CAN DEEP WATER FISHERIES BE MANAGED SUSTAINABLY?

by

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Summary

Governance of deepwater fisheries has a high profile in the international community, including the explicit attention of the United Nations General Assembly (UNGA). This attention reflects concerns about the sustainability of deepwater fisheries and the fragility of deepwater ecosystems, and concern that there is a gap in the international fisheries governance framework when it comes to deepwater fisheries on the high seas.

Deepwater fisheries are considered by Food and Agriculture Organization of the United Nations (FAO) as those fisheries that occur beyond the continental shelf/slope break which typically occurs at about 200 metre (m). The current technological limit of these fisheries is about 2 000 m. However, many species not usually considered as deepwater are fished at depths well above 200 m (e.g. the North Pacific walleye Pollock fishery, one of the world's most productive, occurs over a range of 90-500 m). According to the FAO statistical database, deepwater fisheries produced 5.9 million metric tonnes (t) in 2004 or less than 4 percent of the total production from fisheries and aquaculture (including freshwater). Most of this catch is of species that generally occur in depths of less than 500 m, and some of the species that account for much of the catch occur in shallow nearshore waters as well as beyond 200 m in depth.

Deepwater fisheries should not all be "painted with the same brush" (or, in other words, hairtails and blue whiting are not the same "kettle of fish" as orange roughy and oreo dories) as there is a great deal of difference between the species fished in the shallow end of the range of deepwater fisheries, and species that are fished at depths centered below 500 m. Species fished in the shallow end of the range have similar biological characteristics to shelf species. They are productive compared to some deeper water species, such as orange roughy. The discourse about deepwater fisheries would be well served by a common understanding of what constitutes a deepwater fishery and what makes them different from other fisheries.

Deepwater fisheries beyond 500 m generally have a history of less than three decades, during which early expectations of sustainable yield have often been too optimistic, the biomass on many fishing grounds has been depleted, and biogenic habitats have been impacted. The deepwater fisheries that have attracted the most attention are those for orange roughy at depths of about 700 m and below. Simply stated, the global track record for sustainable management of deepwater fisheries beyond 500 m is not good. Deepwater fisheries have failed to be sustainable for one or more of the following fundamental reasons:

- they have been unregulated;
- initial scientific assessments based on limited data have often been too optimistic; and/or
- management has not responded to, or has been slow to respond to, scientific advice calling for improved conservation.

This experience clearly points to the need to strictly adhere to the precautionary approach and apply an ecosystem approach. More specifically:

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- all deepwater fisheries should be authorized by a competent management authority with constraints set cautiously, and new fisheries should have a development plan that ensures the rate of development is consistent with the gathering of knowledge;
- management strategies for deepwater fisheries need to be re-examined in light of the poor track record to date; in particular biological reference points should be set more conservatively and explicit “fishing down” phases should be avoided;
- steps need to be taken to address habitat and biodiversity impacts of deepwater fisheries;
- research is needed to improve resource assessments, knowledge about the distribution of resources off fishing grounds, understanding of stock structure, and understanding the functional value and vulnerability of habitat and biodiversity;
- new multilateral arrangements are needed to manage high-seas fisheries in some areas, although individual nations could prevent overfishing on the high seas if they consistently applied the FAO Code of Conduct for Responsible Fisheries (CCRF) and the Agreement to Promote Compliance with International Conservation and Management Measures by Fishing Vessels on the High Seas (Compliance Agreement); and
- there is a need to improve compliance with fishery conservation measures and reporting of fishery-dependent data. It is time to seriously consider extending catch documentation schemes, such as the Commission for the Conservation of Antartic Marine Living Resources (CCAMLR) scheme used to reduce illegal, unregulated, and unreported (IUU) fishing of toothfish, to all fish that enter into international trade.

An unanswered question is, will the benefit-cost ratio for deepwater fisheries for long-lived, low-productivity species be positive if the full costs of research and management are taken into account?

1. INTRODUCTION

Management of deepwater fisheries has a high profile[2] within scientific communities, environmental organizations, and policy makers including the United Nations General Assembly (UNGA). Interest in these fisheries is stirred by concern about their sustainability and their impact on habitats and biodiversity. However, the term “deepwater fishery” means different things to different people. In fact, these fisheries are diverse and they should not be “painted with the same brush.”

Ocean depth zones are indicated in Figure 1 (FAO, 2005). In general, continental shelves are thought of as extending to about 200 m depth. For fisheries, the deepwater zone can be taken beginning at the continental shelf/slope break. This corresponds to the Terms of Reference of this paper which considers deepwater fisheries to be off-shelf and generally deeper than 200 m. However, the International Council for Exploration of the Sea (ICES, 2005)[3] applies the term deepwater to fisheries at depths greater than 400 m. New Zealand, a country where deepwater fisheries are particularly important, defines deepwater fisheries as fisheries with a center of distribution greater than 500 m. One problem with using 200 m to define deepwater fisheries is that many shelf fisheries, including some of the world’s largest and most productive fisheries, extend to much greater depths. For example, the Alaska pollock fishery, which yielded about 2.7 million tonnes from the North Pacific Ocean in 2004, takes place from 90 to 500 m.

Another aspect of deepwater fisheries is their relationship to the water column or sea floor. Fisheries for mesopelagic and bathypelagic species (defined by the ocean depth zones in Figure 1), which live in

[2] Over 100 scientists participating in the tenth Deep-Sea Biology Symposium and the second International Symposium on Deep Sea Corals issued a statement of concern which was submitted to the United Nations General Assembly calling for a moratorium on deep-sea bottom trawl fishing on the high seas. Similarly, the Marine Conservation Biology Institute collected 1136 signatures of scientists expressing profound concern about bottom trawling impacts on deep-sea coral and sponge communities and calling on the United Nations to take appropriate action. see http://www.mcbi.org/DSC_statement/sign.htm
[3] See http://www.ices.dk

the water column without association with the sea floor, might be considered deepwater fisheries (as the species occur at depths of at least 200 m). However, these species generally do not grow to a large enough size to make them valuable commercial fisheries (FAO, 2005; p. 189) and/or they have not proven to be viable commercial fisheries due to processing or marketing problems. Their distributions may be too diffuse to make fishing them practical. The important deepwater fisheries are for demersal species which are close to, or in contact with, the seafloor much of the time, and benthopelagic species that are associated with the seafloor.

It is important to recognize the diversity in fisheries referred to as deepwater by FAO, as those at the shallower end of the deepwater range are similar to shallow water fisheries in terms of biology, scientific issues, management regimes and sustainability. This is especially true if 200 m is used to define the shallow end of the deepwater range. Fisheries at depths in the vicinity of 1 000 m and deeper are relatively recent (developing over the last three decades), and they are quite different from shallow water fisheries in terms of species biology, scientific challenges, and management issues. These are the fisheries for which there is the greatest concern about long-term sustainability.

This paper discusses the species caught by deepwater fisheries, the catch history and state of deepwater fisheries, the habitat and biodiversity impacts of fishing, scientific challenges, and current management regimes. It concludes with recommendations to address concerns about the sustainability of deepwater fisheries and impacts on habitat and biodiversity. The paper emphasizes deepwater fisheries with the center of their range greater than 500 m. It draws heavily on experience in New Zealand, where deepwater fisheries beyond 500 m are particularly important. Orange roughy fisheries in Australia, Namibia, Chile and the South Tasman Rise are also used as illustrative examples.

2. DESCRIPTION OF DEEPWATER FISHERIES

FAO lists 76 species (by common name) as deepwater species (FAO 2005, Table C3.1, page 195). The trend in reported catch[4] of these deepwater species is given in Figure 2. A substantial amount of the catch probably comes from continental shelf fisheries which are not normally considered to be deepwater, although the species caught are known to range to depths greater than 200 m. Unfortunately, the spatial resolution of catch reporting to FAO is inadequate to categorize catch by depth or to determine if it is from within Exclusive Economic Zones (EEZs) or from the high seas.

The total reported catch of deepwater species (defined as above) in 2004 was 5.9 million tonnes which is less than 4 percent of the total global production (including freshwater) from capture fisheries and aquaculture. The reported catch in 2004 is the highest on record. The reported catch has increased steadily since the 1950s, with an accelerating trend since the mid-1990s.

Table 1 gives the 2004 reported catch for selected deepwater species. The species in the table were selected either because of their high reported catch (greater than 100 000 t) in 2004 and/or because they have received attention due to management concerns. Appendix 1 gives the reported 2004 catch for all deepwater species (according to FAO 2005) by ocean area.[5]

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[4]Reported catches throughout this paper (unless otherwise stated) are from the FAO Fisheries Global Information System (FIGIS) Global Capture Production 1950-2004 on line database, at: http://www.fao.org/figis/servlet/TabLandArea?tb_ds=Production&tb_mode=TABLE&tb_act=SELECT&tb_grp=COUNTRY

[5] Note that FAO's list of deepwater species did not include *Sebastes* spp. (redfish), although these species are commonly considered deepwater. This paper uses the same list of species as FAO (2005). Thus *Sebastes* spp. are not included in Figure 2, Table 1, or Appendix I. However, the status of redfish stocks is considered in Section 2.4 and Table 3.

Table 1. Reported 2004 catch of selected "deepwater" species. Catches were not necessarily made in "deep" waters (i.e. many of the catches have been recorded from waters shallower than 200 m).

Species	Scientific name	2004
Alfonsinos nei	*Beryx* spp	7 199
Antarctic toothfish	*Dissostichus mawsoni*	2 584
Black scabbardfish	*Aphanopus carbo*	11 987
Blue grenadier	*Macruronus novaezelandiae*	163 305
Blue ling	*Molva dypterygia*	7 785
Blue whiting(=Poutassou)	*Micromesistius poutassou*	2 427 862
Bombay-duck	*Harpadon nehereus*	162 873
Greenland halibut	*Reinhardtius hippoglossoides*	111 785
Hairtails, scabbardfishes nei	*Trichiuridae*	182 917
Largehead hairtail	*Trichiurus lepturus*	1 587 451
Ling	*Molva molva*	35 384
Northern prawn	*Pandalus borealis*	446 138
Orange roughy	*Hoplostethus atlanticus*	25 881
Oreo dories nei	*Oreosomatidae*	20 284
Patagonian grenadier	*Macruronus magellanicus*	216 401
Patagonian toothfish	*Dissostichus eleginoides*	24 827
Southern blue whiting	*Micromesistius australis*	152 041
Tilefishes nei	*Branchiostegidae*	73 894
	Grand total	5 660 598

The species listed in Table 1 account for more than 96.3 percent of the reported catch of deepwater species in 2004. Two species, blue whiting and largehead hairtail, account for about 75 percent of the reported catch. The species that has received the most attention due to management concerns, orange roughy, accounts for only 0.5 percent of the reported catch of deepwater species in 2004 and a trivial amount of the total global production of fisheries. These three species illustrate the diversity in species and fisheries referred to as deepwater by FAO. Largehead hairtail is a relatively fast growing, early maturing species that is taken mostly near shore. However, its depth range extends to about 300 m, so it is listed as a deepwater species by FAO (2005). Blue whiting is also a relatively fast growing, early maturing species, but it is typically fished at a depth of about 400 m, mostly in the Northeast Atlantic. Thus it is defined as a deepwater species by both FAO and ICES. Blue whiting is a straddling stock in the Northeast Atlantic. Orange roughy is very long lived, with an advanced age of maturity of at least 25-30 years. The species is fished at depths of about 700-1 250 m and beyond. Fishing grounds for orange roughy may occur entirely within EEZs, or straddle the boundary between EEZs and international waters of the high seas, or be entirely on the high seas. The catch history of orange roughy (as reported to FAO) is given in Figure 3.

Table 2 gives some relevant characteristics of species that have been classified as deepwater (according to FAO 2005). Most of the information is from Fishbase,[6] an online database for fish species. There are numerous different entries in Fishbase for some species, and they do not always agree. The values in Table 2 are typical values found in Fishbase. In some cases, information was not available in Fishbase, although this does not necessarily mean it is unknown.

[6]See: http://www.fishbase.org/search.php

Table 2. Characteristics of selected deepwater species. Primarily from Fishbase (website address given in footnote 4).[7]

Species	Recorded depth range (m)	Main depth range (m)	Maximum age (yr)	Age of maturity (yr)
Alfonsino	180–1 300	400–600	23	
Antarctic toothfish	0–1 600	500–1500	31	
Black scabardfish	200–1700	600–800	32	
Blue grenadier (hoki)	10–1 000	300–800	25	3–7
Blue ling	150–1 000	250–500	20	9–11
Blue whiting	mostly 300–400	300–400	20	2
Bombay duck	inshore to deepwater			
Hairtails	0–400		15	
Greenland halibut	1–2 000	350–1500	22	7–12
Ling	100–1 000		25	
Northern prawn	20–1 330		5	
Orange roughy	180–1 800	500–1200	150	≥ 25–30
Oreos	220–1 550	600–1200		
Patagonian grenadier (hoki)	30–500		14	
Patagonian toothfish	0–1 600	500–1500	21	6
Tilefish	30–400			

Clearly, the species that account for most of the reported FAO deepwater catch (blue whiting, Bombay duck and hairtails) are a very “different kettle of fish” from the species that have attracted the most concern about their sustainability (orange roughy and oreos). Much of the catch of the high volume species actually takes place in relatively shallow water. For example, hairtails are taken in shallow coastal waters and estuaries in Asia, and Bombay duck are taken with bag nets in deltas in coastal India. Most of the so-called deepwater species overlap with typical shallow water species in terms of their depth range and biology. For example, Atlantic cod has a depth range from nearshore to 600 m, it has a life span of about 25 years, and it matures at 2-7 years (based on typical entries in Fishbase). In terms of life span and age at maturity, none of the species differ much from cod, except for orange roughy and oreos. It is also important to keep in mind that deepwater species of sharks, which have a very low fecundity, are likely to be particularly vulnerable to overfishing. However, deepwater species are not all long-lived and late maturing, and thus they do not necessarily have low productivity and low resilience, as is often stated.

2.1 Deepwater fisheries of the North Atlantic Ocean

Deepwater fisheries of the North Atlantic account for more than 50 percent (3.1 million tonnes) of the global deepwater catch reported to FAO. Most of the deepwater fishing in the Atlantic is in the Northeast Atlantic. Gordon (2001) and Gordon *et al.* (2003) give a general description of these fisheries. Deepwater fishing by longliners began in the mid 1800s, but it expanded after World War II as technology for deepwater trawling developed, and the expansion accelerated in the 1990s when new markets for deepwater species were created. Spain, Ireland, the Faroe Islands, Scotland, United Kingdom, Ireland and Norway are important participants in deepwater fisheries.

Deepwater fisheries occur along the northern part of the Mid Atlantic Ridge and around Rockall Plateau, northeast of Ireland. The total catch of deepwater species in the Northeast Atlantic in 2004 was 2.7 million tonnes, more than half of the global total. Blue whiting accounted for 2.4 million

[7] Recorded depth ranges include numerous records some of which may be sporadic and therefore may not be useful for characterizing species as deepwater or otherwise. Most of the main depth ranges of the fisheries taking place on these species were compiled by participants at the Expert Consultation after the initial draft of this paper was presented.

tonnes (almost 90 percent). Other important species in terms of volume were Greenland halibut, ling, northern prawn, roundnose grenadier, and tusk (also known as cusk). Orange roughy accounted for 1 240 t of the reported catch.

Deepwater fisheries of the Northwest Atlantic date back to the early 1960s with the arrival of western European and USSR fleets. The reported catch from the Northwest Atlantic in 2004 was smaller than that in the Northeast Atlantic with a total reported catch of 421 438 t, mostly of northern prawn and Greenland halibut. Northern prawn is primarily taken on the Flemish Cap southeast of Newfoundland. Greenland halibut are taken on the continental shelf and slope on the so called "tail" of the Grand Banks, and off Labrador. Blue whiting, the dominant species reported from the Northeast Atlantic, was not present in the Northwest Atlantic reported catch.

2.2 Deepwater fisheries of the South Pacific Ocean

The total reported deepwater fisheries catch in the South Pacific was 426 112 t in 2004 or about 7 percent of the global deepwater total, small compared to the reported catch from the North Atlantic. However, the South Pacific accounted for most of the global reported catch of orange roughy.

Most of the deepwater fishing of the South Pacific takes place in the Southwest Pacific near New Zealand and Australia and in the Southeast Pacific near Chile. The most important species in the Southwest Pacific in term of volume of catch in 2004 were blue grenadier or hoki (154 532 t), southern blue whiting (42 276 t), pink cusk-eel (21 176 t), oreo dories (19 787 t) and orange roughy (18 157 t or 70 percent of the global total of 25 881 t). The Southeast Pacific reported catch was primarily Patagonian grenadier (also known as hoki; 71 177 t) and southern blue whiting (33 169 t). Patagonian toothfish (6 470 t) is another important deepwater species in the Southeast Pacific. The Pacific Antarctic had a reported catch of Antarctic toothfish of 2 558 t.

2.3 Other oceans

The remaining ocean areas accounted for about 43 percent of the global total reported catch of deepwater fish species in 2004, but this amount is deceiving. Most of the catch is from a few species which have a depth range including the FAO definition of deepwater (greater than 200 m), but they are probably caught primarily in continental shelf fisheries, sometimes very nearshore.

The reported deepwater catch for the North Pacific Ocean in 2004 was 1.6 million tonnes, or 27 percent of the global total. However, most of this catch was hairtails (1.5 million tonnes) which are probably taken on the Asian continental shelf (they are reported from the Northwest Pacific).

Historically, there was a significant fishery for pelagic armourhead along the Hawaiian and Emperor Seamount chain beginning in 1969 (Shotton 2005). The total catch of pelagic armourhead by USSR vessels is estimated to have been 133 400 t during the period 1967-1977. The catch by Japan during the period 1969-1977 is estimated to have been from about 180 000 to 285 000 t. By the late 1970s, the catch of pelagic armourhead had declined sharply and it was replaced by catches of alfonsino for a period. Eventually, the fisheries for both species disappeared, and there is no evidence the stocks will recover in the foreseeable future. Recently, Clark *et al.* (in press) estimated that about 800 000 t of armourhead were taken between 1968-1985. Although the actual amount of catch may be uncertain, it is clear that it was substantial. These fisheries provided an early warning of the fragility of deepwater fisheries.

The reported catch of deepwater species from the South Atlantic in 2004 was 294 063 t (5 percent of the global total), mostly of Patagonian grenadier (hoki, 145 224 t), southern blue whiting (76 596 t), and pink cusk-eel (19 293 t). Patagonian toothfish (16 081 t) are important in the Southeast Atlantic and Atlantic zone of the Antarctic Ocean. Orange roughy (1 845 t) were also in the reported catch. They were probably caught almost entirely by the fishery that developed in the Namibian EEZ during the late 1980s and early 1990s.

The reported deepwater catch from the Indian Ocean totaled 351 267 t or 6 percent of the global deepwater total. The reported catch was dominated by hairtails (174 771 t) and Bombay duck (154 277 t), which are most likely caught near shore on the South Asian continental shelf. A total of 13 457 t catch of toothfish (mostly Patagonian) was reported from the Indian Ocean and Indian Ocean zone of the Antarctic. The reported Indian Ocean catch of orange roughy in 2004 was 2 559 t. It was the unregulated high-seas fishing for orange roughy in the Indian Ocean in the late 1990s and early 2000s that raised concerns about the adequacy of the international framework for managing deepwater high-seas fisheries. Reported orange roughy catches from the Indian Ocean are given in Figure 4. The figure indicates a peak in the catch in 1999. Interesting, only four countries have reported Indian Ocean catches of orange roughy according to the FAO official database. The Second *Ad Hoc* Meeting on the Management of Deepwater Fisheries Resources of the Southern Indian Ocean (FAO 2002) indicates catches by several other countries and a significantly higher total catch.

2.4 Status of deepwater fisheries

At present, the most comprehensive global information on the state of fisheries is FAO (2005). FAO is currently updating this information. Table D1-17 of FAO (2005; 214-235) consider 584 species (or species group)-statistical area combinations, which are referred to as stocks. In actuality, these so-called stocks are often comprised of several biological stocks. However, this is the highest resolution information that is available on a global scale. Of the 584 stocks, information on the status of the stock is given for 441 or 76 percent. The stocks are classified as follows:

- **Not Known (N) -** Not enough information to make a judgment.
- **Underexploited (U) -** Underdeveloped or new fishery. Believed to have significant potential for expansion in total production.
- **Moderately exploited (M) -** Exploited with a low fishing effort. Believed to have some limited potential for expansion in total production.
- **Fully exploited (F) -** The fishery is operating at or close to optimal yield/effort, with no expected room for further expansion.
- **Overexploited (O) -** The fishery is being exploited above the optimal yield/effort level believed to be sustainable in the long term, with no potential room for further expansion and a high risk of stock depletion/collapse.
- **Depleted (D) -** Catches are well below historical optimal yield, irrespective of the amount of fishing effort exerted.
- **Recovering (R) -** Catches are again increasing after having been depleted or a collapse from a previous high.

Maguire *et al.* (2006) updated some of the status of stock determinations in FAO (2005) primarily based on reports of the International Council for Exploration of the Sea (ICES) and information collected from Regional Fishery Management Organizations (RFMOs). Status of stock information for deepwater species extracted from FAO (2005) and Maguire *et al.* (2006) is given in Table 3 for those stocks where there is enough information to make a judgment.

Table 3. Status of stock information for fisheries for deepwater species (extracted from FAO 2005, Tables D1-17, and Maguire *et al.* 2006, Table 4).

When two or more letters are given for state of stock, a "-" means the status is either of the two ratings (e.g. F-O means either fully or overexploited, N-O means uncertain but probably overexploited). A "/" means that there are ratings for more than one stock (e.g. M/F means there is a stock that is moderately exploited and another that is fully exploited).

Ocean Area	Species	Status of stock
NW Atlantic	Greenland halibut	O/O
	Tusk	F
	Northern prawn	F
	Redfish	D
NE Atlantic	Blue ling	N-O
	Black scabbardfish	N-O
	Blue whiting	O
	Bluntnose sixgill shark	N-O
	Common mora	N-O
	Forkbeards	N-O
	Greenland halibut	N-O
	Greenland shark	N-O
	Ling	N-O
	Longnose velvet dogfish	N-O
	Orange roughy	N-O
	Rabbit fish, Rattail, Chimaera	N-O
	Redfish	F/O
	Roundnose grenadier	N-O
	Roughhead grenadier	N-O
	Northern prawn	N-F
	Tusk	N-O
	Wreakfish	F-O
SW Atlantic	Patagonian grenadier (hoki)	M
	Southern blue whiting	F-O
	Patagonian toothfish	M-F
	Pink cusk-eel	M-F
SE Atlantic	Kingklip	N-F
	Geryons	F
W Indian	Bombay duck	F
E Indian	Hairtails, scabbardfishes	M-F
	Largehead hairtails	M-F
NW Pacific	Largehead hairtails	F-O
W Central Pacific	Hairtails, scabbardfishes	M-F
	Largehead hairtails	M-F
SW Pacific	Blue grenadier (hoki)	M/F
	Southern blue whiting	F
	Orange roughy	F-O
	Oreo dories	F-O
	Silver gemfish	F-O
SE Pacific	Blue grenadier (hoki)	F-O
	Patagonian toothfish	M
Southern Ocean (Antarctic)	Lanternfishes	U
	Patagonian toothfish	F/F/O/D
	Antarctic toothfish	F-O

A striking feature of Table 3 is how few stocks of species subject to deepwater fishing are represented in the global database. There are 50 determinations of stock status in Table 3, of which 29 (58 percent) are approaching being overexploited (N-O or F-O), overexploited (O), or depleted (D). This is greater than the percentage of all stocks combined that are in these three categories (25 percent), as reported by FAO (2005). However, the number of stocks of deepwater species for which information is available may be too small to make this comparison meaningful, particularly since many of the determinations are uncertain (e.g. given as N-O). Most of the information is for the North Atlantic where two Regional Fisheries Management Organizations and ICES routinely consider stock status, including the status of deepwater stocks. Most other regions of the world either lack RFMOs and international scientific bodies, like ICES, or they are less active.

Another way of examining the overall status of deepwater fisheries is through analysis of catch trends based on a simple generalized fishery development model incorporating five phases: (1) Undeveloped: low initial catches; (2) Developing: rapidly rising catches; (3) Maturing: catches reaching and remaining around their historical maximum; (4) Senescent: catches consistently falling below the historical maximum; (5) Recovering: catches showing a new phase of increase after a period of senescence. This approach was applied by Maguire *et al.* (2006) using the methodology described by Grainger and Garcia (1996). The method was applied to all oceanic deepwater species that produced more than 100 000 t of total reported landings for the period 1950-2004. The species were: Argentines, Beaked redfish, Black Scabbardfish, Blue grenadier, Blue ling, Blue whiting, Deep-sea smelt, Electron sub Antarctic, Geryons, Greenland halibut, Grenadiers, Hector lanternfish, Ling, Longspine snipefish, Orange roughy, Patagonian grenadier, Patagonian toothfish, Queen crab, Roundnose grenadier, Sablefish, Silver gemfish, Silver scabbardfish, Silver warehou, Southern blue whiting, and Tusk (also known as Cusk). These are not exactly the same species as FAO (2005) categorises as deepwater, but there is a great deal of overlap between the two lists.

The catch history of oceanic deepwater species is given in Figure 5. The results of the analysis are given in Figure 6. The results indicate that fisheries for these deepwater species developed slowly in the 1950s when most such fisheries were underdeveloped. Maguire *et al.* (2006) commented that oceanic deepwater fisheries have been relatively slow to develop compared to oceanic epipelagic fisheries. However, the deepwater fisheries caught up in the 1980s. By the early 2000s, more than 50 percent were already classified as senescent or recovering. This is somewhat higher than about 35 percent reported as senescent or recovering from a similar analysis for the development of global fisheries overall (Garcia *et al*. 2005).

3. ECOSYSTEM CONCERNS

Deepwater fisheries have three types of ecosystem effects:

- Food web effects - Removal of deepwater species from marine ecosystems can alter energy flow and change the way ecosystems function. Catches of a large volume of some species may indirectly affect predators and/or prey. The catches of other species that are relatively small in volume are less likely to affect energy flow.

- Discards - As with most fisheries, some organisms are unintentionally caught and discarded at sea. Mortality of discarded species may also alter energy flow, and the mortality inflicted on some discarded species may be unsustainable.

- Alteration of habitat and biodiversity - Aside from organisms that are caught (retained or discarded), when fishing gear comes in physical contact with the sea floor it may damage physical structures and kill organisms even if they are not captured. Other forms of unobserved mortality such as fish that are not caught but die as a result of contact with the gear, and "ghost fishing" by lost or abandoned gear may also be substantial.

While logically, food web effects must occur, very little is know about them. They may be more important for shallow water fisheries where large volumes of forage (prey) species are caught, and for oceanic large pelagic or highly migratory species fisheries, where top predators are usually caught. Food web effects of this nature have been highlighted as a concern for blue whiting in the Northeast Atlantic where catches of this important "deepwater" prey species exceed 2 million tonnes annually. Food web effects are also likely to be a consideration in waters below 500 m, where it is common for one or two species to dominate the fish biomass. For example, it seems likely that the removal of 70-90 percent of the biomass of orange roughy from ecosystems in which they were initially by far the most abundant fish species will have a major effect on ecosystem structure and function (Section 6).

Much more is known about discarding than other mechanisms through which fisheries affect ecosystems. The most recent global information on discards is in an FAO report by Kelleher (2005). Maguire *et al.* (2006) summarized relevant information from Kelleher (2005).

It is estimated that the overall average rate of discarding is about 8 percent for all marine fisheries, but there are large differences by fishery and country. Shrimp trawling has the highest estimated discard rate (62.3 percent, ranging from 0 to 96 percent). Most of the estimates of discards from shrimp fisheries are for shallow water fisheries. However, there are estimates for deepwater northern prawn fisheries, such as the NW Atlantic Flemish Cap fishery. The aggregate discard rate for cold/deepwater shrimp fisheries is 39 percent, but it can be reduced to about five percent when bycatch reduction devices (BRDs) are used. BRDs are mandated for the Flemish Cap fishery, which accounts for most of the deepwater catch of northern prawn.

The estimated overall discard rate for bottom trawling for finfish is 9.6 percent. There is no basis to judge if the rate is higher or lower for deepwater bottom trawling. However, bottom trawling for finfish overwhelmingly occurs in less than 200 m depth such that deepwater fisheries cannot account for much of the estimated 1.7 million tonnes of total discards from this type of fishing. For deepwater fisheries, the species discarded may be small specimens of the target species, and numerous invertebrates including coldwater corals (*Lophelia* spp.). Many of the discarded species of finfish, and especially of invertebrates, are probably not yet described in the scientific literature.

Discarding of coldwater corals by deepwater bottom trawlers has received particular attention. In addition to the potential ecological significance of coldwater corals, they have also gained status as charismatic species akin to marine mammals and sea turtles. They form deep-sea reefs that rival tropical coral reefs in their beauty. Rarely has the impact of expanding deepwater trawling been documented in its initial stage, before habitats have been impacted. However, there were observers on board the vessels fishing for orange roughy on the South Tasman Rise (south of Tasmania, Australia, straddling the Australian EEZ) for the first four years of the fishery. Anderson and Clark (2003) estimated that in the first year of fishing an average of 1.6 t of coral were brought up per hour of trawling, which extrapolates to 1 700 t of coral bycatch compared to an orange roughy target catch of 4 000 t. Gianni (2004) estimated the bycatch of coldwater coral in the first year of the fishery as 10 000 t compared to an orange roughy catch of 4 000 t. Apparently, Gianni scaled up Anderson and Clark's estimate to take account of the observer coverage level of 15%. However, Anderson and Clark had already taken account of the level of observer coverage in their estimate. Thus, Gianni's estimate is incorrect.

Bycatch of coldwater corals is an obvious indication of the impact physical contact of trawl gear on the sea bed can have on habitat. The amount of coral brought up in trawl nets must be minor in comparison to the impact of heavy bottom trawl gear when it comes in contact with the bottom. The scientific literature, conservation campaigns of environmental non-governmental organizations (NGOs), and the popular media routinely publish vivid "before and after" photos of bottom habitat that has been impacted by bottom trawling (Figure 7). The ecological importance of this habitat alternation is difficult to quantify, but complex "three dimensional" biogenic structure is known to provide shelter from predators for some species. When the structure is destroyed, these species may disappear. Another concern is that seamounts and other deepwater areas where deepwater trawl fisheries occur appear to have a high proportion of endemic species (species that are not known to occur elsewhere) which means that if they are exterminated locally, the species may be lost globally. However, the degree of endemism is uncertain (Section 4.2.4).

Deepwater fisheries are also prosecuted with demersal longlines. This type of gear is particularly important in the Southern Ocean, but also in the Northeast Atlantic. The overall discard rate for demersal longliners is 7.5 percent (ranging from 0.5 to 57 percent), and in the Commission for the Conservation of Antarctic Living Marine Resources (CCAMLR) area it is estimated at 12.7 percent. In addition to discards of many species of finfish by longline fisheries in the Southern Ocean, bycatch of seabirds has been a serious problem. In 2003, concerns about the longline bycatch of seabirds led the FAO Committee on Fisheries (COFI) to adopt an International Plan of Action for the Reducing the Incidental Catch of Seabirds in Longline Fisheries.[8] The Commission for Conservation of Antarctic Marine Living Resources (CCAMLR)[9] introduced a seabird bycatch reduction program which has reduced the mortality of seabirds by 80 percent.

4. SCIENTIFIC CHALLENGES

Some of the scientific challenges for deepwater fisheries are similar to those for all fisheries and some are unique. The key types of scientific information that are needed for an ecosystem approach to managing deepwater fisheries are stock assessments and habitat and biodiversity impact assessments.

4.1 Stock assessments

Stock assessments provide a scientific evaluation of the status of a fish stock and its potential yield. There are several key elements of a stock assessment.

4.1.1 Stock structure

Ideally fisheries should manage an interbreeding group of fish that are reproductively isolated from other fish of the same species. Such groups of fish are referred to as stocks. The challenge is to determine stock structure (i.e. which groups of fish are stocks) for a species and to assess the individual stocks. A variety of methods are used to determine stock structure including tagging, genetics, microconstituent and stable isotope analysis of hard parts (e.g. ear bones), and differences in the occurrence of parasites. Some of these approaches are impractical for deepwater species (e.g. traditional tagging – although new methods of *in situ* tagging have been shown to be feasible for some deepwater species; Sigurdsson *et al.* 2006, www.star-oddi.com), while others that are routinely applied to shallow water species are equally applicable (e.g. genetics). An additional challenge for deepwater species is collecting samples, particularly in areas and seasons where fishing does not occur.

For some deepwater species, the range of the species is unknown. This means that it is unknown if a fishery on a local fishing ground is exploiting an entire stock, or merely fishing a small portion of a stock which is distributed over a vast area far away from the main fishing ground. This is a particular problem for orange roughy, to the extent that it is unknown if declining catch rates experienced for many orange roughy fisheries is a threat in terms of the reproductive potential of a stock, or if it is simply a problem of localized depletion.

In general, stock structure is poorly known for deepwater species compared to species fished at shallower depths. This reflects both unique challenges of determining the stock structure of deepwater species, and the fact that researchers have been studying the stock structure of shallower water species much longer than they have been studying any aspect of the biology of deepwater species.

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[8] See: http://www.fao.org/figis/servlet/static?dom=org&xml=ipoa_seabirds.xml for the FAO International Plan of Action for Seabirds.

[9] See: http://www.ccamlr.org/default.htm

4.1.2 Demographics

One of the most important factors determining the productivity and resilience of a fish population is the lifespan of the species (which is closely related the natural mortality rate) and its age of maturity. Species with a long life span that mature at an advanced age have low productivity and low resilience. Unfortunately, it has proven difficult to determine the age of deepwater fish species. The typical way that age is determined for shallow water species is to look for patterns in hard parts (ear bones, vertebrae and scales) that correspond to seasonal differences in growth. These patterns can be validated by modal analysis, with tagging studies or by keeping animals in captivity. In deepwater, there is little seasonal variability in environmental conditions that might be associated with seasonal patterns in growth. However, Mace *et al.* (1990) found clear evidence of annual rings and a seasonal progression of marginal increments in juvenile orange roughy otoliths and were able to validate these rings using modal analysis for ages 0-4. Thus, even the low seasonal variation in deep water may be adequate, at least for juveniles. Radioisotope analyses have been used to determine the age of some species. However, this method is not practical for the large number of age determinations (thousands per year) that are used in state-of-the-art assessments for shallow water species. Information on the age composition of the fish in the commercial catch and in the population (based on fish collected by research vessels) is also valuable in assessment models to estimate the fishing mortality rate and population size.

In general, the demographic information available for deepwater species is much less than for shallow water species, at least compared to shallow water fishery assessments conducted in North America and Europe. Lack of information and misinformation on the age and growth of orange roughy during the early period of development of the fishery in New Zealand (until the late 1980s) led to a serious overestimate of the productivity of the species and its potential sustainable yield (Mace *et al.* 1990, Clark 1995 and Section 6).

4.1.3 Fishery-dependent information

Data on (1) catch biomass, (2) size and age composition of the catch, (3) fishing effort, and (4) discards, provides the basic information on fisheries used in stock assessments. Age composition data may be more difficult to obtain for deepwater species than for shallow water species for the reason discussed above. However, the other types of fishery-dependent data should be no more difficult to obtain for deepwater fisheries. The fact that there are relatively few large vessels engaged in deepwater fisheries could be an advantage in keeping track of fishing activity and collecting data. For some countries, where most of the deepwater catch enters international trade, catch data can be verified by export records.

While collection of fishery-dependent information for deepwater fisheries is not inherently more difficult than for other fisheries, in practice, the amount of available fishery-dependent data is problematic in some cases. As noted above, the reported catch by deepwater fisheries on the high seas in the Indian Ocean during the early 2000s is not consistent with unofficial reports on the magnitude of catches and the countries participating in the fishery. There are no reported catches of pelagic armourhead from the Pacific Ocean during the period when the former USSR and Japan are estimated to have taken hundreds of thousands of tonnes of the species from the Hawaiian and Emperor seamounts (as described in Section 2.3). Recent reports of ICES on deepwater fisheries of the Northeast Atlantic also raise concerns about fishery-dependent data. For example, ICES (2005) stated,

> "It is also of concern that the landings statistics that are available may not reflect the true scale of the recent fishing activity, especially in waters outside the national EEZs."

Another challenge for assessments of deepwater species is that it is also difficult to interpret catch per unit effort data for fisheries that are conducted on dense concentrations of fish (Clark 1996), particularly those on spawning aggregations. However, this problem is also common for shallow water species (e.g. purse seine fisheries for schooling species like herring). It is one important reason that fishery-independent abundance indices are a valuable information source for stock assessments.

4.1.4 Fishery-independent relative abundance indices

An important input to stock assessments is an index of relative abundance which tracks changes in the size of a population. Since fishery-dependent catch per unit effort data often track abundance poorly, fishery-independent resource surveys are usually considered to be superior sources of data for tracking abundance. The most common fishery-independent methods for tracking relative abundance are trawl surveys, acoustic surveys, and surveys of planktonic fish eggs and larvae. Photographic techniques may also be used for surveys. All of these techniques have been tried for deepwater fisheries, especially in New Zealand (see reviews by Clark 1996, 2005).

Unfortunately, application of all of these methods is difficult for deepwater fisheries. Trawl surveys are logistically difficult and time consuming when trawls are towed at great depth. Also, the entire area occupied by deepwater species is vast. Thus, trawl surveys are usually limited to spawning and/or fishing grounds, not the entire range of a stock as may often be covered for shallow water species.

Egg and larval surveys are rarely used for deepwater species, but they have been tried and abandoned for deepwater species in New Zealand (Clark 2005). Again, such surveys are challenging because potentially vast areas may be involved, eggs can disperse rapidly in strong currents, and little is known about the planktonic early life history of most deepwater species.

Deepwater acoustic surveys have also been used to assess deepwater species. Designing and building acoustical systems that can be towed at great depth is technically challenging. More importantly, the target strength of deepwater species is difficult to determine. Species like orange roughy which have oil filled swim bladders have low target strength, making them hard to detect. In addition, they are often associated with other species with much higher target strengths. Another problem is that for acoustic surveys of deepwater species that are associated with seamounts and canyons, it is hard to distinguish dense concentrations of fish from bottom features. Undoubtedly, inaccurate acoustic survey results have led to some overly optimistic assessments of the potential yield, with disastrous results, for several deepwater fisheries (particularly orange rough, Section 6).

Surveys using cameras to sample for deepwater species of fish have also been attempted. However, photographic techniques cannot sample enough water volume or area of sea bottom to be practical except perhaps for a few specific research applications.

4.1.5 Spatial and temporal patterns of spawning and recruitment

Most shallow water species spawn annually after they reach maturity. While interannual variability in recruitment of shallow water species is a major source of uncertainty in stock assessments and management, the general pattern is understood. There is some detectable or measurable recruitment to the stock annually, and the spatial distribution of recruits is similar from year to year. For deepwater species, the patterns are unknown, and difficult to determine because it is difficult to determine the age of individual fish and the full spatial range of the stock may be unknown.

Orange roughy illustrate the uncertainty. Does the abundance on a spawning ground where a fishery occurs track the abundance of spawners as they return annually to spawn, or is it tracking interannual variability in the component of the population that returns to the particular location to spawn? Is there annual recruitment such that a fishery can be sustained, or is recruitment extremely intermittent, as it might be for a species with a life span of more than 100 years? Might recruitment variability for orange roughy be expressed spatially (where there is a good year-class) instead of temporally (when there is a good year-class)? The answers to these questions are fundamentally important to the issue of sustainably fishing the resource over the range of a stock, even if a fishery cannot be sustained at each individual site where recruitment might intermittently occur. For example, if recruitment variability is expressed spatially rather than temporally, fisheries might be allowed to overfish some concentrations of orange roughy on some fishing grounds, so long as the number of concentrations left unfished is sufficient to result in a total fishing mortality that is appropriate to sustain the stock. Such knowledge would allow an area rotation harvest strategy to be designed, but it would require knowledge of the relationships between spawning concentrations (e.g. are they part of the same stock such that spawning in one location has the potential to be the source of recruitment at another location?). Unfortunately, there are no orange roughy stocks for which recruitment has been able to be estimated at the population level, let alone on finer spatial scales. This problem largely hinges on the difficulty of ageing this species.

4.1.6 Models

Models are used to integrate various sources of data on fisheries to assess trends in abundance, population biomass, current sustainable yield, and long term potential sustainable yield or Maximum Sustainable Yield (MSY). The assessment models used for deepwater species range from simple analyses of trends in catch or relative abundance indices, to complex computer models using sophisticated statistical techniques. Some of the modelling techniques used for deepwater species in New Zealand and Australia are especially complicated as they attempt to integrate disparate types of input data and to capture the full range of uncertainty in the biology of deepwater species in relationship to fisheries. Unfortunately, these models estimate so many parameters that it is not unusual for quite different interpretations of the available data to fit the data equally well (or equally poorly). In some cases, the best fit to the data may give parameter estimates that are inconsistent with each other or implausible (Section 6).

In general, input data to assessment models is much more of a limiting factor for assessments than the models themselves. To a degree, more sophisticated models give a more rigorous interpretation of the available data, but they also run the risk of lulling scientists and managers into a false sense of confidence. Use of poor data can be misleading and result in poor assessments and poor consequent management actions (Boyer *et al.* 2001). This is ironic since one of the reasons for building sophisticated models is to capture uncertainty more realistically.

In Section 6, orange roughy assessments in New Zealand are used to illustrate the potential value and pitfalls of sophisticated models that are used to assess deepwater fisheries.

4.2 Habitat and biodiversity impact assessment

Taking an ecosystem approach to managing fisheries requires consideration of the impact of fisheries on habitat and biodiversity. Habitat and biodiversity assessments are difficult to conduct for shallow shelf ecosystems, but they are even more of a challenge for deep-sea ecosystems. This is an extremely controversial issue with some people comparing the impact mobile bottom fishing has on benthic communities to clear cutting forests. It is unclear if the comparison is in terms of how humans see it visually, or the impact on ecosystem processes, or in terms of the proportion of the earth's land area that has been cleared to the proportion of the sea floor that has been altered, or if it is merely a statement intended to steer emotions. Regardless, the impact of fishing on habitat and biodiversity is an issue that has gained importance at high levels, such as the UNGA, and it needs to be addressed with objective research. There are several scientific issues to be addressed.

4.2.1 Habitat change caused by gear contact

The first issue to be addressed to assess the habitat and biodiversity impact of fishing is to determine the changes that are caused when fishing gear comes in contact with the seafloor. Damage to biogenic communities, such as coldwater coral reefs, is obvious, but what about other types of habitats? There is also a need to characterize habitat alteration in the context of functional aspects of the habitat rather than relying on aesthetics from a human perspective.

4.2.2 Recovery time of habitat

Some studies have followed the recovery of habitat in areas that are protected from further fishing activity, such as extensive studies on the northern edge of Georges Bank of the Northeastern United States (Collie *et al.* 2000). There is also evidence that some coldwater coral reefs are very old. For example, fragments taken from the coldwater coral reef at the Sula Ridge off the Norwegian coast have been dated at 8 500 years old, which is just after the end of the last ice age. This 300 m deep reef is about 13 km long and 400 m wide with an average height of 15 m, rising to 35 m in some places. The growth rate of the reef has been estimated as 1 mm per year.[10] Clearly, the recovery time from trawling damage to such a reef is very long. However, there are many types of habitat that are impacted by contact with fishing gear, and not all habitats are as fragile and slow to recover as coldwater coral habitat.

4.2.3 Habitat mapping

A key to protecting habitat from fishing impacts is knowledge of where the most fragile habitat is located. Side-scan sonar is increasingly used to survey and map habitat off North America, Europe, and elsewhere. These efforts have identified previously unknown areas of coldwater coral, and in some cases, managers have responded by closing the areas to bottom fishing.

4.2.4 Degree of endemism

Many studies of the biodiversity associated with coldwater coral reefs and deep-sea ecosystems on seamounts have discovered species that appear to be endemic. This raises the concern that the localized impact of fishing may drive endemic species to extinction. However, is the rate of endemism really as high as it appears to be, or is the apparent large number of endemic species an artifact of under-sampling? Many studies indicate that the number of new species discovered increases steadily with an increase in sampling intensity, suggesting that there are many more species to be discovered in the area being sampled (Parin *et al*. 1997, Richer de Forges 2000, Rowden *et al*. 2002). If this is the case, many species that now appear to be endemic on a particular seamount, might be discovered on other seamounts in the future if sampling is more intense. Realistically, there will never be absolute proof that a species is endemic. This would require a complete inventory of species with complete knowledge of their geographic range. Therefore it would be useful for marine scientists to agree on statistically rigorous criteria for labeling a species endemic, perhaps with a range of degrees of certainty (e.g. possibly endemic, probably endemic, endemic). Such criteria need to take account of the possibility that a species that at first appears to be localized, might later be discovered to be global. Orange roughy are an example of this issue. They were probably presumed to be a relatively rare species with localized distribution in the Atlantic when they were discovered. They are now known to be common in the Pacific and Indian Oceans.

The fact that it is difficult to say with certainty that species are endemic does not mean that management should ignore the possibility that some species that are endemic may be jeopardized by fishing. Scientists need to objectively assess the risk so that managers can fulfill their responsibility to manage risk.

4.2.5 Spatial overlap between fishing and unique elements of deep-sea ecosystems

It is known that some deepwater fisheries concentrate on the peak of seamounts, and other submarine feature, which are also areas commonly covered with fragile biogenic communities, such as coldwater coral reefs. These areas may also be the habitat of endemic species. What is unknown is the degree of spatial overlap between fishing activity and fragile habitat and endemic species. For example, do endemic species on the tops and gentle slopes of seamounts where fishing occurs also inhabit the steep slopes of the seamount outside of the area that is feasible to fish with existing technology? The degree

[10] See http://www.ices.dk/marineworld/deepseacoral.asp

of overlap between fishing and endemic species is probably a key factor in determining the risk of extinction.

4.2.6 Functional value of habitat and biodiversity

While humans may value some aspects of deep-sea ecosystems for their beauty, existence value, and potential undiscovered benefits (such as new pharmaceuticals that might cure dreaded diseases), their value in terms of the functionality of the ecosystems is also an important consideration of an ecosystem approach. For example, how important are coldwater coral reefs as habitat for young fish, and thus, how might the loss of this habitat adversely impact production of fisheries? It seems likely that coldwater corals provide shelter from predators for some species. However, it is difficult to translate the association between young fish and habitat into the productivity of a population. Another issue is the functional importance of biodiversity, such as its importance in terms of ecosystem stability and robustness.

The scientific challenges associated with the functional value of habitat and biodiversity are daunting for shallow water ecosystems. They are not tactical for deep-sea ecosystems. Realistically, the best option is to use lessons learned from shallow water ecosystems to make inferences about deep-sea ecosystems.

4.2.7 Mitigation options

The impact of fishing on habitat and biodiversity might be mitigated by modifying fishing gear and/or fishing practices. There are many examples of such changes (sometimes referred to as "conservations engineering") successfully mitigating ecosystem impacts, such as the CCAMLR program to reduce seabird bycatch in deepwater longline fishing for toothfish and the use of bycatch reduction devices in the Northwest Atlantic fishery for northern prawn to protect juvenile fish (Section 3). Since the significance of habitat and biodiversity impacts on deep-sea ecosystems is unlikely to be scientifically understood for the foreseeable future, it is prudent to mitigate potential impacts. Experience has shown that mitigating impacts by conservation engineering requires the fishing industry to apply their fishing gear expertise for catching more fish regardless of impact, to reducing impact with a minimum loss of fishing power. Engineers and scientists can help, but a cooperative approach with the industry works best. Mitigating impacts requires not only successful conservation engineering, but also incentives to apply the mitigation techniques (e.g. enforcement of regulations on gear). It will probably be easier to enforce gear regulations if the fishing industry believes in the gear because they helped design it. Ultimately, the fishing industry should have the incentive to cooperate with efforts to mitigate ecosystem impacts since these impacts may adversely affect the productivity of fisheries, and even if they don't, the industry risks being found guilty in the court of public opinion of crimes against marine ecosystems if it does not respond to the public's concerns.

5. MANAGEMENT FRAMEWORKS AND EXPERIENCE MANAGING DEEPWATER FISHERIES

5.1 National frameworks

Most fisheries for true deepwater species probably occur within national EEZs. As noted in Section 1, much of the catch of species FAO has characterized as deepwater is probably taken in relatively shallow water fisheries on the Asian continental shelf (e.g. about 2 million tonnes in total of Bombay duck and hairtails from the Indian Ocean and largehead hairtail from the NW Pacific Ocean). True deepwater fisheries occur in the EEZs of North America (the United States and Canada), Europe (Iceland, Norway, and members of the European Union), Africa (in particular Namibia), South America (in particular the southern area), Australia and New Zealand.

In general, the deepwater fisheries within the EEZs mentioned above are subject to well-developed fishery management frameworks. These frameworks require collection and reporting of fishery-dependent data. Fishery-independent resource surveys are conducted for some (but certainly not all) fishery resources. The management frameworks include mechanisms for obtaining scientific advice based on stock assessments, and legally binding conservation measures are implemented and updated regularly. There is usually some capability to enforce conservation measures, although compliance is a problem in many cases (e.g. note concerns expressed by ICES about the accuracy of catch reporting for some northeast Atlantic deepwater fisheries, Section 4).

National management frameworks that apply to deepwater fisheries within EEZs usually have policy goals requiring fisheries to be conducted in a sustainable manner using an MSY-based harvest strategy, or of maintaining stocks at biomass levels near or above those associated with MSY. General goals are often operationalized in the form of harvest strategies and control rules. Ecosystem considerations, such as impacts on habitat and biodiversity, are also addressed by some national management frameworks. For example, Norway protected the Sula Ridge coldwater coral reef described in Section 4 from bottom trawling within a few months of its discovery by a research cruise. In 2003, the European Commission promulgated regulations to protect coldwater corals on the Darwin Mounds, off Western Scotland.[11] Similarly, coldwater coral habitat in several areas off North America, New Zealand and Australia has been closed to bottom trawling. However, vast areas of coldwater corals are not protected. For example, it is estimated that 30-50 percent of the coldwater corals within the Norwegian EEZ have been damaged by bottom trawling.[12]

In spite of the existence of well-developed national frameworks for managing most deepwater fisheries within EEZs, many of these fisheries have been overfished and some have collapsed. This is indicated by the state of deepwater fisheries reviewed in Section 2. The case study of deepwater fisheries for orange roughy and related fisheries in Section 6 illustrates the difficulties of managing deepwater species even within EEZs where management frameworks are well developed.

5.2 International frameworks

As noted earlier, the FAO fisheries statistical database does not allow high-seas fisheries to be readily distinguished from EEZ fisheries. However, based on knowledge of the species caught, bottom topography, and reports of RFMOs and ICES, it is clear that high-seas deepwater fisheries occur in the Northeast Atlantic, Northwest Atlantic, Southwest Pacific, Southern Ocean and Indian Ocean. Gianni's (2004) review of high-seas bottom trawl fisheries is consistent with this conclusion.

The Northeast Atlantic Fisheries Commission (NEAFC)[13] provides the fisheries management framework for high-seas deepwater fisheries in the Northeast Atlantic. NEAFC receives scientific advice on management from ICES. As described in Section 4, ICES has expressed concern about the quality of fishery-dependent data for deepwater fisheries of the Northeast Atlantic. The amount of fishery-independent data and demographic information is also limited for deepwater fisheries. Nevertheless, ICES (2005) repeated a previous warning on deepwater fisheries, other than deepwater sharks, as follows:

> "Most exploited deepwater species are considered to be harvested unsustainably: however, it is currently not possible to provide advice for specific fisheries for deep-sea species. Consistent with a precautionary approach, ICES recommends immediate reduction in established deep-sea fisheries unless they can be shown to be sustainable. Measures should also be implemented to reduce exploitation of deep-sea species by fisheries primarily targeting shelf species (hake, anglerfish, and megrim). New deep-sea fisheries or expansion of existing fisheries into new

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[11] Commission Regulation (EC) No 1475/2003 of 20 August 2003 on the protection of deep-water coral reefs from the effects of trawling in an area north west of Scotland. L 211/14. Official Journal of the European Union, 21.8.2003. Cited by Gianni (2004).

[12] See http://www.ices.dk/marineworld/deepseacoral.asp

[13] See http://www.neafc.org/index.htm

fishing areas should not be permitted unless the expansion is very cautious, and is accompanied by programmes to collect data which allow evaluation of stock status as the basis for determining sustainable exploitation levels.

Ling and tusk are in many fisheries taken together and therefore the advised effort reduction, calculated on the basis of ling should apply to all fisheries taking ling and tusk as their main catch. The advised reduction is 30% compared to the 1998 effort level.

Concerning blue ling, there should be no directed fisheries. Technical measures such as closed areas on spawning aggregations should be implemented to minimize catches of this stock in mixed fisheries."

For deepwater sharks, ICES (2005) advised:

"The stocks of Portuguese dogfish and Leafscale Gulper shark are considered to be depleted. Given their very poor state, ICES recommends a zero catch of deepwater sharks."

ICES (2005) also gave advice on the "Seamounts, distribution of cold-water corals, and other vulnerable deep-water habitats"[14] identifying four candidate areas on Hutton Bank (Figure 8), northwest of Ireland for closure to bottom trawling.

NEAFC responded by propagating new regulations in 2006 on reporting fishery-dependent data,[15] and by reducing fishing effort on deepwater fisheries to 70 percent of the previous level.[16] This is a step in the right direction relative to advice from ICES, but it is unknown if this reduction in fishing effort will translate into a reduction in catch and fishing mortality sufficient to conserve deepwater stocks. It is too early to tell if there will be compliance with new regulations on reporting of fishery-dependent data.

According to the report of the 2005 annual meeting of NEAFC (7-11 November), some members of the Commission felt that more time was necessary to consider ICES's recommendation on closed areas to protect coldwater corals.[17] No action was taken. However, NEAFC has agreed to management measures prohibiting fishing with bottom trawls and static fishing gear on (a) the Hecate and Faraday seamounts and a section of the Reykjanes Ridge, (b) the Altair seamounts and (c) the Antialtair seamounts.[18]

The Northwest Atlantic Fisheries Organization (NAFO)[19] is the competent RFMO for the Northwest Atlantic. It has its own scientific body, referred to as the Scientific Council, to advise on scientific aspects of fisheries management. NAFO members are required to report fishery-dependent data, and there are several fishery-independent resource surveys conducted in the NAFO area, some sampling as deep as 1 500 m. The main deepwater species that are fished in the Northwest Atlantic are redfish, northern prawn and Greenland halibut.

NAFO (2006) gives the Scientific Council's most recent assessment of the state of the main deepwater fisheries. As noted in Section 2, Greenland halibut and redfish have been assessed to be overexploited and/or depleted, while northern prawn is fully exploited. The report of the Scientific Council expresses concern about the quality of fishery-dependent data, particularly about the lack of information on discards. A brief excerpt from the Scientific Council's advice on one of the stocks of Greenland

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[14] See http://www.ices.dk/committe/acfm/comwork/report/2005/sept/NEAFC%20Request%20and%20OSPAR%20request%2027%209%20without%20annex.pdf
[15] See http://www.neafc.org/measures/dss_info.htm
[16] See http://www.neafc.org/measures/dss_conservation.htm
[17] See http://www.neafc.org/reports/annual-meeting/docs/full_reports/24neafc_annual_vol-1-main-report_2005.pdf
[18] See http://www.neafc.org/measures/deep-water_05_06.htm
[19] See http://www.nafo.int/

halibut (NAFO Subarea 2 and Div. 3KLMNO off Newfoundland and Labrador) illustrates the management situation for at least one key deepwater fishery in the area:

> "The 2003 catch could not be precisely estimated, but was believed to be within the range of 32 000 t to 38 500 t. A fifteen year rebuilding plan has been implemented by Fisheries Commission for this stock. The catches in 2004 and 2005 were 25 500 and 23 000 t, which exceed the rebuilding plan TACs by 27% and 22%, respectively."

The Scientific Council estimated that the 2006 exploitable biomass was the lowest since 1970, the first year for which an estimate is available. It was also "strongly recommended" that steps be taken to address bycatch in the fishery.

For the Southern Ocean, the Commission for Conservation of Antarctic Marine Living Resources (CCAMLR)[20] provides a framework for international management of deepwater fisheries. The Convention that empowers CCAMLR calls for an ecosystem approach as described in Article II:

> "…maintenance of the ecological relationships between harvested, dependent and related populations of Antarctic marine living resources and the restoration of depleted populations …"

CCAMLR also applies a precautionary approach. Its website states that:

> "Where insufficient data are available to assess sustainable harvesting levels or other conservation measures, a 'precautionary approach' has been developed to take account of the potential risks associated with incomplete knowledge about the dynamics of a particular resource."

CCAMLR has a Scientific Committee which gives scientific advice on fisheries management and ecosystem issues.

The main deepwater species fished in the Southern Ocean are Antarctic and Patagonian toothfish. The total catch (Figure 9) of these two species reported from the Southern Ocean peaked at 18 508 t in 2003 before declining to 13 766 t in 2004. The species are considered to be fully to over-exploited. Illegal, unregulated and unreported (IUU) fishing has been a serious problem with these fisheries, although CCAMLR has taken steps to improve compliance with its conservation measures (e.g. a catch documentation scheme). The toothfish stock near the Prince Edward Islands (South Africa) illustrates the vulnerability of toothfish resources to IUU. In this area, IUU fishing drove the stock down to a few percent of its pre-exploitation level (Maguire *et al.* 2006).

In keeping with CCAMLR's ecosystem approach and its adoption of the precautionary approach, CCAMLR has protocols for exploratory fishing and fisheries development. Historically, fisheries have developed without regulation until enough scientific evidence has accumulated to convincingly indicate that regulation is needed. CCAMLR, however, requires that exploratory fishing and development of new fisheries be authorized, monitored and accompanied by collection of data for scientific purposes. This approach should serve as a model for all fisheries, especially deepwater fisheries which seem to be particularly susceptible to overfishing.

The remaining ocean area where high-seas deepwater fisheries are significant is the Indian Ocean. At present, there is no international convention for management of these fisheries, and they have been largely unregulated. There are reports of fishing in the Southwest Indian Ocean quickly fishing out local concentrations of deepwater species, such as orange roughy (summarized by Gianni 2004). Habitat damage from these fisheries is undocumented, although it almost certainly occurred. Catches seem to have been under-reported (Section 2).

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[20] See http://www.ccamlr.org/default.htm

In response to unregulated fishing in the Indian Ocean, the Southern Indian Ocean Deepwater Fisheries Association,[21] a fishing vessel operators' organization, with members that have been fishing for deepwater species in the Indian Ocean since 1996, agreed to a voluntary closure to fishing of 309 000 km^2 to conserve deepwater corals. Much of the area is pristine, never before subjected to bottom trawling.

A promising development in terms of a fisheries management framework for high-seas fisheries in the Indian Ocean is the South Indian Ocean Fisheries Agreement (SIOFA) signed by six countries in July 2006. Unfortunately, there are several countries with a history of deepwater fisheries in the Indian Ocean that are not yet parties to the agreement. The Agreement[22] commits the six countries to take concrete action to:

- establish effective mechanisms to monitor fishing in the SIOFA;
- provide annual reports on fishing operations, including amounts of captured and discarded fish; and
- conduct inspections of ships visiting ports of the Parties to verify they are in compliance with SIOFA regulations, and to deny landing and discharging privileges to those who do not comply.

While the agreement represents a clear commitment to monitor fisheries, it is not clear on intentions about sustainably managing fisheries. However, it is a step in the right direction.

For the Southwest Pacific, bilateral arrangements have been used to manage high-seas deepwater fishing on straddling stocks. For example, Australia and New Zealand have bilateral arrangements to manage the orange roughy fisheries on the South Tasman Rise (South of Tasmania, Australia) and the Challenger Plateau (west of New Zealand). Unfortunately, these arrangements have often not been successful in sustaining the fisheries (Section 6). Other high-seas deepwater fisheries in the Southwest Pacific are managed by flag state control of their own vessels. For example, New Zealand requires its vessels fishing on the high seas to have a high-seas fishing permit and to land their catch at a New Zealand port. This improves reporting on high-seas catches, but it does not restrict catches.

There are many other international arrangements concerning fisheries.[23] To date, none of them have played a significant role in managing high-seas deepwater fisheries. Clearly many of them lack competency to do so, such as the tuna commissions. It is unclear if others could manage deepwater fisheries even if their members agreed to do so.

Since high-seas deepwater fisheries in areas other than those discussed above appear to be minor, there is little call for additional international management arrangements. However, no one knows when a new international deepwater fishery might emerge or become known (some may be occurring now without being detected). Experience indicates that such fisheries develop and collapse quickly when unregulated (e.g. the pelagic armourhead fishery in the North Pacific during the late 1970s and 1980s), such that it may already be too late to negotiate an agreement once a new fishery begins.

6. CASE STUDY – ORANGE ROUGHY FISHERIES

In this section, a moderately-detailed summary and evaluation of the specific case of orange roughy (*Hoplostethus atlanticus*) fisheries on the Chatham Rise, New Zealand will be presented, followed by much briefer summaries of the history of other orange roughy fisheries in New Zealand, Australia, Namibia, Chile and the South Tasman Rise. There are also a few comments about oreo (*Allocyttus*,

[21]See: http://www.fao.org/newsroom/en/news/2006/1000360/index.html
[22] See Web address in the previous footnote 14.
[23] See the following FAO Web address for intergovernmental fishery organizations: http://www.fao.org/fi/body/rfb/index.htm

Neocyttus and *Pseudocyttus* sp.) fisheries in selected areas. The Chatham Rise orange roughy fisheries epitomise the evolution of the development of fishing, data collection, stock assessment and management of major deepwater fisheries.

6.1 Specific example: Chatham Rise orange roughy

The Chatham Rise orange roughy stock complex, located off the east coast of New Zealand from about 174.5°E to 173.667°W and 42.167°S to 46°S (Ministry of Fisheries 2006) is the largest known stock or stock-complex of orange roughy yet discovered, has been and still is supporting the longest-running orange roughy fishery, has the longest history of data collection, has had the greatest investment in research, and uses "state-of-the-art" stock assessment models and management tools. As such, it should have the greatest chance of any orange roughy fishery of being a success story. Whether or not this is the case is considered below.

For the period before the declaration of New Zealand's EEZ in 1978, it is known that vessels from the former Soviet Union were fishing for orange roughy in this area. Catches are unknown, but are believed to have been of the order of 2 000 - 3 000 t annually since 1973 (Robertson 1985). Fishing on the Chatham Rise during 1979 and 1980 was unregulated and recorded catches increased to 31 100 t (Table 4). An arbitrary total allowable catch (TAC) was set at 23 000 t in 1981.

6.1.1 Brief history of assessment methods and results

The discovery of "huge" aggregations of orange roughy on the Chatham Rise generated considerable excitement at the time. In retrospect, scientists, managers and fishers alike were misled by the apparently large biomass and dense aggregations, implicitly equating high biomass with high productivity. In fact, fisheries scientists thought they were taking a conservative approach by assuming life history parameters that were similar to or lower than averages used for other temperate water teleosts (e.g. a natural mortality of 0.1, a Brody growth coefficient of 0.2, and ages of maturity and recruitment of 5; Robertson 1986, Robertson and Mace 1988).

A wide area trawl survey was conducted for the first time in 1982. Based on various area expansion assumptions, this resulted in an estimate of then-current biomass of 792 800 t. As a result, the TAC was increased to 30 000 t. Two further (stratified random) trawl surveys in July 1984 and July 1985 led to estimates of the 1985 biomass of 509 500 t and an estimate of the unfished biomass, B_0, of 608 700 t (Table 4). Applying $Y = ½ MB_0$ (where Y = long-term sustainable yield and M = natural mortality; Gulland 1971), and using a "conservative" estimate of M=0.1, resulted in a yield estimate of 30 435 t and a TAC recommendation of 30 000 t. In the following year, the 1984 and 1985 survey results were re-analysed by adjusting for local high density and school height. Biomass estimates were multiplied by 10 whenever dense schools were observed on the colour sounder during a research tow. This increased the estimate of unfished biomass to 935 000 t. Applying $Y = ½ MB_0$ resulted in an estimate of long-term sustainable yield of 46 700 t and a TAC recommendation of 47 000 t, excluding catch overruns. However, it was believed that the difference between total removals and recorded landings was substantial (the former being up to 30 percent higher than the latter, Table 4) due to burst nets, escape windows in nets and lost or abandoned gear. Therefore, it was recommended that the TAC should only increase by about 8 000 t.

Table 4. Estimates of the unfished biomass, B_0, estimates of sustainable yields, annual TACs or catch limits, reported catches and catches adjusted for estimated overruns for Chatham Rise orange roughy.

Catches are reported to the nearest 100 t and are estimated for a 1 October-30 September fishing year. Estimates of B_0 and sustainable yields are calculated about six months in advance of the fishing year indicated and are used to inform the catch limits for that year. Where ranges are given, they represent the range of medians resulting from alternative assumptions; confidence intervals are not included. Estimates of sustainable yields are based on ½ MB_0 for 1985-86 and 1986-87, and the application of F_{MSY} or proxies to current biomass thereafter (see text). Blanks indicate that estimates were not made.

Fishing year	Estimates of B_0 (t)	Estimates of sustainable yields (t)	TAC or catch limit (t)	Estimated catch (t)	Catch plus estimated overruns (t)
1978-79			–	11 800	15 300
1979–80			–	31 100	40 400
1980–81			–	28 200	36 700
1981–82			23 000	24 900	32 400
1982–83			23 000	15 400	20 000
1983–84	> 792 800		30 000	24 900	32 400
1984–85			30 000	29 200	38 000
1985–86	608 700	30 435	29 865	30 100	38 500
1986–87	935 000	46 750	38 065	30 700	38 700
1987–88	406 500	17 430	38 065	24 200	30 000
1988–89	389 000	8 000	38 300	32 800	40 000
1989–90			32 787	31 600	37 900
1990–91	411 000	5 500	23 787	20 600	23 700
1991–92	383 000	2 200	23 787	15 500	17 100
1992–93	399 000-473 000	3 200	14 300	14 000	15 400
1993–94	411 000-508 000	2 900-7 000	14 300	13 500	14 900
1994–95	416 000-442 000	2 900-4 800	8 000	8 000	8 400
1995–96		3 200-5 100	7 200	7 500	7 900
1996–97			7 200	7 200	7 600
1997–98	482 000-503 000	7 940-8 940	7 200	8 600	9 000
1998–99			7 200	7 500	7 900
1999–00			7 200	7 800	8 200
2000–01	449 000-495 000	5 870-8 540	7 200	7 550	7 900
2001–02	475 000-589 000	10 270-15 940	10 400	9 600	10 100
2002–03			10 400	10 800	11 300
2003–04			10 150	9 550	10 000
2004–05	469 300-558 300		10 150	10 400	10 900
2005–06			10 150	9 900	10 400
2006-07	531 600	13 830	9 400		

Subsequently, there were two rapid developments that substantially reduced the estimates of sustainable yields. First, Mace and Doonan (1987) suggested that uncertainty about B_0 and uncertainty about then-current stock size relative to B_0 meant that use of $Y = ½ MB_0$ might no longer be applicable and that it would be more prudent to base yield estimates on the product of $F_{0.1}$[24] and an estimate of current biomass, $B_{current}$. The estimate of $F_{0.1}$ was 0.18 (still based on the assumption of M = 0.1), while the estimate of the 1987 biomass was 96 800 t, resulting in a revised yield estimate of 17 430 t. It was recommended that the TAC needed to be reduced to avoid collapse to dangerously low levels within 20 years.

Next, in early 1988, a survey was conducted to locate small juveniles for ageing studies (using modal analysis and marginal increments) in the hope of being able to differentiate between eight substantially

[24] This is a level of fishing mortality that has been used as reference level in several fisheries around the world.

different competing estimates of the age-length relationship. The results indicated that none of the extant age-length relationships were likely to be even remotely correct and that orange roughy were much longer-lived with a much higher age of maturity and much slower growth than indicated by any of the eight previous studies (the new results suggested that M = 0.05 or less, the Brody growth coefficient was of the order of 0.06, and the average age of maturity was at least 20 years; Mace *et al.* 1990).

The 1989 assessment used a draft version of the Mace *et al*. (1990) results in a simple stock reduction model (Sissenwine 1988) with M = 0.05, an age of recruitment of 20, $F_{0.1} = 0.067$, $B_0 = 389\ 000$ t and a 1988 biomass of 128 000 t (Robertson 1989). This resulted in a long-term sustainable yield estimate of about 8 000 t. Subsequent studies have resulted in even smaller estimates of M (0.03-0.045) and higher estimates of the median age of maturity (28-34 years).

Thus, over a period of only two years, the estimate of unfished biomass was reduced from 935 000 t to 389 000 t, while the estimate of sustainable yield was reduced from 46 750 t to 8 000 t. Over the ensuing 17 years (1990-91 to 2006-07), considerably more data were collected on commercial catch per unit effort (CPUE), commercial length-frequency data from observer programmes, fishery-independent stratified trawl surveys, length-frequency data from trawl surveys, deepwater acoustic surveys using trawls for species identification, and ageing of samples from both commercial catches and research trawl catches. As data have accumulated, the sophistication of assessment models has increased. Bayesian models were first introduced in 2001 (Smith *et al.* 2002, Bull *et al*. 2003). Resulting estimates of sustainable yields (median estimates for alternative runs) are included in Table 4.

6.1.2 Brief history of management

Table 4 shows that catch limits and estimated removals (last column) exceeded or far exceeded estimates of sustainable yields for all years from 1988-89 until about 1997-98. The early TACs and catch limits were influenced by what, in retrospect, were overly optimistic stock assessments, along with a belief that these assessments were "conservative". In 1997-98, the Chatham Rise was split into three sub-areas for assessment and management purposes (the East Chatham Rise, often referred to as the Northeast Chatham Rise – which contains the largest spawning aggregation; the Northwest Chatham Rise – which contains smaller, known spawning aggregations; and the South Chatham Rise – which may actually be a continuation of the East Chatham Rise since no major spawning aggregations have been located there). It is interesting to note that since this time, estimates of the re-combined B_0 have increased moderately, while estimates of combined sustainable yields have increased substantially and have been somewhat higher than the catch limit. The assumption that these are separate populations with no migration between them may have resulted in erroneously high estimates of the biomass of each component (through, for example, "double counting").

A comprehensive individual transferable quota (ITQ) system was introduced in New Zealand in October 1986 and shortly thereafter the New Zealand government increased the Chatham Rise orange roughy quota by 7 800 t (to 38 000 t), selling off the increase to the industry for $NZ 23 400 000 (ITQs were initially designated as absolute tonnages; Sissenwine and Mace 1992). This increase in quota preceded the beginning of the substantial downward revisions of both biomass and productivity, summarised in the previous section, by only a few months. However, since ITQs had been awarded in terms of absolute tonnage and the industry had already paid a substantial amount for the increase in quota, it was difficult to rapidly reduce TACs. This situation was no doubt one of the key reasons for moving to a proportional ITQ system (in which ITQs are set as a proportion of the TAC) in April 1990, as it would have cost the government more than $NZ 100 000 000 to buy back sufficient quota to reduce the TAC to the then-estimated long-term sustainable yield (Sissenwine and Mace 1992).

In response to the dramatic reductions in estimates of long-term sustainable yields, it was decided to manage the fishery in a "fishing-down phase" while gradually reducing quotas towards the long-term sustainable yield. It was agreed that the TAC would be reduced by 5 000 t per year to the sustainable level, the latter being recalculated periodically as new data became available. Resistance to quota reductions meant they never came into force at this level for the entire quota management area (ORH3B, which includes the Chatham Rise, hill complexes to the east and a vast area to the south which extends into the sub-Antarctic), although they were more or less approximated for the Chatham Rise portion of the management area. Over the period 1988-89 to 1995-96, the catch limit for the Chatham Rise was reduced from 38 300 t to 7 200 t (Table 4) and a number of different management measures were introduced: in 1997-98, the Chatham Rise was split into three parts, various catch-spreading arrangements to reduce the focus on the main spawning ground during the spawning season were implemented, the main spawning fishery was closed for two years, and exploratory fishing in the southern sub-Antarctic regions of the management area was encouraged. Most of these measures were introduced in cooperation with the fishing industry as part of several formal and informal voluntary agreements.

6.1.3 Recent assessment and management events

Assessments for the East Chatham Rise (then referred to as the Northeast Chatham Rise) conducted in 2001 produced what many scientists, managers and industry representatives believed were overly optimistic estimates of current biomass. Results from 13 model runs suggested that biomass had declined from an unfished level of 350 000-400 000 t, down to a low of 90 000-130 000 t in 1991-92 or 1992-93 around the time the main spawning fishery was closed, and had subsequently rebuilt to 120 000-190 000 t (34-54 percent B_0) in 2001. However, there were no data to support such a substantial rebuild. Short-term sustainable yields based on F_{MSY} were estimated to be 7 800-11 800 (Table 4), with corresponding long-term sustainable yields of 6 600-7 700 t. The catch limit for the East Chatham Rise (excluding the Northwest Chatham Rise and the South Chatham Rise) was set “conservatively” at 7 000 t.

In early 2005, a similar assessment was conducted with updated information. However, this assessment was even more optimistic in that it estimated a greater extent of rebuild even though all indices applicable to recent years continued to decline. In fact, the model was insensitive to any of the post spawning fishery closure datasets. No matter which sets of such data were included or excluded (or even if all of them were excluded), the estimated extent of rebuilding since the spawning fishery closure was similar (Dunn 2006).

As a result, it was determined that a major review of the assessment inputs and model assumptions was needed and the assessment was rejected. Three major workshop reviews, all including external experts, were undertaken between October 2005 and February 2006. Workshop participants determined that the ageing data for orange roughy were not only extremely imprecise, they were biased in a way that could not easily be rectified. Otoliths collected in adjacent years but read several years apart often led to substantially different length-age relationships. A considerable amount of research has been put into orange roughy ageing in New Zealand and Australia and it has been possible to conclude with a high degree of certainty that growth is slow, the median age of maturity is about 25-30+, and maximum age is of the order of 120-150; however, production ageing to determine the annual age composition of the catch has proven to be very imprecise and inconsistent, to the extent that it is impossible to estimate the number of new fish recruiting to the fishery each year to an acceptable degree of precision. Workshop participants recommended that the use of ages in orange roughy stock assessment models should be abandoned, at least until adequate ageing techniques can be developed. Research into ageing will still continue, but at a reduced level. In the meantime, the hypothesis that the fishery started on a large accumulated biomass and that recruitment has been extremely low for the last decade or two cannot be rejected. This could be the result of a pattern of episodic recruitment for orange roughy. Episodic recruitment with a periodicity of the order of 1-2 decades has been shown for some other long-lived species (e.g. some *Sebastes* spp, Mayo 1980), but it could be even longer for orange roughy which has an unusually high age of maturity and a very long lifespan.

It is interesting to note that stock assessment scientists in New Zealand were already issuing warnings about the possibility of recruitment failure as early as 1987.

The three workshop reviews also identified problems with commercial length frequency data and acoustic estimates of biomass. Regarding the latter, orange roughy have an oil-filled swim bladder and, as a result, have a very low target strength that may be swamped by other species with much larger target strengths when they occur in mixed species aggregations. In addition, there is no definitive estimate of their actual target strength with the two primary estimates (Barr and Coombs 2001, Kloser and Horne 2003) resulting in a 2-fold difference in biomass estimates. Finally, they are frequently found associated with submarine knolls or seamounts and often seem to be hard on the bottom, which means that a potentially large but unknown tonnage may occur in the acoustic shadow zone. It was recommended that acoustic estimates of biomass, which previously had been treated as absolute, should be treated as relative estimates and expert groups should be formed to develop appropriate Bayesian priors for them. The review panels also made recommendations for further work to be undertaken.

Armed with the recommendations of the three review panels, the assessment was repeated in early 2006. However, despite numerous refinements, the results changed relatively little between 2005 and 2006, even though all post closure indices continued to decline with the addition of one more year of data. For the base run for the main spawning plume and surrounding flat area (a sub area of the East Chatham Rise, but estimated to encompass more than 90 percent of the total biomass in that area), B_0 was estimated to be 323 800 t, with biomass declining to 37 percent of this level in 1991-92 and thereafter increasing to 56 percent B_0 (181 000 t in 2004-05; top panels in Figure 10). Again, the estimated increase in biomass was insensitive to all datasets collected following the spawning fishery closure. The median short-term yield based on F_{MSY} was estimated to be 11 200 t, with a corresponding long-term yield of 6 100 t. The 2006 assessment was accepted, but with strong reservations.

Based on sensitivity analyses in which recruitment was estimated, rather than the base case where it was assumed to be constant over time, or where natural mortality was arbitrarily halved (bottom panels in Figure 10), it was concluded that the largest uncertainty was the extent of the biomass increase, “which appears to be driven by model assumptions about productivity, rather than recent data” (Ministry of Fisheries 2006). The absence of data on incoming recruitment levels and the time lag between spawning and maturity (50 percent maturity about 28-34 years) compared to the current duration of the fishery (28 years) necessitates the assumption that recruitment has been constant over time. Attempts to estimate recruitment in (unconstrained) assessment models result in a single unbelievably large spike in recruitment that has fed the current fishery, with extremely low levels of recruitment since. The default hypothesis of constant recruitment cannot fit both the catch history and the recent declining trends in abundance indices (Figure 10).

It should also be noted that the assessment runs presented in Figure 10 did not include consecutive annual (2002-2005) industry-derived acoustic estimates of the biomass of the main spawning plume that have declined monotonically to an extent that exceeds the cumulated catch from the spawning box (an area encompassing the main historical and current spawning plumes). The most recent (2006) industry point estimate continues the declining trend. The catch limit was not changed as a result of this assessment (although 250 t had been added by moving quotas from the Northwest Chatham Rise, due to sustainability concerns for that sub-area).

6.2 Other orange roughy fisheries

Other orange roughy fisheries have exhibited similar patterns of overestimation of initial biomass, rapid fishing down and overshooting of biomass targets.

6.2.1 New Zealand

The second largest orange roughy stock discovered in New Zealand waters is the Challenger stock off the west coast of the two main islands. Approximately 18 months before the discovery of small juveniles that demonstrated slow growth, probable high ages of maturity and longevity, and low productivity, an "adaptive management experiment" was initiated for Challenger orange roughy. The TAC was increased from 6 190 t to 10 000-12 000 t beginning in 1986-87 to determine the response of the stock to increased fishing mortality. The result was that the stock crashed dramatically within three years, with the TAC being reduced from 12 000 t to 2 500 t in a single year (1989-90) and, over the next few years, it was further decreased to 1 900 t, then 1 425 t, then in 2000-01 it was essentially closed and remains so today, except that industry-sponsored research surveys have taken place in the last two years.

This experience certainly resulted in New Zealand taking a more precautionary approach subsequently. However, assessing and managing orange roughy fisheries has remained a difficult task. Currently, of 10 "stocks" or management areas, three are believed to be near or above the target biomass (B_{MSY} = 30% B_0), five are believed to be below this level, and the status of the other two (exploratory) fisheries is unknown. Most fisheries have historically been characterised by sequential depletion of particular underwater features (Clark 1999), but there are now measures in place to reduce this tendency in some areas (e.g. feature limits of 100-500 t).

6.2.2 Australia

Australian orange roughy fisheries began around 1982, but substantial catches were not made until 1986. Early catches were of a similar magnitude to those being realised in New Zealand at the time (Bax *et al.* 2005). Initial scientific estimates of biomass were in the hundreds of thousands to millions of tonnes (Harden Jones 1987, Kenchington 1987). An assessment based largely on anecdotal information suggested a biomass of 500 000-700 000 t in the Sandy Cape area off the Tasmanian coast (Kenchington 1987). However, this "aggregation" was essentially fished out in a single year with a catch of 5 000 t. In fact, according to Bax *et al.* 2005, until 1989 most aggregations were essentially fished out in the first year.

The discovery of large aggregations on the hills off southern and eastern Tasmania resulted in a substantial increase in catches (37 000 t in 1989 and 58 600 t in 1990; Bax *et al.* 2005). The initial (unsupported) biomass estimate (in 1989) for the eastern zone was 300 000 t. An acoustic survey in 1990 resulted in an estimate of the spawning biomass of 57 000 t. Acoustic and egg production estimates conducted in 1991 provided confirmation for the 1990 estimates, and scientists suggested that the "fishdown" phase had been completed, and that the stock was potentially below the target of 50 percent B_0. Further surveys in 1992 resulted in a reduction in the previous year's biomass estimate of almost 40 percent. By the end of 1992, the then-current biomass was estimated to be 25-30 percent of the unfished level. In 1995, it was estimated that the stock had a 73-75 percent probability of being below 30 percent B_0 (the revised management target). Throughout this period, TACs were set several times higher than scientifically-recommended levels. The 2005 TAC was set at 720 t, compared with TACs in the range of 12 000-20 000 t from 1987 to 1990. These overly-optimistic TACs were exacerbated by catches that were much higher than TAC levels in some years.

The situation was similar in the southern zone except that there it was further exacerbated by an adaptive management experiment in which the TAC was set at 13 000 t even though sustainable yields were estimated to be of the order of 2 100-3 000 t (Bax *et al.* 2005). The TAC for the southern zone was 100 t in 2005 and was revised to 10 t for 2006.

The Cascade Plateau fishery off the east coast of Tasmania may be the one Australian example where a truly precautionary approach has been adopted from the start. A precautionary quota of 1 000 t was instituted before substantial catches had been taken (Bax *et al.* 2005). The 1 000 t limit was reached in 1997 after which a cooperative research and management programme was developed with the fishing industry and the TAC was increased to 1 600 t. This fishery has continued to the present day with TACs in the range of 700-1 600 t. The 2006 assessment indicated that the female spawning biomass was about 73 percent (range 62-82 percent) of the unfished level.

6.2.2.1 Recent developments in Australia

In late October 2006, the Australian Fisheries Management Authority (AFMA) closed all orange roughy fisheries except the Cascade Plateau fishery to directed fishing. Bycatch quotas for 2007 in the closed fisheries range between 25-50 t. The 2007 quota for the Cascade Plateau itself has been reduced from 700 t to 400 t.

In early November 2006, the Australian Department of Environment and Heritage listed orange roughy under its Environment Protection and Biodiversity Conservation Act as "conservation-dependent". In the authors' opinion, this listing is not warranted as rough calculations indicate that there are at least 50 million orange roughy in Australian waters, and AFMA has already taken appropriate steps to facilitate rebuilding of the stocks, and to conserve the one remaining stock that has a directed fishery. It is nevertheless interesting that the addition of orange roughy to Australia's threatened species list does not preclude fishing.

6.2.3 Namibia

Exploratory fishing for orange roughy in Namibian waters began in 1994 and management controls on catches were first imposed in 1997 (Butterworth and Brandao, 2005). Only four consistently fishable aggregations were found in the 1990s, although a more southern fishery has recently developed. In 1998, a biomass estimate of 300 000 t (200 000 – 500 000 t) for the entire area was estimated from exploratory commercial trawl data using a swept area method (Branch 1998). Following the approaches adopted by New Zealand and Australia, a deliberate fishing down strategy was implemented with an initial TAC of 12 000 t and a gradual reduction towards 5 000 t (90 percent of the MSY estimated at that time) over a 14-year period (Figure 11). Within a year, the swept area estimate was revised downward to 225 000 t, and acoustic/trawl research surveys suggested an even lower estimate of 150 000 t. Subsequent research survey estimates of biomass continued to decline and the TAC was reduced to 9 000 t in 1999 (Boyer *et al.* 2001). This TAC was substantially under caught and the following year the TAC was further reduced to 1 875 t, though it was increased again to 2 650 t for 2003. Recent assessments suggest that the unfished biomass for the entire area was probably in the region of 100 000 t (Butterworth and Brandao 2005).

6.2.4 Chile

The following section summarizing the history of Chilean orange roughy fisheries was contributed by Edwin Niklitschek of the Universidad Austral de Chile.

The Chilean orange roughy fishery began after the first seamount exploration around the Juan Fernandez Archipelago in 1998. Managed under a special regime for developing fisheries, individual 10-year quotas were auctioned in 1999. With limited information on stock size, a 2 000 t quota was considered precautionary compared to orange roughy quotas elsewhere in the world, and the quota was maintained at that level through the first seven years of the fishery. At the commencement of the fishery, a collaborative agreement was signed and implemented between the fisheries management authority and the quota holders, initiating a research program which included a biological monitoring program from 1999. A low-cost acoustic monitoring program was implemented in 2002, with annual acoustic surveys since then, and several complementary research initiatives (Boyer *et al.* 2003, 2004, Niklitschek *et al.* 2006). Commercial catches reached a peak of 1 870 t in 2001, declining to less than 800 t in 2005 (Figure 12). Given this trend, the fisheries management authority and the industry agreed to close the commercial fishery in 2006, allocating only a research quota of 500 t.

Total biomass estimates for the Juan Fernandez seamounts (where more than 80% of historical catches in Chile have been taken) show a decreasing trend from 27 000 t in 2003 to 14 500 t in 2006 (Figure 13). Nonetheless, individual seamounts have shown inconsistent trends, suggesting high inter-annual variability that does not appear to be directly related to fishing pressure (Figure 13).

Interpreting the causes for the rapid reduction in orange roughy landings and the apparently correlated changes in estimated biomass is far from simple. Lower catches are at least partly the result of large effort reductions from about 450 vessel-days in 2002 to less than 150 vessel-days in 2004. This effort reduction resulted from agreements between quota holders to consolidate fishing activities in response to the high operational costs for fresh fish vessels (which, by regulation, are the only vessels allowed to fish for orange roughy) operating on only four major seamounts at Juan Fernandez, 280 nm offshore from the coast at Talcahuano. The long distance from operating ports to fishing grounds and the high seasonal variability in abundance on the four seamounts has adversely affected the viability of commercial fishing operations.

Cumulated catches of 3 780 t between 2003-2006 cannot explain the apparent reduction in estimated biomass of about 12 500 t. [25] Some other factors must be playing a relevant role. Three main hypotheses being considered in Chile to explain this are: i) emigration or behavioral changes due to habitat degradation or perturbation by fishing activity; ii) intermittent spawning behavior leading to different components of the population spawning in different years; and iii) methodological problems associated with the interaction between fish behavior and the acoustic dead zone.

6.2.5 South Tasman Rise

Aggregations of orange roughy were discovered south of Tasmania on the South Tasman Rise just outside the Australian fishing zone in late 1997. Catches had already peaked at 3 930 t by 1997-98. The following year, they declined to 1 705 t, then increased to 3 360 t in 1999-00, declined to 830 t in 2000-01, and have ranged from 2-170 t since. This fishery illustrates the rapidity with which an orange roughy fishery can develop and crash. A formal Memorandum of Understanding to regulate the fishery was signed by New Zealand and Australia in late 1998, only about a year after the stock was discovered (Tilzey, 2000). An initial precautionary TAC was set at 2 100 t, increased to 2 400 t in 2000-01 and was then gradually reduced to 600 t in 2004-05. However, although Australian and New Zealand catches were regulated, there was heavy fishing in 2000 by vessels from South Africa and Belize. Since 2000-01, recorded catches have been substantially less than the “precautionary” TACs. In 2003-04, 67 tows were made for a total of 2 t of orange roughy catch. New Zealand vessels have not fished in the area since 2000-01. There has been no formal stock assessment agreed for this fishery, although standardized CPUE analyses have been carried out (Wayte *et al*. 2001, 2003).

6.3 Summary for orange roughy

Based on the cases summarised above for New Zealand, Australia, Namibia, Chile and the South Tasman Rise (as well as cases not included in these brief summaries), there have essentially been two patterns of fishery development:

- Small stocks have frequently been fished down to low, often uneconomic, levels within a few years of being discovered, long before effective management can be put in place.

- Larger stocks have mostly been characterised by initial estimates of the unfished biomass that have typically been 2-10 or more times the retrospective estimates of the unfished biomass. Unrealistically high initial estimates of unfished biomass have in turn led to unreasonably high estimates of sustainable yields. In most cases, managers, the industry and some scientists have

[25] Note that the 2006 biomass estimate is currently under review and could change; however, the observation that estimated biomass appears to have declined faster than cumulated catches is still likely to hold (and has also been noted in several other orange roughy fisheries).

labelled these initial estimates as "conservative" or "precautionary" and when they have ultimately found that they were not at all conservative, they have generally taken refuge in the belief that it is permissible to institute a "fishing down" phase in which TACs are gradually reduced over time to the new estimates of sustainable yields (which tend to keep going down faster than the TACs). In almost all cases, this has led to biomass targets (even those as low as 30% B_0) being overshot. As a result, many orange roughy fisheries now have TACs that are less than 2 000 t and are likely to remain at these levels until and unless the stocks rebuild. Orange roughy fisheries actually do have the potential to produce higher sustainable yields but, unfortunately, it will take many years if not decades for most of them to rebuild back to biomass levels near or above B_{MSY}.

For both patterns, the discovery of new stocks seems to have almost invariably led to a gold rush mentality.

These two patterns of fishery development have been repeated over and over and, at least on the surface, it appears that previous experience has had little influence on management approaches. In fact, even though previous experience has ultimately influenced scientific advice, which has generally become progressively more precautionary, management has continued to be hampered by the rapidity with which an orange roughy fishery can develop, followed by the difficulty of dealing with the fishing fleet overcapacity that develops as a result. In retrospect, very few orange roughy fisheries have been managed in a precautionary way. If they had been, the build up of fishing capacity and overshooting of biomass targets might have been mitigated or avoided altogether.

6.4 Oreo fisheries

Oreo fisheries have developed along the way, as a "poor cousin" of orange roughy, even though they were being commercially fished off New Zealand before orange roughy. There has been less assessment and management attention paid to them because of their lower value. But their lower value may have also protected them relative to orange roughy because there has been less of a gold rush and they may also be slightly more productive than orange roughy. In New Zealand, both smooth and black oreos and, to a lesser extent, spiky oreos are often caught in conjunction with orange roughy, although there are also areas where they predominate in the catch. Where assessments have been conducted, they have generally shown that the assessed stock is above the specified target (B_{MSY} = 25% B_0), or that the assessment has been inconclusive. However, few assessments have been conducted because oreos are spread over very large areas and, due to their relatively low commercial value, it has generally not been cost-effective to conduct fishery-independent surveys on them.

6.5 Evolution of data collection programmes and stock assessment models for deepwater species

The discussions in the next three sections are restricted to the situations in New Zealand and Australia.

In New Zealand, biomass estimates were initially based on area swept estimates from stratified random trawl surveys conducted between depths of 750-1 200 m, using the mean of the estimates based on the door spread and the distance between the wingtips. Yield estimates were then calculated as $Y = \frac{1}{2} MB_0$, where Y = yield, M = natural mortality and B_0 is the unfished biomass (Gulland 1971). Once a sufficiently long series of trawl surveys had been developed, the biomass estimates derived from them were treated as relative estimates of biomass rather than as absolute estimates. At that time, stock reduction models (Sissenwine, 1988; Francis, 1990, 1992b) were used to estimate the unfished biomass, and the current status of the stock relative to this level. The stock reduction method was extended to allow stochastic recruitment in 1995 (Francis *et al.* 1995). Subsequently, age-structured Bayesian models were developed to incorporate information from a number of different sources as well as allowing the use of priors based on other fisheries and other information outside the model (Smith *et al.* 2002, Bull *et al.* 2003). Smith *et al.* (2002) produced the first formally accepted Bayesian assessment of Chatham Rise orange roughy in 2001. From this point on, Bayesian assessment models have been used in most New Zealand orange roughy and oreo assessments, with numerous refinements continuing to be incorporated. However, the utility of these models for species that are difficult to age and for which there is virtually no information about incoming recruitment is currently being questioned (Sections 6.1.3 and 6.5.1)

Over the past few years, there has been an increasing tendency to favour acoustic surveys as the mechanism for obtaining estimates of biomass, and Bayesian models for stock assessments, at least for the largest, most important stocks. Australia has also favoured the use of full Bayesian analysis and acoustic surveys for their most important fisheries.

6.5.1 Future prognosis for deepwater assessments, particularly orange roughy assessments

Orange roughy stock assessments have always been uncertain, and various beliefs have been held about whether estimates of stock size and sustainable yields were biased in one direction or the other. However, in recent years, there has been growing unease that stock assessments for several New Zealand orange roughy stocks have been decidedly over-optimistic, as reflected by concerns expressed in stock assessment reports (Ministry of Fisheries 2006).

For example, since the most recent assessment of the East Chatham Rise orange roughy stock was completed in April 2006, assessment scientists, managers and the commercial fishing industry itself have become increasingly concerned about the assessment results and the future of the East Chatham Rise stock. In fact, Mace (in press) has suggested it is an example of a failed stock assessment. In retrospect, the 2001 assessments, which gave similar results, are also likely to be deficient.

Even though the 2006 East Chatham Rise assessment suggests a short-term F_{MSY} yield of about 11 200 t, experienced fishers are concerned that they may not even be able to catch the current quota of 7 250 t in the next fishing season. Given the low productivity of the species, F_{MSY} yields have been calculated to be only 6.5 percent of the available biomass (which itself may be an overestimate) and, given that orange roughy on the East Chatham Rise form dense aggregations in well-known locations, fishers ought to (at least acoustically) encounter of the order of 10-16 times the F_{MSY} yield. If the assessment is correct, fishers should be complaining that their catches are being unduly restricted, not that they believe they will have difficulty catching the quota. Another ominous indicator of the optimism of the stock assessment is that some fishers have now switched to much larger (squid) trawls, in order to maintain commercially viable catch rates.

Punt (2005) suggested that the following will be features of assessments of deepwater species in the future:

- several alternative models will be included in assessments and hypotheses regarding spatial structure will be emphasised to a greater extent;
- most model parameters will be estimated within assessment models, rather than being pre-specified;
- uncertainty will be quantified by means of Bayesian posterior distributions; and
- prior distributions will be developed based on meta-analysis.

We think it is more likely that the current Bayesian models may be discarded in the near future, along with other age-structured models, in favour of simpler approaches. Age-structured models are generally thought of as superior to other assessment models because they can be used to track both large and small year classes as they move through populations, they can provide retrospective estimates of recruitment and recruitment variability, and they may enhance the ability to make informed short-term predictions of future stock size based on estimates of the sizes of incoming year classes. However, these advantages will not be realised if age readings are both highly imprecise and substantially biased, as is currently the case for New Zealand orange roughy. In addition, as mentioned above, age readings are not the only problematic source of data for orange roughy assessments.

Regarding the second bullet point in Punt's list, the concept of estimating as many parameters as possible within a Bayesian model does not seem to have worked well for orange roughy in New Zealand. It may be misleading to estimate multiple model parameters within assessment models when most or all of the data are imprecise or biased and estimates of parameters are confounded. For example, for assessment runs conducted for East Chatham Rise orange roughy in 2005, it appeared that CPUE data were not fit much if any better when β (a power function parameter determining the relationship between CPUE and biomass) was estimated; rather, the fit of the model was improved for some other data set such as the survey data or the age data. Since the purpose of estimating β was to get a better fit to the CPUE, the assessment working group questioned whether it actually should be estimated at all. As another example, estimating the age of 50 percent recruitment for orange roughy often resulted in a selectivity ogive that was well to the right of the maturity ogive implying a vulnerable biomass that is much smaller than the mature biomass (e.g. vulnerable biomass as low as 15 percent of mature biomass for the Mid-East Coast orange roughy stock, Ministry of Fisheries 2006). This is not supported by knowledge of how the fisheries currently operate – fishing has actually become less concentrated on spawning aggregations during the spawning season, and fishing outside the spawning season results in catches that include large juveniles. Therefore, the selectivity ogive should probably be somewhat to the left of maturity ogive.

In general, the evolution of Bayesian models for orange roughy in New Zealand has been to estimate as many parameters as possible within the model during the start of an assessment cycle, but then to fix progressively more of them as the assessment has evolved, in order to prevent the model from providing biologically unreasonable results.

It is possible that the "evolution" of assessment models for orange roughy may culminate in a reversion to simpler methods of estimating sustainable yields, such as the product of F_{MSY}, $F_{0.1}$ or M and a survey estimate of current biomass, at least until and unless better ageing techniques can be developed and/or some other source of data can be shown to be useful for assessing stock status. This would actually amount to a reversion to a methodology similar to that used in newly-developed fisheries when few data were available, except that future results are likely to be more reliable as they will have the benefit of past experience.

6.6 Evolution of management strategies and paradigms for deepwater species

The management strategy in New Zealand has been explicitly based on "moving stocks towards B_{MSY}", as required in the New Zealand Fisheries Act of 1996. In practice, this has meant implementing a fishing-down phase for fisheries on new stocks and setting quotas considerably higher than long-term sustainable yields until the stock approaches B_{MSY}. The estimate of B_{MSY} that is commonly used is 30 percent B_0 (Francis 1992a), based on a stock-recruitment steepness parameter (Mace and Doonan 1988) of 0.75. Several scientists have questioned the validity of such a low percent B_0 as an estimate of B_{MSY} for a low-productivity species like orange roughy, even on a single species basis. Using the same steepness parameter of 0.75, Brandao and Butterworth (2003) estimated B_{MSY} for Namibian orange roughy as being only about 25 percent B_0. From an ecosystem perspective, removing 70-75 percent of the biomass of what is often the dominant fish species in deepwater areas is almost certain to alter the structure and function of the remaining biological community. A steepness parameter of 0.75 is well above the range of values estimated or assumed for long-lived stocks off the northwest coast of the U.S. (Dorn 2002).

For most New Zealand stocks, quotas have been progressively reduced as biomass has declined towards 30 percent B_0. However, the 30 percent level has almost invariably been overshot due to changes in stock assessment models, gaps of 2-5 years between assessment updates, underestimates of the extent of decline and downward revisions of estimates of B_0. As a result it has been necessary to implement rebuilding plans or, in some cases (Challenger and Puysegur stocks), to close fisheries.

Until recently, Australia used a similar management approach, although in some years the target biomass was set at 40 percent B_0 or even 50 percent B_0. More recently, a harvest strategy framework based on fishing mortality target and limit reference points (Smith and Smith 2005) has been adopted to set recommended biological catches. Essentially, the harvest strategy now involves setting a target fishing mortality that will result in a stock fluctuating around 50-60 percent B_0, and closing a fishery once it falls below 20 percent B_0. Based on these strategies, the recommended biological catch for several species is 0 t, and most orange roughy fisheries have been restricted to bycatch quotas only (Section 6.2.2.1).

New Zealand is now planning to develop Management Strategy Evaluation approaches for orange roughy stocks. However, it is currently unclear which dataset(s) will be used to inform the management strategy. All of the traditional data inputs to stock assessment models seem to be fraught with problems. Commercial CPUE is problematic for orange roughy because it often seems to decline too rapidly at the beginning of a fishery to be attributed to a fishing down effect alone (Butterworth and Brandao 2005, Section 6.2.4 and footnote 25) while, after the fishing down phase, it may be maintained by improvements in methods of capture and locating new, previously untouched aggregations. Trawl surveys have been useful in certain circumstances, but their utility is questionable if most of the orange roughy are contained in large, dense aggregations that saturate the trawl net. Acoustic surveys may work reasonably well when they are focussed on schools of almost pure orange roughy on flat areas, but there are numerous problems when orange roughy are on seamounts or knolls, or when they are mixed with other species, most of which have higher target strengths.

6.7 The bottom line for orange roughy

For orange roughy, there is a poor understanding of the dynamics of the species, there are major stock assessment challenges, and the species is valuable. This is a dangerous combination of factors, which is acutely illustrated by the failure to sustain most orange roughy fisheries.

7. CONCLUSIONS AND RECOMMENDATIONS

The title of this paper asks if deepwater fisheries can be managed sustainably. The authors' first conclusion is that the discourse about the management of deepwater fisheries would be a lot more meaningful if terminology categorizing fisheries by depth zone was less ambiguous. Nevertheless, our short answer to the question is that most of the fisheries discussed in this paper can be managed sustainably. Most of the species classified as deepwater overlap in their depth range with continental shelf species, and other shallow water species. Their life history characteristics are similar. They are subject to management frameworks that are also similar, if not identical. Not all shelf/shallow water fisheries are managed sustainably, but it is generally accepted that sustainable management is an achievable objective.

However, for the "poster child" deepwater fisheries for orange roughy, the track record so far is discouraging. The jury is still out on their sustainability in the future. The experience with orange roughy and other species with relatively low productivity (e.g. pelagic armorhead, tilefish, wreckfish and Pacific Ocean perch; Moore 1999, Moore and Mace 1999) is somewhat unique, but as technology for deepwater fishing advances, and demand for a wide variety of marine products increases, more "orange roughy like" situations may emerge in the future.

To manage deepwater fisheries sustainably, we recommend strict adherence to the precautionary approach and application of an ecosystem approach. More specifically:

- All deepwater fisheries should be authorized by a competent management authority with constraints set cautiously, and new fisheries should have a development plan that ensures the rate of development is consistent with the gathering of scientific knowledge. The CCAMLR approach might be a useful model. Australia's approach for the orange roughy fishery on the Cascade Plateau off the east coast of Tasmania (described in Section 6) might also serve as a good example.

- For fisheries, the idea of preauthorizing exploration and development before it begins may seem "foreign" since most fisheries have been unregulated until it is demonstrated that regulation is necessary. However, other industries that exploit natural resources must be preauthorized. In the United States, the National Environmental Protection Act requires an Environmental Impact Statement (EIS) before such activities can be authorized. Similar processes exist in other countries, and applying them to fisheries is one of the elements of a precautionary approach.[26]

- Strategies that have been applied to manage deepwater fisheries need to be re-examined and improved in light of the poor track record to date. Management reference points (such as MSY and B_{MSY}) need to be set more conservatively, and TAC decisions or decisions on other conservation measures, need to account for uncertainty by erring in favor of conservation and sustainability. We are not able to specify how much more conservatively reference points and TACs should be set, but a more focused review of this specific aspect of experience with deep water fisheries might yield some useful guidance.

- Strategies that explicitly incorporate a "fishing down phase" for new fisheries should be abandoned, due to the universal tendency to substantially overestimate the pre-fishery biomass. For species with very low productivity, the so-called fishing down phase seems more like a rationalization for mining the resource.

- Steps need to be taken to address habitat and biodiversity impacts of deepwater fisheries. This should include habitat mapping for candidate areas for fishing, and protection from fishing of a representative portion of the habitats. Conservation engineering should be applied to reduce bycatch and habitat impacts.

- Research is needed to improve resource assessments, knowledge about the distribution of resources off fishing grounds, understanding of stock structure, and determining the functional value and vulnerability of habitat and biodiversity. Research efforts of countries involved in deepwater fisheries might benefit from more international coordination, cooperation and information sharing.

- New multilateral arrangements are needed to manage high-seas fisheries in some areas. The Indian and South Pacific Oceans are the highest priorities for such arrangements, but there is a potential need in other ocean areas as well. Like tuna fisheries, fishing fleets for high-seas deepwater fisheries are likely to operate globally. This means that international organizations dealing with these fisheries would benefit from close coordination and routine communication, or even more formal linkage mechanisms.

- Where multilateral arrangements to manage high-seas deepwater fisheries sustainably are lacking, individual nations should prevent overfishing on the high seas by consistently applying the FAO Code of Conduct for Responsible Fisheries[27] and the Compliance Agreement,[28] as described in Maguire *et al.* (2006). The former is not binding, but it describes steps most nations have agreed they should apply to their fisheries to be responsible, such as the precautionary approach and an ecosystem approach. The later is legally binding and requires states to authorize the fishing activities of the vessels flying their flag.

- In general, there is a need to improve compliance with fishery conservation measures, such as TACs and reporting of fishery-dependent data, for all fisheries. This includes deepwater fisheries. It is time to seriously consider extending catch documentation schemes, such as the CCAMLR

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[26] See FAO Technical Guidelines for the Precautionary Approach: http://www.fao.org/DOCREP/003/W3592E/W3592E00.HTM

[27] See: http://www.fao.org/figis/servlet/static?xml=CCRF_prog.xml&dom=org&xp_nav=4

[28] See: http://www.fao.org/figis/servlet/static?xml=CCRF_prog.xml&dom=org&xp_nav=2,2

scheme used to reduce IUU fishing of toothfish, to all fish that enter into international trade. A global catch documentation scheme that would allow buyers and consumers to know the origin of fish would have many benefits. It would be more efficient than the current trend for international fisheries of re-developing catch documentation schemes for individual fisheries.

An unanswered question is, will the benefit-cost ratio for "orange roughy like" deepwater fisheries be positive if all the costs of research and management, as characterized above, are taken into account? The New Zealand examples, in which the fishing industry pays for all of the costs of research and compliance, and some of the costs of management, indicates that these fisheries have had a positive benefit-cost ratio for periods of up to 25 years for at least one stock (the East Chatham Rise stock, which is the largest orange roughy stock yet discovered worldwide). However, all stocks that have been discovered since about 1990 have been relatively small and many have only yielded large catches for 2-5 years. It remains to be seen whether small fishing operations (of the order of a few hundred tonnes, up to about 2 000-5 000 t) will be both economically viable and sustainable. If not, such fisheries should probably be closed for sufficient time to enable biomass to accumulate to levels well above B_{MSY}, at which point a surplus may again be made available for harvest. Unfortunately, it may take several decades for biomass to rebuild to such levels.

Our final thought about deepwater fisheries concerns their priority in the list of issues that are currently before fishery scientists, managers, the fishing industry, international fisheries organizations and other stakeholders. The deepwater fisheries that are receiving the most attention are trivial in terms of global yield, food security, employment and environmental impact, in comparison to shallow water fisheries, particularly the large number of small scale coastal fisheries in developing countries. Both need to be managed responsibly, but we hope that the current high profile that deepwater fisheries have is not detracting from critically needed efforts to improve the condition of other fisheries upon which millions of people depend for food and livelihoods.

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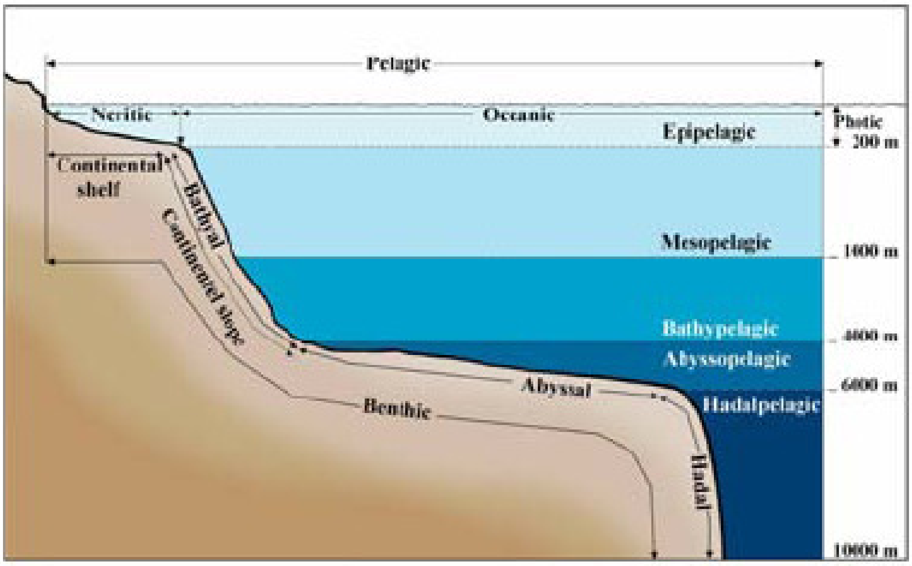

Figure 1. Ocean depth zones (FAO 2005).

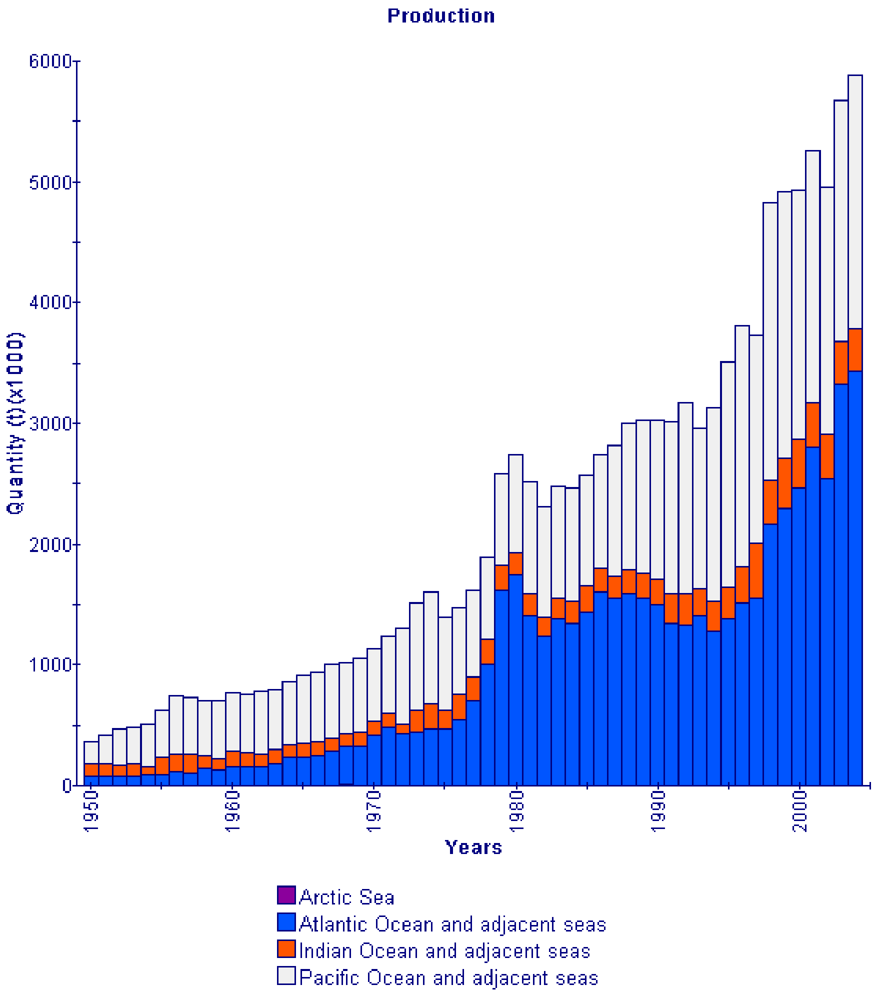

Figure 2. Reported catch of deepwater species by ocean from 1950-2004 (from FAO FIGIS online database).

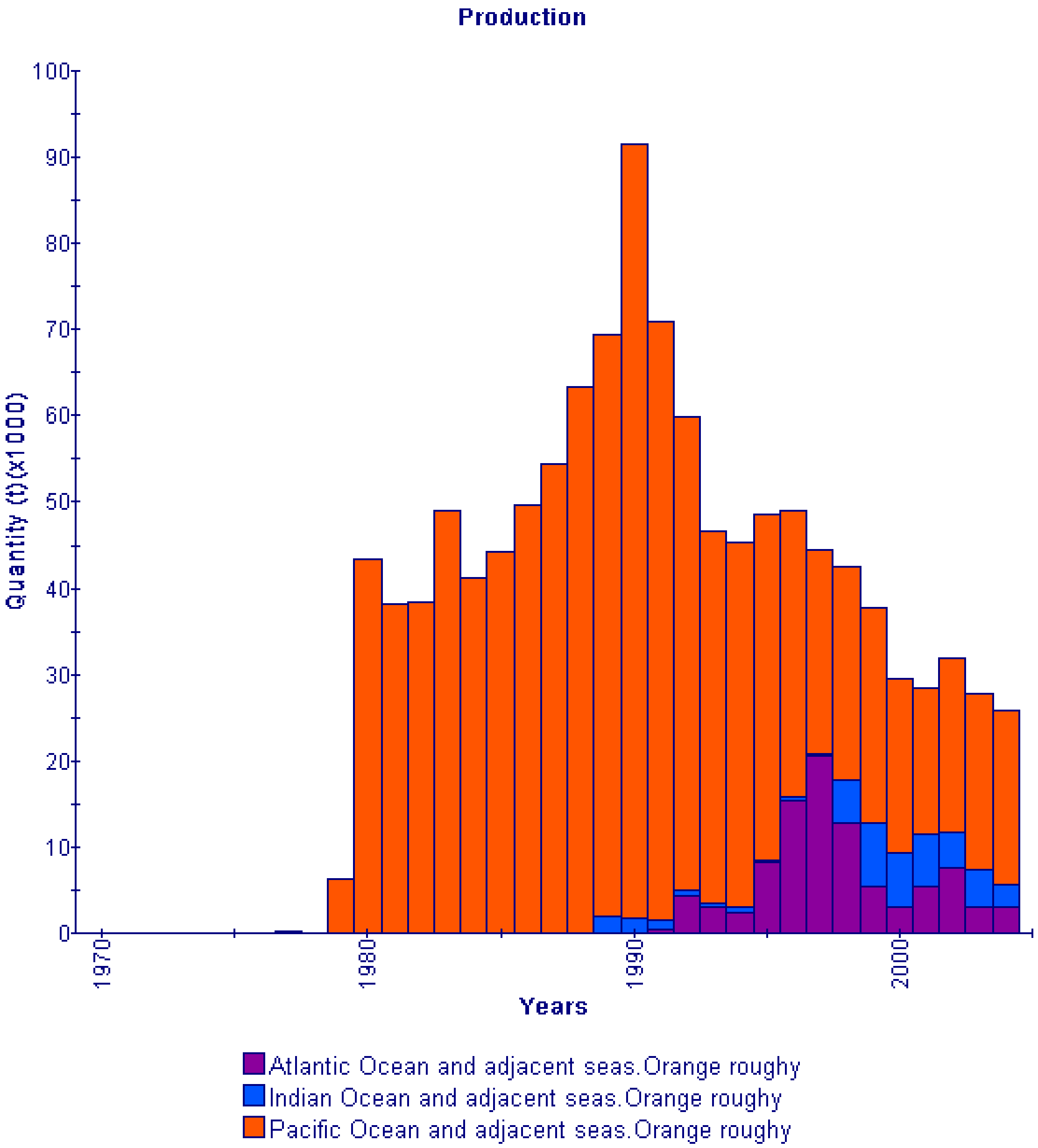

Figure 3. Reported catch of orange roughy by ocean, 1950-2004.

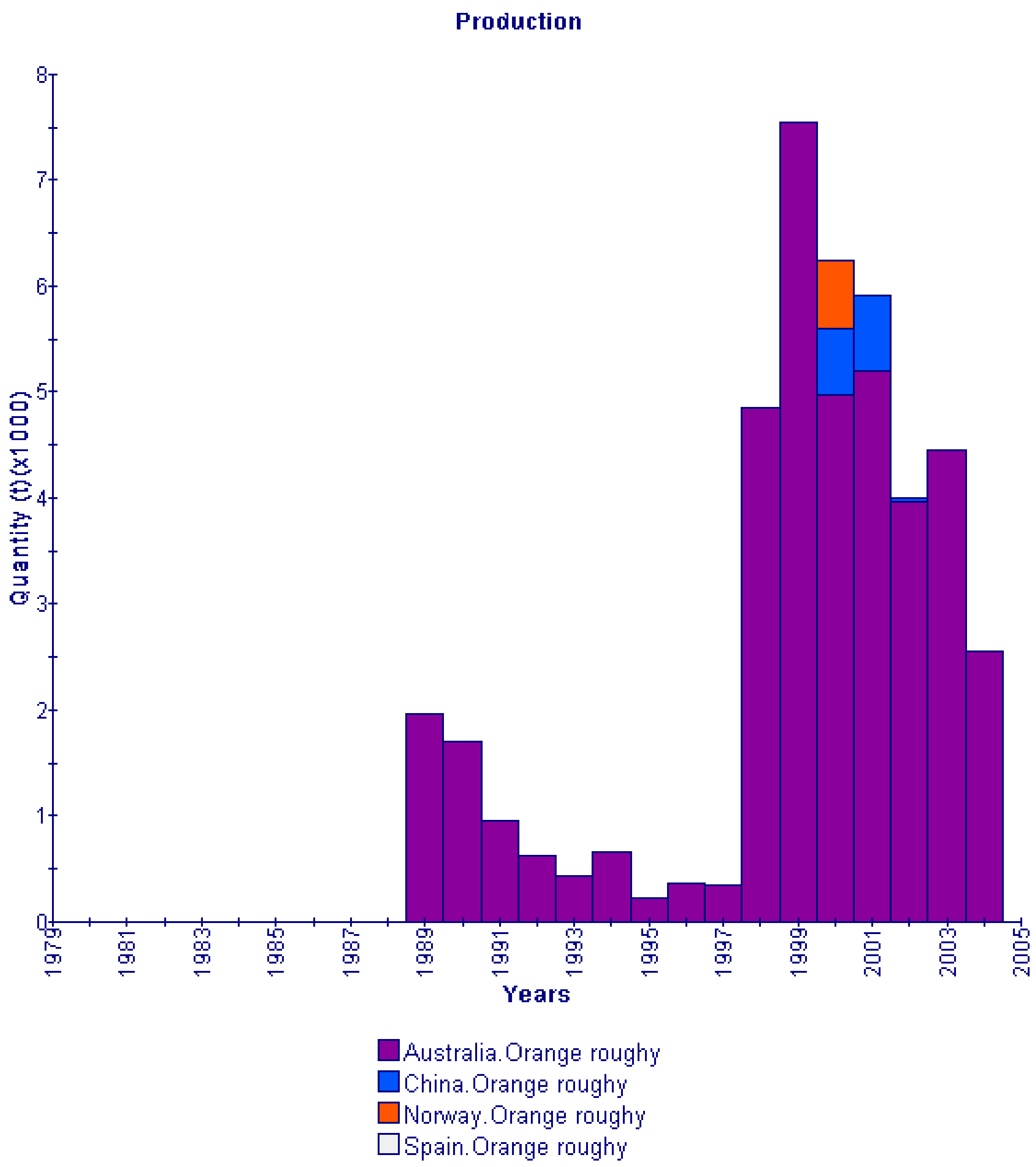

Figure 4. Reported Indian Ocean catch of orange roughy.

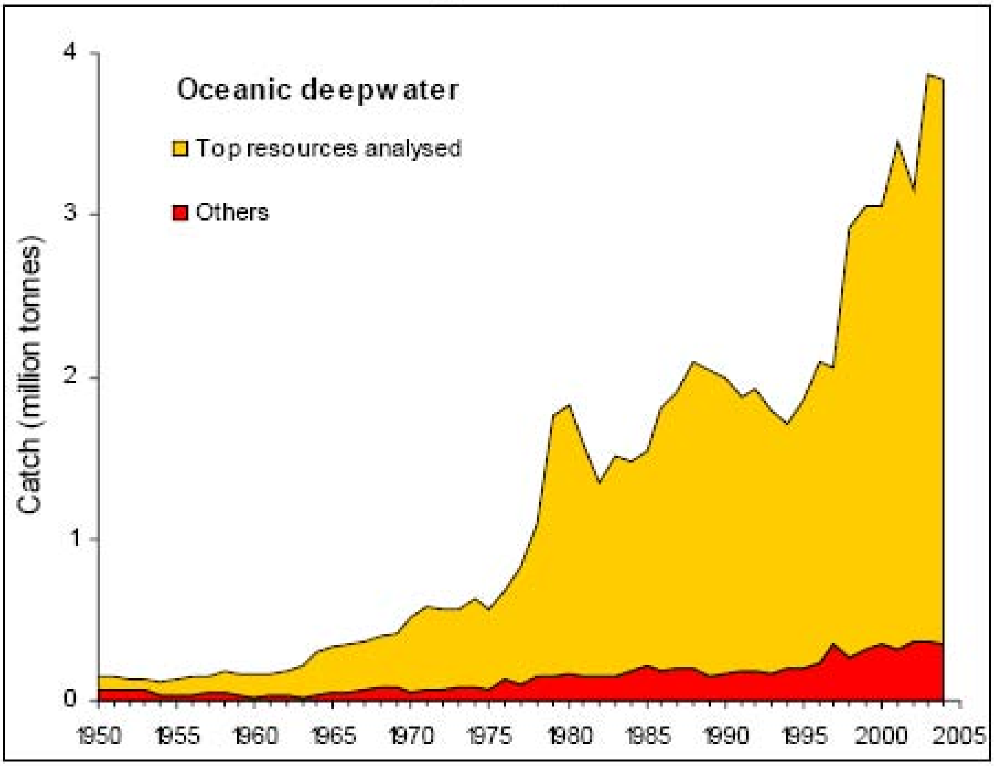

Figure 5. Catch history of oceanic deepwater species (from Maguire *et al.* 2006)

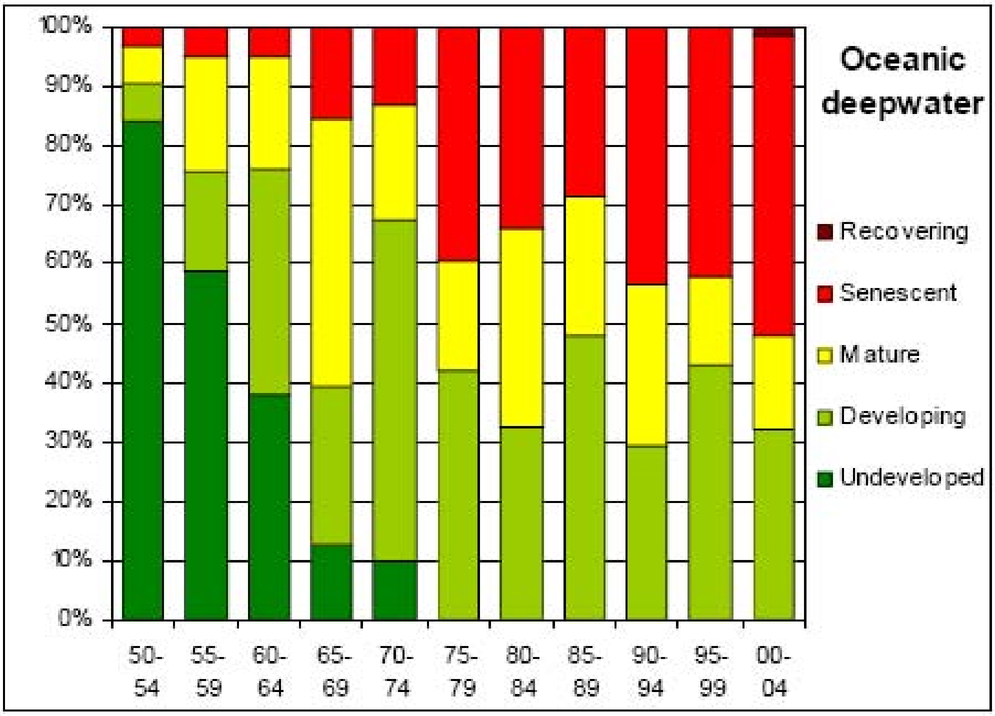

Figure 6. The status of development of the world's top oceanic deepwater fisheries (in terms of cumulative catch 1950-2004).

Figure 7. Before and after pictures of the impact of bottom trawling on a biogenic community including coldwater corals (from Gianni 2004). Original photos by Dr. Keith Sainsbury, CSIRO, Australia.

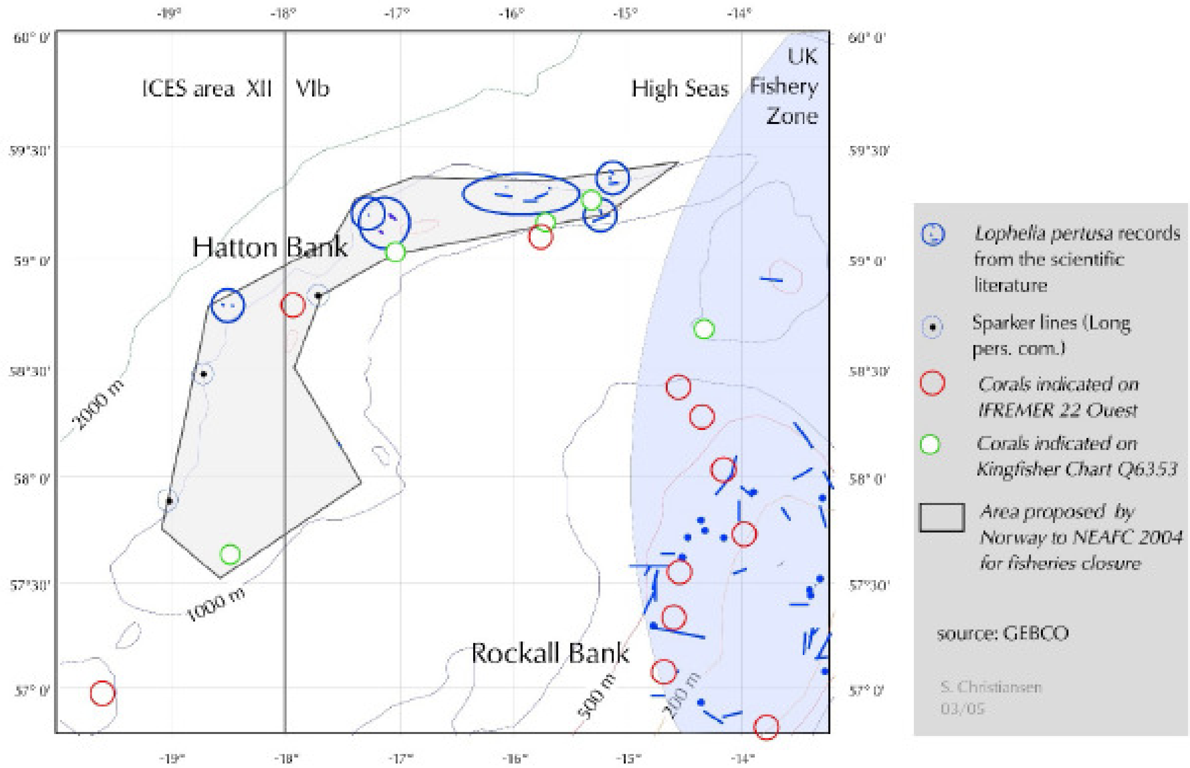

Figure 8. Known and likely locations of coldwater corals on Hutton Bank in the Northeast Atlantic (ICES 2005).[29]

[29] See http://www.ices.dk/committe/acfm/comwork/report/2005/sept/NEAFC%20Request%20and%20OSPAR%20request%2027%209%20without%20annex.pdf

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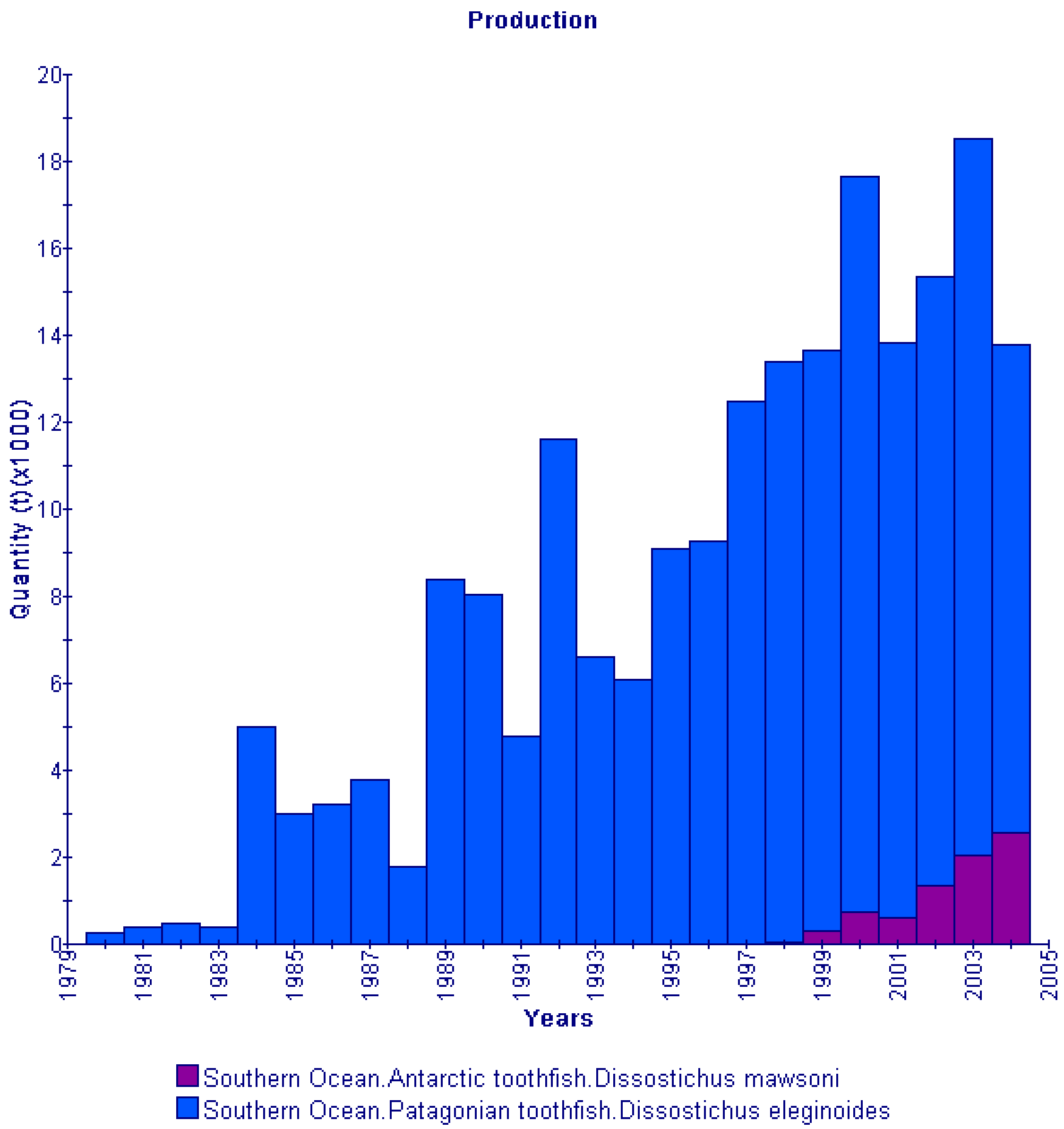

Figure 9. Reported catches of toothfish from the Southern Ocean.

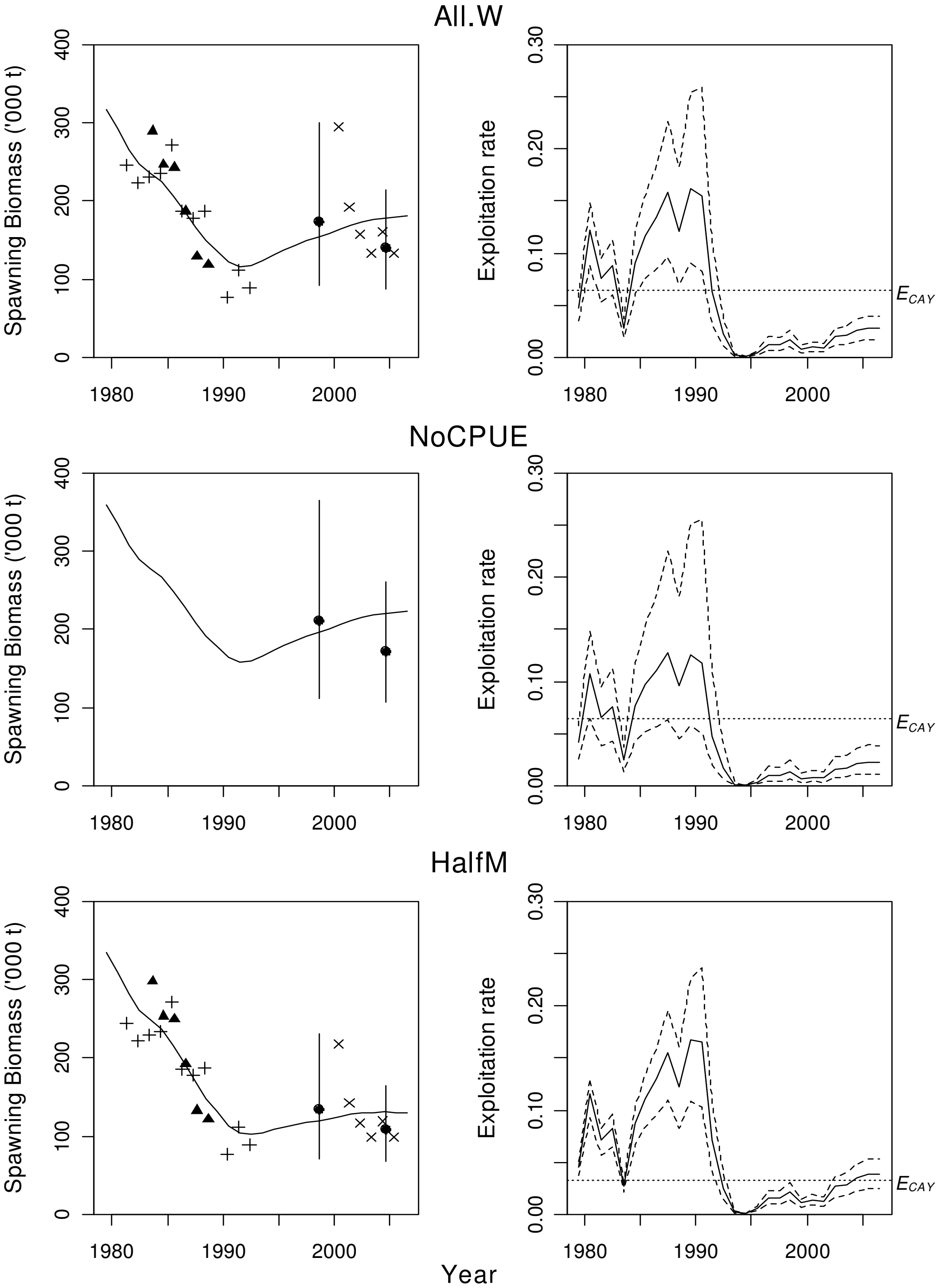

Figure 10. Estimated spawning biomass and exploitation rates for the main fishing and spawning area for orange roughy on the East Chatham Rise in New Zealand (Figure 5, p 425 in Ministry of Fisheries 2006). All.W includes all available abundance indices (+, spawning box pre-closure commercial CPUE; x, spawning box post-closure commercial CPUE; ▲, non-spawning commercial CPUE; all plotted without confidence intervals; and wide-area acoustic surveys including 95% confidence intervals. Estimated exploitation rates include 95 percent confidence intervals. All alternatives also included trawl survey estimates of biomass for the years 1984-90, 1992 and 1994. NoCPUE excludes all commercial CPUE indices. HalfM is the same as All.W except that natural mortality (M) was arbitrarily halved (0.0225 vs. 0.045). E_{CAY} is the exploitation rate associated with an F_{MSY} harvest strategy.

Over a 14-year period, a "soft-landing" at a TAC of 90 percent of the estimated MSY was envisaged, with resource abundance still in excess of the MSY level at the end of the period.

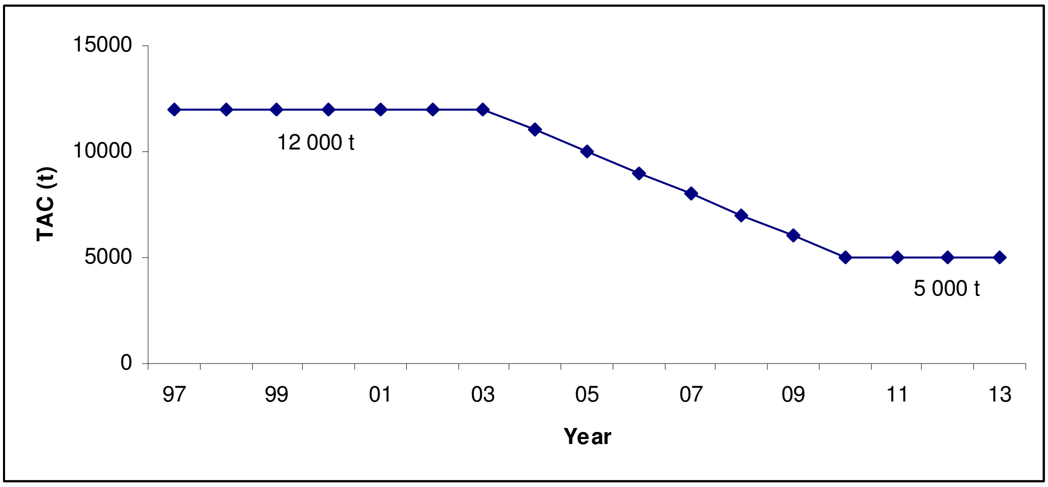

Figure 11. The fishing down strategy for Namibian orange roughy as planned in 1997 (Figure 2 from Butterworth and Brandao 2005)

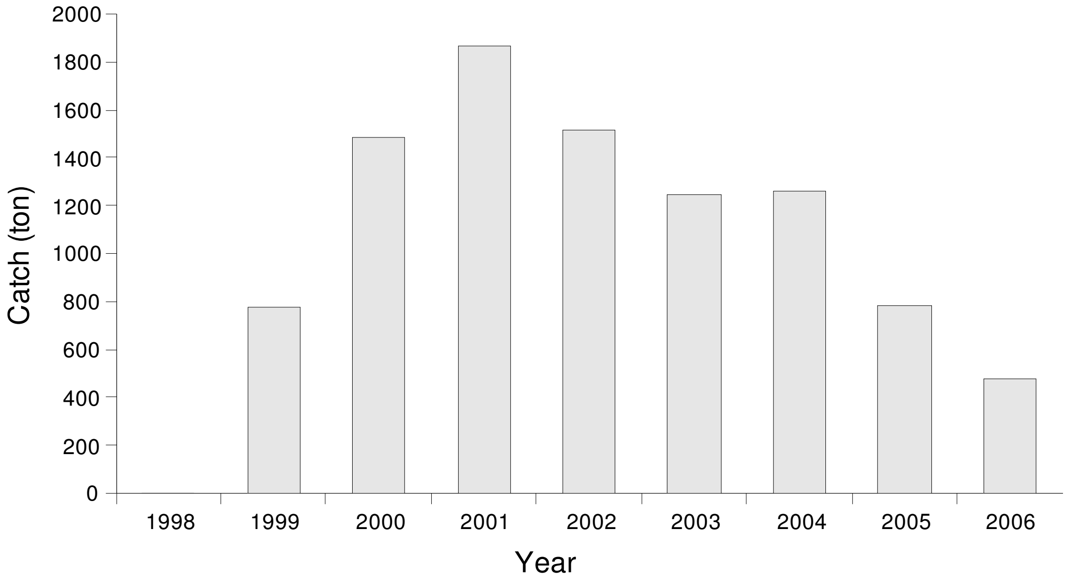

Figure 12. Total orange roughy landings in Chile 1998-2006.

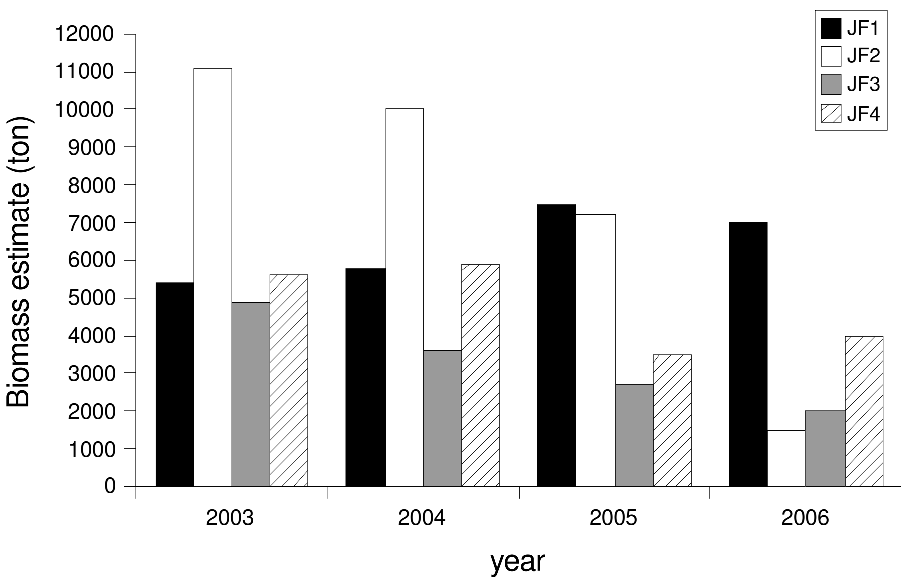

Figure 13. Estimated biomass for orange roughy in Juan Fernandez seamounts JF1-JF4, the main fishing area off Chile.

APPENDIX 1 - 2004 CATCH OF DEEPWATER SPECIES

Reported catch in metric tonnes (t) in 2004 and other selected years of species FAO considers to be deepwater (FAO 2005, page 195, Table C3.1). Extracted from FAO's FIGIS on-line database.

Ocean Area	Species	Scientific name	1970	1980	1990	2000	2004
Arctic Sea	Greenland halibut	*Reinhardtius hippoglossoides*	200	0 -	0 -	0 -	0 -
	Roundnose grenadier	*Coryphaenoides rupestris*	500	0 -	0 -	0 -	0 -
		Total Arctic Sea	700	0 -	0 -	0 -	0 -
Atlantic Ocean and adjacent seas	Alfonsinos nei	*Beryx spp*	0 -	91	534	537	1 701
	Black scabbardfish	*Aphanopus carbo*	0 -	0 -	8 328	12 387	11 987
	Blue antimora	*Antimora rostrata*	0 -	0 -	0 -	21	44
	Blue ling	*Molva dypterygia*	6 700	36 817	14 000	16 146	7 785
	Blue whiting(=Poutassou)	*Micromesistius poutassou*	38 811	1 108 535	577 493	1 472 105	2 427 862
	Bluntnose sixgill shark	*Hexanchus griseus*	0 -	0 -	0 -	0 -	30
	Boarfishes nei	Caproidae	0 -	0 -	0 -	0 -	747
	Bonnetmouths, rubyfishes nei	Emmelichthyidae	0 -	0 -	25	0 -	6
	Cape bonnetmouth	*Emmelichthys nitidus*	0 -	769	568	50 *F*	156
	Cape elephantfish	*Callorhinchus capensis*	0 -	237	546	380 *F*	559
	Cardinalfishes, etc. nei	Apogonidae	0 -	0 -	0 -	0 *0*	699
	Common mora	*Mora moro*	0 -	0 -	50	0 -	147
	Cusk-eels nei	*Genypterus spp*	0 -	0 -	0 -	57	0 -
	Cusk-eels, brotulas nei	Ophidiidae	0 -	0 .	0 -	524	580
	Elephantfishes nei	*Callorhinchus spp*	300	1 687	850	1 390	1 619
	Elephantfishes, etc. nei	Callorhinchidae	0 -	0 -	0 -	0 -	6
	Escolar	*Lepidocybium flavobrunneum*	0 -	0 -	0 -	82	98
	Forkbeards nei	*Phycis spp*	100	108	0 -	762	1 697
	Geryons nei	*Geryon spp*	0 -	5 834	2 326	6 605	4 410
	Greeneyes	Chlorophthalmidae	0 -	15 656	0 -	0 -	0 -
	Greenland halibut	*Reinhardtius hippoglossoides*	164 728	93 625	121 839	107 691	109 906
	Greenland shark	*Somniosus microcephalus*	0 -	48	54	45	70
	Grenadiers nei	*Macrourus spp*	1 500	737	19 987	10 505	5 331
	Hairtails, scabbardfishes nei	Trichiuridae	0 -	0 -	112 *F*	10 070	7 807
	Hector's lanternfish	*Lampanyctodes hectoris*	18 200	40	571	0 -	0 *0*
	Kingklip	*Genypterus capensis*	3 600	10 317	4 524	7 922 *F*	12 310
	Lanternfishes nei	Myctophidae	0 -	586	0 -	1 065	175
	Largehead hairtail	*Trichiurus lepturus*	15 811	67 480	91 187	26 028	38 848
	Ling	*Molva molva*	47 700	56 496	52 397	43 320	35 384
	Longnose velvet dogfish	*Centroscymnus crepidater*	0 -	0 -	0 -	1	301
	Longspine snipefish	*Macroramphosus scolopax*	0 -	29 020	2 813	0 -	0 -
	Northern prawn	*Pandalus borealis*	38 759	122 727	226 033	362 936	438 552
	Oilfish	*Ruvettus pretiosus*	0 -	0 -	0 -	52	142
	Orange roughy	*Hoplostethus atlanticus*	0 -	0 -	0 -	3 009	3 085
	Oreo dories nei	*Oreosomatidae*	0 -	0 -	0 -	10	497
	Pandalus shrimps nei	*Pandalus spp*	2 100	9 096	19 433	35 640	2 425
	Patagonian grenadier	*Macruronus magellanicus*	0 -	6 642	30 123	142 676	145 224
	Patagonian toothfish	*Dissostichus eleginoides*	0 -	494	9 165	16 387	11 577
	Pink cusk-eel	*Genypterus blacodes*	1 100	6 722	35 344	17 521	19 293
	Portuguese dogfish	*Centroscymnus coelolepis*	0 -	0 -	1 543	1 868	4 021
	Rabbit fish	*Chimaera monstrosa*	0 -	0 -	0 -	15	617
	Ratfishes nei	*Hydrolagus spp*	0 -	0 -	0 -	573	551
	Red crab	*Geryon quinquedens*	0 -	2 546	1 527	8 391	6 220
	Red scorpionfish	*Scorpaena scrofa*	0 .	0 .	0 .	1	0 *0*

	Roughhead grenadier	*Macrourus berglax*	0 -	0 -	3 220	8 795	2 054
	Roundnose grenadier	*Coryphaenoides rupestris*	31 689	22 586	11 884	30 770	24 751
	Royal red shrimp	*Pleoticus robustus*	100	233	135	391	272
	Scarlet shrimp	*Plesiopenaeus edwardsianus*	1 084	994	23	55	118
	Silver scabbardfish	*Lepidopus caudatus*	16 700	9 894	19 352	3 734 *F*	7 802
	Slimeheads nei	Trachichthyidae	0 -	0 -	0 -	3	46
	Southern blue whiting	*Micromesistius australis*	0 -	78 047	193 630	84 321	76 596
	Tilefishes nei	Branchiostegidae	1 400	168	351 *F*	1 119	1 052
	Tusk(=Cusk)	*Brosme brosme*	30 578	55 619	44 909	32 531	20 041
	White snake mackerel	*Thyrsitops lepidopoides*	0 *0*	0 -	21	10	77
	Wreckfish	*Polyprion americanus*	500	248	543	617	475
Total Atlantic Ocean and adjacent seas			421 460	1 744 099	1 495 440	2 469 118	3 435 753
Indian Ocean and adjacent seas	Alfonsinos nei	*Beryx spp*	0 -	0 -	0 -	1 668	6
	Antarctic stone crab	*Paralomis spinosissima*	0 -	0 -	0 -	0 -	1
	Antarctic toothfish	*Dissostichus mawsoni*	0 -	0 -	1	0 -	26
	Blue antimora	*Antimora rostrata*	0 -	0 -	0 -	24	1
	Blue grenadier	*Macruronus novaezelandiae*	0 .	0 .	1 372	8 964	8 773
	Bombay-duck	*Harpadon nehereus*	78 700	116 190	142 559	175 001	154 277
	Bonnetmouths, rubyfishes nei	Emmelichthyidae	0 -	3 691	0 -	0 -	0 -
	Cardinal fishes nei	*Epigonus spp*	0 -	0 -	0 -	6	6
	Cardinalfishes, etc. nei	Apogonidae	0 .	0 .	0 .	0 .	450 *F*
	Geryons nei	*Geryon spp*	0 -	552	664	886	204
	Ghost shark	*Callorhinchus milii*	0 .	0 .	0 .	82	112
	Grenadiers nei	*Macrourus spp*	0 -	0 -	0 -	348	551
	Hairtails, scabbardfishes nei	Trichiuridae	28 300	63 830	60 933	148 702	134 391
	Lanternfishes nei	Myctophidae	0 -	6	0 *0*	0 -	1
	Largehead hairtail	*Trichiurus lepturus*	1 390	5 507	6 714	43 155	40 380
	Oilfish	*Ruvettus pretiosus*	0 -	0 -	0 -	0 -	18
	Orange roughy	*Hoplostethus atlanticus*	0 -	0 -	1 712	6 239	2 559
	Oreo dories nei	Oreosomatidae	0 -	0 -	0 -	175	0 -
	Pacific sleeper shark	*Somniosus pacificus*	0 -	0 -	0 -	0 -	8
	Patagonian toothfish	*Dissostichus eleginoides*	0 -	142	1 250	13 600	6 765
	Pelagic armourhead	*Pseudopentaceros richardsoni*	0 -	0 -	0 -	121	0 -
	Pink cusk-eel	*Genypterus blacodes*	0 *0*	0 -	2 *F*	1 148	1 265
	Redfish	*Centroberyx affinis*	0 -	0 -	0 -	337	968
	Silver gemfish	*Rexea solandri*	0 .	898	992 *F*	447	503
	Wreckfish	*Polyprion americanus*	0 -	0 -	0 -	0 -	2
Total Indian Ocean and adjacent seas			108 390	190 816	216 199	400 903	351 267
Pacific Ocean and adjacent seas	Alfonsinos nei	*Beryx spp*	1 900	2 337	1 956	7 264	5 492
	Antarctic toothfish	*Dissostichus mawsoni*	0 -	0 -	0 -	751	2 558
	Blue antimora	*Antimora rostrata*	0 -	0 -	0 -	0 -	16
	Blue grenadier	*Macruronus novaezelandiae*	100	18 757	261 168	274 615	154 532
	Bluenose warehou	*Hyperoglyphe antarctica*	0 .	0 .	1 485	2 793	3 178
	Bombay-duck	*Harpadon nehereus*	200	8 453	12 527	2 752	8 596
	Bonnetmouths, rubyfishes nei	Emmelichthyidae	0 .	0 .	0 -	582	2 812
	Cape bonnetmouth	*Emmelichthys nitidus*	0 .	0 .	0 .	2 825	3 248
	Cardinal fishes nei	*Epigonus spp*	0 .	0 .	0 -	5 792	2 070
	Cardinalfishes, etc. nei	Apogonidae	0 *0*	1	132	60 *F*	0 *0*
	Chimaeras, etc. nei	Chimaeriformes	0 .	0 .	0 .	40	193
	Common mora	*Mora moro*	0 .	0 .	0 -	1 358	1 403
	Cusk-eels nei	*Genypterus spp*	1 300	1 029	1 652	557	563
	Cusk-eels, brotulas nei	Ophidiidae	0 -	0 -	0 -	1	383
	Dark ghost shark	*Hydrolagus novaezealandiae*	0 .	0 .	0 .	1 819	1 793
	Deepsea smelt	*Glossanodon semifasciatus*	16 500	9 601	6 355	5 970	5 223
	Elephantfishes nei	*Callorhinchus spp*	100	1 289	2 900	603	1 297

	Escolar	*Lepidocybium flavobrunneum*	0 -	0 -	0 -	53	36
	Ghost shark	*Callorhinchus milii*	1 100	1 200	1 461	1 228	1 191
	Golden king crab	*Lithodes aequispina*	0 .	0 .	0 .	1 797	982
	Greenland halibut	*Reinhardtius hippoglossoides*	15 800	0 -	10 159	6 186	1 879
	Grenadiers nei	*Macrourus spp*	0 -	2 305	0 -	0 -	219
	Grenadiers, rattails nei	Macrouridae	0 -	0 -	2 209	3 428	24 909
	Hairtails, scabbardfishes nei	Trichiuridae	15 500	18 372	28 764	47 085	40 719
	Hapuku wreckfish	*Polyprion oxygeneios*	1 600	2 273	1 105	1 513	1 540
	Lanternfishes nei	Myctophidae	0 -	0 -	0 -	0 -	578
	Largehead hairtail	*Trichiurus lepturus*	535 010	603 817	660 161	1 413 779	1 508 223
	Longnose velvet dogfish	*Centroscymnus crepidater*	0 .	0 .	0 .	0 .	1
	Longspine snipefish	*Macroramphosus scolopax*	0 .	0 .	0 -	0 -	544
	Northern prawn	*Pandalus borealis*	0 .	0 .	0 -	8 520	7 586
	Oilfish	*Ruvettus pretiosus*	261	803	6 281	2 645	5 659
	Orange roughy	*Hoplostethus atlanticus*	0 -	43 327	89 766	20 206	20 237
	Oreo dories nei	Oreosomatidae	0 -	34 069	20 283	22 775	19 787
	Pandalus shrimps nei	*Pandalus spp*	6 000	1 999	1 326	0 -	0 -
	Patagonian grenadier	*Macruronus magellanicus*	0 -	18 361	128 002	91 310	71 177
	Patagonian toothfish	*Dissostichus eleginoides*	0 -	414	9 387	10 951	6 485
	Pelagic armourhead	*Pseudopentaceros richardsoni*	0 -	0 -	0 -	6	107
	Pink cusk-eel	*Genypterus blacodes*	2 500	10 175	20 005	30 769	26 977
	Ratfishes nei	*Hydrolagus spp*	0 .	0 .	0 -	975	1 452
	Red cusk-eel	*Genypterus chilensis*	1 400	1 849	1 323	608	548
	Redfish	*Centroberyx affinis*	0 -	0 -	0 -	1 246	742
	Silver gemfish	*Rexea solandri*	0 -	4 834	8 183 *F*	1 249	1 262
	Silver scabbardfish	*Lepidopus caudatus*	0 -	3	1 633	1 619	2 891
	Silvery lightfish	*Maurolicus muelleri*	0 -	3 200	0 -	0 -	0 -
	Slimeheads nei	Trachichthyidae	0 -	0 -	0 -	4	14
	Southern blue whiting	*Micromesistius australis*	0 -	12 534	37 981	68 152	75 445
	Spotted gurnard	*Pterygotrigla picta*	0 -	0 -	0 -	55	53
	Thorntooth grenadier	*Lepidorhynchus denticulatus*	0 .	0 .	0 -	3 833	6 341
	Tilefishes nei	Branchiostegidae	4 000	3 599	2 186	8 207 *F*	72 842
	White warehou	*Seriolella caerulea*	0 .	0 .	532	2 407	2 330
Total Pacific Ocean and adjacent seas			603 271	804 601	1 318 922	2 058 388	2 096 113
Grand total			1 133 821	2 739 516	3 030 561	4 928 409	5 883 133

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