seamounts (SM Only). Note that here, a 'fishery' is defined by one catch series, representing the same taxon, within the same Large Marine Ecosystem (see LME definitions and catch data in <http://www.seararoundus.org/>).

Fishery Type*	% collapsed	Years post Max. to collapse	5 yrs post collapse (% max)	10 yrs post collapse (% max)	15 yrs post collapse (% max)
Non-SM	46	8.2	13.3	12.9	13.0
SM	49	7.9	14.1	12.2	14
SM Only	64	3.5	12.7	7.6	8.4

FUTURE WORK

In order to map the catch of seamount associated fishes using the procedures used by the Sea Around Us Project (Watson et al., 2004) it is first necessary to construct distributions for these species. As discussed previously this is challenging as it must recognize that for some species, their abundance on the slope has declined significantly in recent years, leaving only fisheries on isolated seamounts, i.e., in high seas areas. Once these distributions have been constructed, they can be used to guide catch allocations and maps of catches can be constructed such as those found at <http://seararoundus.org/globalcatch/viewer.htm>.

CONCLUSION

The quantification, mapping and evaluation of seamount fisheries are a immediate needs. Many species identified have life histories that place them at great risk (see Morato et al., this vol.), especially in the cooler, relatively low productive waters of the world's southern oceans. Many of these fisheries are outside the current management mandate of any country (Alder and Wood, this vol.). 'Pirate' fleets roam these areas with relatively impunity and the sustainability of the resource is not of great interest to them. Scoping this problem must be a priority before these resources, and the ecosystems upon which they depend, are compromised.

APPENDICES

The list of commercial fish species occurring on seamounts is surprisingly long and is presented in the following appendices:

1. Commercial fish taxa associated with seamounts

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MANAGING AND PROTECTING SEAMOUNTS ECOSYSTEMS

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ABSTRACT

The overwhelming evidence of the fragility of seamounts and their associated resources suggests that they require a high level of protection. Seamounts have a global distribution, existing within and beyond areas under national jurisdiction. Seamounts in areas under national jurisdiction can be protected using legal mechanisms such as protected areas and fisheries restrictions. However, the legal and geopolitical challenges to protecting international waters, including seamounts, are numerous and far-reaching: there is no unified managing authority, and so seamounts in particular are subject to unmanaged exploitation by several countries. The vulnerability of seamount species and lack of management in the high seas has prompted NGOs to call for the designation of international protected areas for fragile deep-sea ecosystems, including seamounts, and for a United Nations moratorium on high seas bottom trawling until a management regime is adopted. In this paper, we present preliminary analyses of: 1) the distribution of seamounts inside and outside areas under national jurisdiction, to assess the extent to which gaps in the international legal regime might compromise the maintenance of the ecological values of seamounts, and 2) the number of seamounts already protected under existing mechanisms within EEZs. We discuss the nature of existing management and protection of seamounts, and examine the various legal and institutional instruments, which may be used to improve seamount management.

INTRODUCTION

Seamounts are unique marine ecosystems, which often support fragile habitats and vulnerable species of flora and fauna (Morato et al., this vol.; Stocks, this vol.). These unique characteristics and their associated biodiversity, high potential endemism (Richer de Forges et al., 2000; Stocks, this vol.), fishery values and threats (both anthropogenic and natural), are explored in detail in other chapters of this report. In general, our knowledge of seamounts is far less comprehensive than for many other marine ecosystems and, so the importance of and need to protect these ecosystems is only just being recognized. However, the fragility of seamount ecosystems, and the magnitude of threats posed to them (Koslow, 1997; Morato, 2003), renders an assessment of their management needs an urgent task.

A preliminary analysis of the distribution of seamounts, inside and outside areas under national jurisdiction, was performed. Using the predicted seamount distribution described in Kitchingman and Lai (this vol.), we estimate that 47% of seamounts (> 1000m tall) fall inside Exclusive Economic Zones (EEZs) and 53% occur in international waters. This result is markedly different from the general perception that most seamounts occur outside areas under national jurisdiction and has profound implications for the ways in which appropriate levels of seamount management protection might be achieved. In this paper, we examine the available instruments and institutional arrangements and suggest options for the future management and protection of seamounts nationally and internationally.

CURRENT PROTECTION

The current level of protection of seamounts was also assessed. Existing marine protected area (MPA) data on the global scale is available through the World Database on Protected Areas (WDPA), maintained by the United Nations Environment Programme's World Conservation Monitoring Centre (UNEP-WCMC). A preliminary overlay analysis was undertaken with this MPA data and the seamount data. Approximately 84 MPAs cover 346 seamounts found in EEZs; this is about 5% of the seamounts located within EEZs and identified by Kitchingman and Lai (this vol.). However, they underestimate the global number of seamounts, and hence this 5% value is almost surely too high, perhaps by as much as a factor of five to ten. However, even this high value indicates that, in comparison to other critical habitats such as coral reefs and seagrasses, seamounts are much less well protected within EEZs (Figure 1), and completely unprotected in the high seas. This difference can be explained by numerous factors. Firstly, people have a greater awareness of the threats and values of coral reefs and mangroves or for charismatic mega-fauna

such as whales and dolphins through their greater visibility as well as the media attention that these habitats and animals receive. Consequently, there is a longer history of protecting them. Secondly, seamounts were little known other than by fishing fleets until more recently. Thirdly, the freedom of the high seas as defined by the United Nations Convention on Law of the Sea (UNCLOS) left the substantial proportion of seamounts in international waters vulnerable to overexploitation and with little legal leverage to prevent it.

Strategies for seamount protection are consequently nascent and as such provide resource managers with the opportunity to review the lessons learned to formulate an effective and efficient model for managing seamounts and their associated resources.

CURRENT MANAGEMENT INSTRUMENTS

National

Most countries have a range of legislative measures that can be used to manage and protect seamounts and their associated biodiversity, although few have actually deployed them. The nature and scope of national legislation and policy instruments that are commonly used include:

Legislation

- Fisheries;
- Minerals (including gas and oil);
- Transportation and Navigation;
- Environmental Impact Assessment;
- Hazardous Waste Disposal;
- Protected Areas;
- Biodiversity Protection.

Policy

- Ocean and Coastal Planning;
- Coast Guard and Defense Force Roles.

Protected area legislation and policies potentially provide one of the most comprehensive instruments for managing seamounts in most countries if the mandate to control other activities such as fishing and mining is included. Few countries have used protected area legislation to protect their seamounts. Despite an estimated 155 countries having seamounts within their maritime jurisdictions, only 22 countries appear to have applied protected area legislation to all or a portion of them, and not in all instances has such legislation resulted in meaningful protection. The most significant areas of protected seamounts are in the Northwestern Hawaiian Islands (341,000 km²) with approximately 66 seamounts, the Galapagos (140,000 km²) with 24, Tasmania (Australia) where more than 17 seamounts within an area of 370 km² are protected from all forms of fishing except for tuna long-lining (DEH, 2004) and in Canada where the Bowie-Hodgkins and Davidson complex is a pilot marine protected area encompassing more than 1400 km² (AXYS Environmental Consulting, 2003).

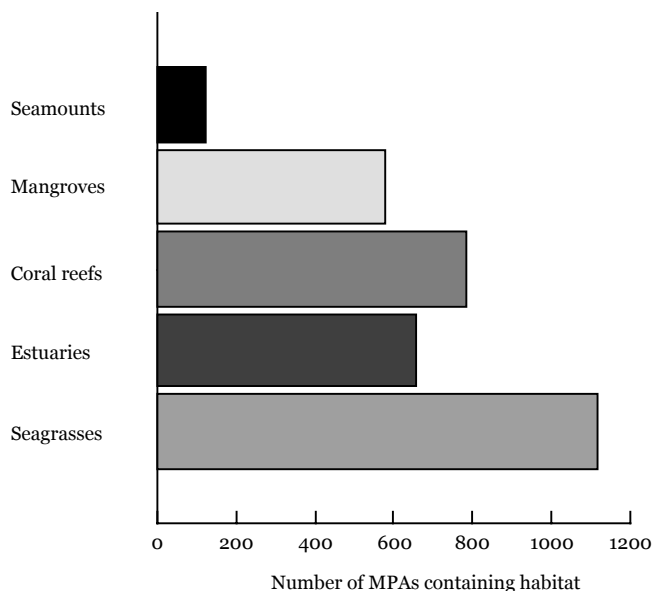


Figure 1. Number of MPAs containing critical habitat globally [adapted from UNEP-WCMC protected areas, coral reef, mangrove and seagrass databases (WDPA Consortium, 2004; WCMC-UNEP, 2004) and Sea Around Us Project estuaries and seamounts database (<http://www.seaaroundus.org>)].

Much more effort is currently given to managing fish resources on seamounts within national jurisdictions than in international waters. Australia, Portugal, New Zealand and the United States all have specific fisheries management measures in place aimed at either sustainably managing resources or in some cases such as New Zealand, rebuilding fish resources (AXYS Environmental Consulting, 2003; Ministry of Fisheries, 2003; Commission of the European Communities, 2002). However, the intrinsic vulnerability of seamount fishes (Froese and Sampang, this vol.; Morato et al. this vol.), the unsustainable nature of seamount fisheries (Watson and Morato, this vol.) and the general history of poor management of many commercially important fish (Ludwig et al. 1993; Pauly et al. 2002) make it abundantly clear that fisheries management alone will not be sufficient to protect these fragile ecosystems, and the fisheries from themselves (see also CDB 2003; Gianni 2004).

Seamounts managed outside of the scope of protected area legislation may be subjected to the same complex institutional and administrative arrangements that are used to manage coastal areas in many countries. Given the limited progress that has been made in effective management of the coasts globally, managers and policy makers are well advised to avoid using many of the coastal management models in current use. National ocean policy may have potential to provide for efficient and effective management of seamounts. However, few countries have developed their ocean policies and even fewer have implemented such policies (Alder and Ward, 2001; Gianni 2004).

International

There are no international instruments that specifically protect or manage seamounts in the high seas. There is growing concern for the management of deepwater ecosystems on the high seas as shown by the recent global and regional initiatives:

- IUCN Amman Resolution on High-Seas MPAs (October 2000) (de Fontaubert, 2001);
- UN General Assembly Resolution on Ocean and Law of the Sea regarding management of risks to marine biodiversity including seamounts (A/58/L.19) (United Nations, 2003);
- High Seas Marine Protected Areas (HSMPAs) Action Plan (WWF-IUCN, 2003);
- Deep Sea Fishing Conference held in December 2003 in Queenstown, New Zealand;
- Recommendations of the 7th Conference of the Parties of the Convention on Biological Diversity (CBD, 2003).

These initiatives, along with earlier ones, all call for the protection and management of deep-sea ecosystems including seamounts within the framework of existing international instruments where possible. There are many international instruments established that provide a range of options for managing and protecting seamounts (Table 1).

UNCLOS together with its subsidiary Mining Act and Fish Stocks Agreement contain provisions to establish and manage areas closed to fishing and other extractive or harmful activities outside of national jurisdictions if such measures are undertaken in co-operation with the States that are involved. This form of cooperative agreement is seen in Regional Fish Bodies that have implemented strict fisheries conservation measures including areas closed to fishing. For example, some international waters within the NAFO Regulatory Program are closed to fishing (DFO, 2004).

While there are a number of international instruments that, if further developed, could be used to manage and protect seamounts, there is no single instrument that has sufficiently wide reaching provisions to manage them on an ecosystem basis. Creating yet another instrument to manage a single ecosystem is possible, but given the jurisdictional disputes that would arise, this option is highly questionable. Many binding instruments have a clause which enables member countries to object to provisions and therefore avoid taking decisions that threaten national interests at the expense of the resources and ecosystems (Alder and Lutgen, 2002). If a new instrument is necessary it should contain mechanisms that compel countries to abide by the instruments provisions and create a disincentive to disregard the provisions as demonstrated, for large pelagic fisheries, by the economic sanctions against countries that fish outside of ICCAT's annual management measures. The lack of an adequate governance regime for bottom fish in the high seas, combined with evidence that seamount fisheries tend to be unsustainable (Watson and Morato, this vol.), has prompted Non-Governmental Organizations (NGOs) to call for an United Nations moratorium on high sea bottom trawling until an appropriate regime can be developed.

Table 1: International Instruments and their Application in Managing and Protecting Seamounts

Instrument	Potential for Seamount Management and Protection
Binding	
UNCLOS-Mining Agreement	Under Article 162.2.x of UNCLOS the International Seabed Authority may disapprove an area for exploitation where substantial evidence exists that mining activities pose a serious risk to the marine environment. Article 145 provides for the protection and conservation of the natural resources of the Area and the prevention of damage to the flora and fauna in the marine environment.
UNCLOS – Pollution	Under Part XII of UNCLOS States are obliged to protect and preserve the marine environment, especially ‘rare or fragile ecosystems as well as the habitat of depleted threatened or endangered species’ and to take measures individually or collectively to not cause pollution within and beyond their jurisdictions.
UNCLOS - Fisheries	UNCLOS obliges States to cooperate and conserve the living resource of the high seas. The States that are party to the Convention can take whatever measures are necessary to ‘maintain or restore populations of harvested species at levels which can produce the maximum sustainable yield’ and measures such as marine protected areas are not prohibited.
Fish Stocks Agreement	This Agreement addresses the shortcomings of UNCLOS in dealing with straddling and highly migratory stocks and is very relevant to fish on seamounts. The Agreement requires States to adopt compatible management measures without specifying which measures prevail in the case of disagreements (de Fontaubert, 2001). The Precautionary Principle also features prominently in the agreement and obliges States to be more cautious when information is inferior and not to use a lack of information as justification to avoid taking appropriate conservation and management measures
Regional Fisheries Agreements/Conventions	Most agreements contain provisions to undertake a range of fisheries management options that could be used to protect and manage seamount resources including closing areas to fishing, restricting the use of specific gear (e.g. trawls) and the size of species caught. Agreements, which restrict the range of species they can manage may need to be amended to include seamount species.
Convention on Biological Diversity and Jakarta Mandate	Article 4 extends the Convention beyond national jurisdictions for processes and activities undertaken by member States while the Jakarta Mandate includes calls for the establishment of MPAs.
Convention on the International Trade of Endangered Species (CITES)	CITES could be used to the management and protection of selected seamount species. Currently there are no seamount species listed, however, there have been calls to add the Patagonian toothfish to the list (Willock, 2002).
London Convention and IMO Particularly Sensitive Sea Areas	Waste disposal at sea is managed through this convention. The activities of ships, including discharges in the vicinity of seamounts can also be managed using Particularly Sensitive Sea Areas (PSSAs).
World Heritage Area Convention	The Convention stipulates that World Heritage Areas must be contained within national boundaries and therefore of limited use in managing and protecting seamounts in international waters.
Regional Seas Programs	Some of the treaties that establish specific Regional Seas Programmes extend into the high seas. In addition some treaties have provisions and protocols to protect areas and wildlife.
Non Binding	
FAO Code of Conduct	The Code can be used to manage fisheries on seamounts.
Agenda 21 and World Summit on Sustainable Development (WSSD)	The international initiatives have called for the establishment of marine protected areas on the high seas. The WSSD called for a network of Marine and Coastal Protected Areas within and beyond national jurisdiction by 2012.
FAO International Plan of Action to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing	Seamounts are considered major centres of IUU fishing and therefore addressing the issue of IUU will contribute to managing and protecting seamounts (Rigg, 2004).

It could be argued that the International Whaling Convention has set the precedent for managing for a single species and it was used to establish two sanctuaries in the high seas (Indian Ocean and Southern Ocean), and therefore management for a single ecosystem is justified. However, recent calls for seamount management and protection promote the use of existing instruments, especially those that are consistent with the United Nations Convention on Law of the Sea. Kenchington (1990) suggested the same for coastal management. In the absence of a single instrument, seamount management and protection will need to use a mix or further elaboration of the above conventions and agreements. This leads to the question of the most appropriate institutional arrangement.

INSTITUTIONAL ARRANGEMENTS

Many of these instruments listed in Table 1 are implemented through international organizations such as the United Nations, Regional Fish Bodies (e.g. the North Atlantic Fisheries Organization), Secretariats (e.g. that of the Convention on Biological Diversity) and Commissions (e.g. the International Whaling Commission). New models for managing and protecting seamounts need to be explored. These current models as well as those used in coastal management are far from ideal since they have not prevented the decline of many fish stocks or the degradation of coastal ecosystems. Alternative institutional arrangements that use cybernetics have been suggested for managing coasts (Kay et al., 2003) and could be considered for managing seamounts.

Any institutional arrangement that is used needs to manage seamounts on an ecosystem basis, embrace the precautionary principle and take an adaptive management approach. The limited knowledge on seamount ecosystems and their vulnerability to overexploitation necessitates a precautionary approach. Management of seamounts as a whole ecosystem on the high seas will be the first attempt to take ecosystem management into a truly international situation. Undoubtedly, there will be several lessons learned before the most appropriate instruments and management arrangements emerge.

Seamounts are well suited to an adaptive management approach since there are some seamounts that are not exploited, which could serve as control sites in an experimental approach, as well as serving as test cases for MPAs. De Fontaubert (2001) suggested that States should seriously consider establishing high-seas MPAs over seamounts that are not fished. In some circumstances, (e.g., when dealing with straddling stocks), States can use instruments such as the Fish Stocks Agreement and institutions such as regional fisheries bodies to take a precautionary and adaptive approach. Seamounts may be the one set of ecosystems where a HSMPA may succeed and provide lessons learned for other countries considering similar initiatives to draw upon (de Fontaubert, 2001).

Enforcement of the provisions of any future instrument or arrangement will need to be considered. Illegal, unreported and unregulated fishing occurs on seamounts and needs to be addressed as part of any seamount management initiative. Many seamounts in the high seas are isolated and the cost of surveillance on the water or remotely will be expensive for any country. This is clearly demonstrated by the cost (more than 3.7 million USD) to capture an Uruguayan vessel illegally fishing for Patagonian toothfish in Australia's EEZ (Goldsmith, 2003).

Current arrangements for enforcing the provisions of regional fisheries arrangement in the high seas are usually the responsibility of member countries. The effectiveness of these arrangements is highly variable depending on the membership composition (Alder and Lutgen, 2002). Regional fish bodies such as NAFO and NEAFC, with most members from highly developed countries in North America and Europe, have relatively well-funded and effective enforcement programs compared to regional fish bodies made up of developing countries such as the Fishery Committee for the East Central Atlantic (West Africa).

In the short-term, regional fish bodies can expand their jurisdiction to include managing fisheries resources on seamounts, especially bottom trawling (Gianni, 2004), and where stocks are at risk close the areas to fishing (CBD, 2003). Similarly regional seas bodies could extend their mandate to include seamounts and work with regional fish bodies to better manage these ecosystems. As well, we believe that increased support should be given to FAO's Action Plan to Prevent, Deter and Eliminate Illegal Unreported and Unregulated Fishing. On the longer term, however, dedicated measures will have to be taken to explicitly protect seamounts in high sea areas.

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GLOSSARY

Abyssal floor/plains: Pertaining to the great depths of the ocean; deep bottom area or portion of submerged earthform between the depths of 4,000 - 7,000 m.

Age at first maturity: Mean or median age at first maturity, i.e., age at which 50% of a cohort spawn for the first time (T_m).

Asymptotic length: A parameter of the von Bertalanffy Growth Function (VBGF), expressing the mean length the fish of a given stock would reach if they were to grow for an infinitely long period (L_∞)

Bathymersal: Living and feeding on the bottom below 200 m.

Bathypelagic: Region of the oceanic zone between 1,000 m to 4,000 m, i.e., between the mesopelagic layer (above) and the abyssopelagic layer (below). Also refers to animals living or feeding in open waters at depths between 1,000 and 4,000 m.

Benthic: Dwelling on, or relative to, the bottom of a body of water; living on the bottom of the ocean and feeding on organisms thereon.

Benthopelagic: Living and feeding near the bottom, as well as in midwater or near the surface. Feeding on both benthic and free-swimming organisms.

Bioluminescence: The light produced by organisms, such as lanternfish (Fam. Myctophidae).

Biomass: The combined weight, at or during a certain time, of all the members of a given population or stock.

By-catch: Non-targeted organisms taken incidentally in a fishery; by-catch species are often of lesser value than the target species, and thus often discarded. Some by-catch species are of commercial value and are retained for landing and sale. By-catch often consists of the juveniles of commercial species, and their loss has a deleterious impact on the overall yield obtained from a certain area.

Carnivores: Feeding on animal tissues, in contrast to herbivores, which feeding on plants. Most exploited fish are second- or higher-order carnivores, i.e., they feed on other carnivorous animals.

Catch: The number (or weight) of all fish killed by fishing operations, whether the fish are landed or not.

Commercially important fishes: species taken in and landed by capture fisheries, or farmed by the aquaculture industry of a country.

Continental shelf: The sea bottom from the shore out to a depth of 200 m; a zone adjacent to a continent or around an island, and extending from the low-water line to the depth at which there is usually a marked increase of slope to greater depth; the edge of the continent that is submerged in relatively shallow ocean water.

Continental slope: Region of the outer edge of a continent between the generally shallow continental shelf and the deep ocean floor, from 200 to 2,000 m; often steep.

Critically endangered: As defined by IUCN, a taxon is 'critically endangered' when it is facing an extremely high risk of extinction in the wild in the immediate future

Deep-sea fishes: Species living below 1000 m; some authors extend this to include species occurring between 500 and 1000 m.

Demersal: Referring to species living on or near the bottom and feeding on benthic organisms, e.g., the flatfishes.

Deposit-feeders: Species that feed on particles in the sediments. Because deep sea areas are far below the zone where light reaches and plants can grow, deposit-feeders are particularly abundant in the deeper waters, where they feed on 'marine snow', falling from surface layers, or drifting down from shallower waters, and consisting mainly of the remain of planktonic algae.

Ecosystem-based (fisheries) management: A concept whose definition is still evolving, but which moves away from an earlier emphasis on a few species of commercial interest, toward an explicit consideration of the food webs within which these species are embedded, and the habitats they require for the different phases of their life cycles.

Endangered: As defined by (IUCN, a taxon is 'endangered' when it is not 'critically endangered', but is facing a very high risk of extinction in the wild in the near future.

Endemism: Native and restricted to a particular area, e.g., a river basin, an island or seamount, a country or a continent.

Epifauna: The animals living on the surface of the bottom of a water body.

Epipelagic- The uppermost (normally lighted) layer of the ocean, between the ocean surface and the thermocline, usually between depths of 0-200 m; living or feeding on surface waters or at midwater to depths of 200 m.

Expert systems: A computer software/database, mimicking some features of the expertise held by professionals, and which can assist them in the exercise of their profession.

Extinction: Disappearance of a taxonomic group (species, genus or higher) of organisms from existence in all regions. Extinction occurs one population at a time, and a species is extinct when its last population is gone. The same applies to genera with reference to their component species, etc.

Fecundity: Number of propagules (eggs, larvae or pups in fishes) an animal produces during each reproductive cycle; the potential reproductive capacity of an organism or population. Usually increases with age and size.

Filter-feeders: Species that capture particles swept past them by water currents. Many filter-feeders take bushy shapes, which make them very vulnerable to mechanical damage.

Fitness: Contribution of an individual to the next generation, relative to the contribution of other individuals. The number of offspring an organism manages to produce, and which manage to grow and reproduce. Organisms use different strategies to realize their fitness, which may be 'called fitness strategies'.

Fuzzy logic: A type of logic that can recognize both true and false simultaneously, along with the degrees of belief associated with these propositions.

Gas glands: see Swim bladder.

Genetic diversity: The variety of genes within a particular species, variety, or breed; the sum of information embedded in the genes of an individual organism, community or ecosystem.

Herbivore: Feeding on plants, also plant eating, phytophagous (*see also* Carnivore).

Hills: Here: underwater mountains of heights below 1000 m; could also be referred as 'seamounts'.

Hyperstability: In fishery science terms, hyperstability refers to a phenomenon in which an observed index of stock abundance (e.g. catch per unit of effort or CPUE) remains stable although the abundance of the stock in question is actually declining.

Intrinsic rate of population increase: the maximum (potential) rate of growth of a population (resulting from the growth of individuals, and the entry of new individuals in the populations. Usually approached when a population are small relative to the resources available to it (r_{max}).

IUCN: International Union for the Conservation of Nature.

Life span: *See* Longevity.

Longevity: oldest fish ever recorded for a species or stock; also the age in an unexploited stock at which only 1% of a cohort has survived (T_{max}).

L_{max} : *see* Maximum length.

L_{∞} : Asymptotic length (*see also* von Bertalanffy growth function).

M : *see* Natural mortality.

Maturity: The stage of the life cycle of an organism at which it is able (during the reproductive season, if any) to develop ripe gonads and to participate in spawning (*See also* Age at first maturity).

Maximum length: Size of longest individual recorded from a stock (L_{max}).

Natural mortality: That component of total mortality not caused by fishing, but by natural causes such as predation, diseases, senility, etc. (M).

Omnivore: Pertain to animals feeding on both plant and animal tissue.

Overexploitation: *See* Overfishing.

Overfishing: Catching more fish than the maximum catch that a population can sustain, thus inducing a decline in its abundance, which then leads to declining catches.

Pelagic: Living and feeding in the open sea; associated with the surface or middle depths of a body of water; free swimming in the seas, oceans or open waters; not in association with the bottom. Many pelagic fish feed on plankton. In FishBase, 'pelagic' refers to fishes of to surface or mid water from 0 to 200 m depth (*see* Epipelagic).

Perciforms: A group of advanced fishes possessing hard spines in their fins, and including the perches, snappers, mackerels, tuna, etc. supporting large fisheries.

Phylogenetic: Based upon natural evolutionary relationships; pertaining to the evolutionary history of a particular group of organisms.

Rate of population increase: in a balanced or equilibrium fishery, the increment due to the rate of population increase replaces what is removed by fishing, and the rate of 'surplus production' (i.e., catch) is numerically equal to the rate of fishing. The maximum rate of increase of a population is determined by its intrinsic rate of increase (r_{max}) (*see* Intrinsic rate of increase).

Reef-associated: Living and feeding on or near coral reefs.

Resilience: The capacity of a system to tolerate impacts without irreversible change in its outputs or structure. In species or populations, this is often understood as the capacity to withstand exploitation.

SCUBA: Self-contained underwater breathing apparatus; aqualung equipment enabling diving by providing air (or other gaseous mixtures) without the need of an air tube to the surface.

Seamounts: undersea mountains (usually of volcanic origin) rising from the seafloor and peaking below sea level. By general consensus states, seamounts should be steep-sided and rise 1,000 m or more from the sea floor. Most are circular or elliptical although very elongated seamounts do occur.

Seamount-associated: Refers to species that aggregate in association with seamounts and similar oceanic features.

Stock-recruitment models: Mathematical, often dome-shaped, functions used in fisheries science to express the relationships between parental stock size (ordinate axis) and the subsequent 'recruitment' of juveniles (abscissa).

Sustainable exploitation: The use of components of biological diversity in a way and at a rate that does not lead to the long-term decline of biological diversity and stock biomass, thereby maintaining its potential to meet the needs and aspirations of present and future generations.

Swim bladder: A tough-walled gas-filled sac located just beneath the vertebral column of many bony fishes; its principal function is to offset the weight of heavier tissue such as bone. In some fishes also used for sound production or respiration. Often lacking in bottom fishes. Sometimes called air bladder, a less appropriate term.

Thermocline- The distinct interface between surface waters and cooler, deeper waters; region between the warm upper layer and the lower cold layer of the sea, where temperature declines abruptly (1C° or more per meter) with increasing depth.

T_{max} : See Longevity.

Trawl: A fishing net that is dragged behind a boat (rarely two). A wide range of demersal (bottom) or pelagic (mid-water) species of fish are taken by this fishing method, which usually has devastating impact on epibenthic organisms, notably on the filter-feeders of seamounts.

Trophic level: A number, usually ranging from 1 to 5, expressing the position of organisms within food webs, with plants having a definitional trophic level of 1, herbivores 2, first-order carnivores 3, etc. Note that due to their mixed diet, fish can intermediate trophic levels, e.g. 3.6 or 4.1. Most fishes caught by fisheries range from 2.2. to 4.2, with a mean about 3.5. The mean trophic level of marine fisheries is declining over time, a process now known as 'fishing down marine food webs'.

von Bertalanffy growth function (VBGF): Mathematical model commonly used to describe the growth of fish and other aquatic organism as a function of their age. The VBGF parameters are: asymptotic length (L_{∞}), and the curvature parameter K (of dimension 1/time), which determines how fast L_{∞} is approached. Low values of K , usually associated with high values of L_{∞} and low natural mortality (M), are generally associated with high vulnerabilities to the effect of fishing.

Vulnerable: As defined by IUCN, a taxon is 'vulnerable' when it is not critically endangered or endangered but is facing a high risk of extinction in the wild in the medium-term future.

Zooplankton: Small animals which drift freely in the water column; most are herbivores.