Can ecological knowledge catch up with deep-water fishing?

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Abstract: Deep-water fishes have only recently moved from being objects of scientific curiosity to objects of commercial exploitation. For an increasing number of species, a single trawl today captures more specimens than science has ever seen since the time of Linnaeus. The deep-water habitats where fisheries are conducted, mostly continental slopes, are known to be physically and biologically more complex than the shallower shelves, yet thinking and experience from the shelf seems mostly to govern deep-water fishery expansion. Ecological considerations suggest that deep-water populations and ecosystems may be even more vulnerable to disruption than were those of the shelf. But the rate at which scientific study progresses lags well behind the rate at which deep-water fisheries develop. It often seems, in fact, that a fishery may be over before scientific study begins in earnest. Approaches to understanding based on theory and an holistic appreciation of how the deepwater world works can help, as can critical examination and mapping of a fishery's history.

Introduction

Continental shelves have supported the great fisheries of the world for more than 500 years. There have been ups and downs in the fortunes of these fisheries, but for the most part they have provided a reasonably reliable base to support long- and well-established fishing communities. The contribution of these great fisheries to the world food supply, and indeed to the wealth of nations (Kurlansky 1997), has been enormous.

The late 20th century, however, has seen an unprecedented number of fishery collapses. The well-known FAO statistic that something over 70% of the world's fishery resources are in deep trouble is commonly cited, even in the popular press and by government ministers. The loss of their supporting fishery has stressed maritime societies to their core, and many long-enduring fishing communities are vanishing along with a way of life (Hamilton and Haedrich 1998). Fishery collapses thus translate into significant social problems, and governments are pressed to seek solutions wherever they can (Matthews 1997).

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One imagined solution has been to embark on quests to find new wild fish resources. To do so there are basically only two options -- by developing previously 'under-utilized' species or by taking up the hunt in new habitats. The commercial exploitation of under-utilized species (itself a problematic term) can do no more than buy a little time. Such "new" fisheries only place increased stress on already compromised ecosystems, in effect adding insult to injury. Because of the global reach of modern fishing technology, there are almost no areas left to be explored. Indeed, new habitats today can mean only the deep sea.

The deepwater habitats that have attracted most attention from governments trying to deal with fishery collapses have been their adjacent continental slopes. These are, however, very different places from the continental shelves where a long experience and tradition has conditioned the style of fishing. Gordon *et al.* (1995) make the point that, although they comprise only something like 8.8% of the ocean bottom, the slopes are among the most complex and dynamic parts of the deep sea. Marking as they do the transition from shallow to deep waters, this is not at all surprising.

Deep-water Fisheries

Fishing in deep-waters is not new. The *Aphanopus* fishery of Madeira, for example, is one of the oldest continuously recorded fisheries in the world. The poet Manuel Tomas made reference to it in 1635. The *Ruvettus* fishery of the south Pacific, conducted with highly specialised wooden hooks, has an equally long history. But large-scale modern fisheries based on deep-sea species only really began in the 1970s, the most well-known case being that of the orange roughy (*Hoplostethus atlanticus*) in Australia and New Zealand (Clark 1995).

Hoplostethus atlanticus was described by Collett from the North Atlantic in 1889. Although subsequently found throughout all oceans, the fish was never considered to be particularly abundant anywhere. The single type specimen is in Monaco and other specimens occur in small lots in natural history museums around the world. The British Museum collection, for example, has a total of 41 specimens. Contrast that to a single tow on a spawning aggregation on New Zealand's Chatham Rise where a few minutes of fishing can take something like 20,000 individual fish, each up to 50 cm in length.

On the whole, however, deep-sea species with the economic potential of the orange roughy are rare. Other established deep-sea fisheries, for example for macrourids, *Reinhardtius*, nototheniids and channichthyids, and deep-water sharks, have not had the same success, a fact that reflects the generally lower market quality of the fish. The modern trend, in fact, seems to be to follow the successful campaign used originally to promote the orange roughy -- advertising to actually build a market. This approach is apparently being used in the development of the *Dissostichus* and oreosomatid fisheries.

Slopes are far more complex topographically than are continental shelves. Highly irregular bathymetry, deep canyons, outcrops, mudslides and internal waves all make fishing in this new habitat considerably more risky to gear and to success than is the case in flat, shallow regions. Nonetheless, most contemporary deep-sea fishing is mostly a refinement of techniques developed for fishing shallow seas (Gunnarsson 1995). The gear is heavier and the navigation very sophisticated, but overall the approach is very much the same.

Ecological knowledge and deep-water fisheries

While most deep-sea fisheries are new, study of the deep-sea ecosystem is not. Serious comprehensive investigations of deep waters began with the great national expeditions of the 19th century, and the wonder and curiosity that popular reports, for example from the Challenger Expedition, evoked then continues even today. So, even though relatively little may be known in detail about any individual deep-sea fish species, a considerable amount is known about the ecological framework within which they live and make their way.

Although debate will always continue, biological oceanographers generally accept a number of conclusions about ecology and ecological processes in the deep sea. These include the realisations that (among other things) biomass tends to decrease as the log of the depth, that growth is usually slow and life spans are long, and that biological communities are diverse and widespread but zoned with depth. Because no plants grow in the deep sea, there is only an indirect link to primary production through food webs and ladders of migration, and, ultimately, all deep-water production must depend on the thin photosynthetic layer at the surface. Mauchline and Gordon (1991) pointed out how important a trophic connection through pelagic animals is for deep demersal fishes, and thus, of course, for any fishery based on them.

The typical continental shelf fishery ecosystem is one where dominance by an abundant top predator is the rule in the fish community. Diversity tends to be low, and production rates are high. In fact, for a fishery to really be successful, the target species must be abundant, rather widespread, easily captured with conventional gear, and capable of rapid replenishment of the harvested population. This is the framework within which the familiar cod, salmon, herring and flatfish fisheries have operated.

But the typical slope fish community is not like that of the shelf. Dominance by single species tends to be lower, and species diversity is high. Species are widespread horizontally but, because the fauna is zoned with depth, quite different fish communities can be encountered over a change in depth of just a few hundred meters. Large fish grow quite slowly, and annual production rates are low. Annual fish production on a temperate ocean continental slope, for example, may be of the order of 2-3 kg/ha/yr Mann 1984). In an upwelling region, for example off Peru and Chile, fish production is as much as 20 kg/ha/yr.

Biological science in the deep-sea has always been aimed more at understanding what the system is like and how it works, rather than planning for commercial exploitation. Thus, although there is a large and relevant literature on deep-sea ecology (e.g. Gage and Tyler 1991), it appears to have had little impact on the development of deep-sea fishing. There, perhaps for expediency's sake, the focus has been on the pragmatic information gathered by national surveys and presented in research documents, which are neither peer-reviewed nor subject to confirmation, and which are revised annually.

History of a deep-sea fishery

The North Atlantic fishery for the roundnose grenadier (*Coryphaenoides rupestris*) provides an interesting, and as it turns out probably rather typical, case study (Fig.1). Atkinson (1995) presents a capsule history. This macrourid fish, a distant relative of the cod, lives in deep water around the rim of the North Atlantic (Haedrich and Merrett 1988). Most abundant from the Newfoundland Banks to Rockall, it extends in very low abundance south to the Bahamas in the west but hardly south of Cape Finisterre in the east. It is most abundant in depths of 600-800 m, but occurs in smaller numbers down to the base of the slope at 2000 m. It has been fished commercially since 1965, with catches climbing quickly to a peak of over 80,000 t/yr in 1971, but then falling off almost as quickly to reach the current modest level of about 6000 t/yr by 1980. Initially, only the Soviet Union took any interest in this fish, but the number of nations fishing it increased steadily until by 1990 ten countries were reporting landings from *Coryphaenoides* fisheries. These included Portugal, Germany, Spain and, most recently, Canada.

Coordinated management has been in place only since 1972, when a quota (TAC) was introduced for the NAFO region. But, as Atkinson (1995) points out, there was very little biological basis for the TAC chosen and, in fact, the annual catch by NAFO countries has never even reached the allowable catch (Fig. 1).

Important papers dealing with *Coryphaenoides* follow a different pattern (Fig. 2). The deep-water abundance of the fish in the western North Atlantic was reported by Pechenik and Troyanovsky (1970), who also mentioned that it had a "superior taste . . . [that has] won wide recognition in the market." Despite this enthusiastic claim, the fishery dropped off significantly from 1975 onwards. Next, Marshall and Iwamoto (in Marshall 1973) worked out the taxonomy and summarised information on its distribution and biology. And then it was not until some time later that Dushchenik and Savvatimsky (1987) published on the population structure, Markle *et al.* (1988) added biogeographic information, Atkinson (1989) provided the first length-weight relationship, and Bergstad (1990) summarised the general biology. Then, only very recently, we have papers by Merrett (1994) on the fecundity, Bergstad and Gordon (1994) on the juveniles, Atkinson's (1995) review, Gordon and Swan (1996) on age validation, Merrett and Barnes (1996) on the eggs, and Kelly *et al.* (1996, 1997) on age, growth and maturity.

Thus, it would seem that even the most elementary of information for supporting a rational fishery -- from length-weight to age and growth -- only came under serious study 15-25 years after the fishery had peaked and declined with no sign of recovery. In fact, the recent information on age at maturity (Kelly *et al.* 1997) may help explain part of what has happened: since the fish take at least 8-10 years to mature, the peak catch in 1971, right after Pechenik and Troyanovsky's (1970) enthusiastic report, must have bitten so deeply into the spawning population that the recruitment that should have appeared in 1980 never materialised, and stocks have stayed low ever since. The 'killer spike' came early to this fishery.

So even the best science, aimed at offering a base for rational management, has come too late for the roundnose grenadier. The populations, and the system itself, now under scientific study are most certainly today very different from the situation that characterised *Coryphaenoides rupestris* and the community to which it belongs in their 'natural' state thirty years ago. There is a real problem here. Ecological science has always assumed that it was addressing a rather stable situation in the deep sea, and, therefore, that any conclusions drawn were general ones that held true over long periods of time and expansive areas of space. But even this one rather modest macrourid fishery has created a situation in considerable flux, i.e. surely undergoing change on an annual basis, and one where it is difficult to predict what the end state will be.

Furthermore, there has been an important spatial component to the evolution of the *Coryphaenoides* fishery. In reviewing a fishery's history, information of this sort is not often made explicit, but it can be very instructive when displayed directly in maps (Fig. 3). The NAFO historical data show that the *Coryphaenoides* fishery began in the far north, at about the limit of the species' distributional range between Greenland and Canada. That was in 1968, but 10 years later it had shifted south to waters off Labrador and northern Newfoundland. In 1988, the greatest catch came from off Newfoundland and in 1993, as the fishery essentially came to an end, the only catches were from the southern Grand Bank and off southeastern Nova Scotia, near the southern limit of where the species is found in any number. The fishery in the western North Atlantic never concentrated in just one area, but ranged widely and eventually swept systematically across almost the entire range occupied by the species.

Some other deepwater fisheries

Other deep-water populations show similar patterns in regard to fisheries that exploit them. Probably the most dramatic are the deepwater notothenioid fish endemic to the Antarctic region. Many of these fish were only first described in the early 20th century, and the first comprehensive review of their taxonomy and biology was published less than a decade ago (Gon and Heemstra 1990). Yet major fisheries based on these fish built up in the 1970s, in some cases to peaks over 400,000 t/yr, with classic killer spikes that left the stocks almost entirely depleted within 20 years (Fig. 4). Concentration was at first on the more robust nototheniids, but when these were quickly exhausted there was a shift to the more lightly built channichthyids. Always, though, as the fishery diminished more and more species were added to the list exploited so as to keep the landings up. The entire notothenioid fauna appears to have been affected, and now the last remaining large top carnivore, the nototheniid *Dissostichus eleginoides* (aka Chilean Sea Bass), is under severe assault as the trendy (designer) fish of the 90s.

As was the case in *Coryphaenoides*, the notothenioids were fished at first by only the USSR. Over time, however, more and more countries joined in, first from the eastern bloc and then from Europe generally, and finally from Chile. Finally, 16 countries were involved, but by the mid-1990s the annual fishery, excluding *Dissostichus*, had declined to only a few hundred tons (Fig. 4). The data are not available to determine the extent to which the fishery has switched from place to place, but there is some evidence, on a very coarse scale, that the *Dissostichus* fishery today is doing so (Fig. 5).

In the North Atlantic, two deep-water fisheries appear to display remarkable staying power, those for redfish (*Sebastes*) and Greenland halibut (*Reinhardtius*). *Sebastes*, which was developed in the US as a replacement for the collapsed freshwater perch (*Perca*) fishery (Murawski *et al.* 1997), has been fished at a very high level for a long time. This is particularly surprising given *Sebastes's* viviparous reproductive habit, and its slow growth and high age at maturity (not to mention the fact that the taxonomy is not even well worked out!). Nonetheless, the overall trend in the landings has been down over time (FIGURE), and the mean size of individuals in scientific surveys appears to be dropping (Haedrich and Barnes 1997) in recent years.

The history of the *Sebastes* fishery (Fig. 6) is a bit different from those just considered. It was developed first by the US in the 50s, but the landings in that country declined to just about vanish in the mid-80s. The USSR, eastern European countries and Iceland joined the fishery in earnest in the late 50s, and Canada started to fish then as well. An important fishing nation, Portugal, entered the fishery seriously only in 1985, but over time, the proportion of the catch taken by Canada has increased so that it dominates the fishery today. Nonetheless, even with a downward trend in landings there has been an increase in the number of countries involved, up from an original three to about 15 in the early 90s. Spatial considerations show that the fishery has not moved particularly, although it does display periods of expansion and contraction in range (Fig. 7). The most important regions for *Sebastes* fishing in the western North Atlantic have always been to the south of Newfoundland and Nova Scotia, and in the deep waters of the Gulf of St. Lawrence.

Reinhardtius fisheries have likewise remained at high levels for a long time, but these are much more clearly in trouble and very likely on the verge of collapse. At first, only Greenland took any interest in this deepwater flatfish (Smidt 1989), but there was a big buildup in the late 60s (Fig. 8). Canada, East Germany, Poland and the USSR were the main countries involved. Within 10 years, by the late 70s, only Canada was left as an important player; Greenland's landings were continuing to increase slowly and Portugal began to fish in about 1980. In 1989, there were 14 countries in the fishery. Spain only became involved in the early 90s, but her catch quickly grew to dominate the overall landings from the western North Atlantic. This rapid movement into the fishery was certainly a root cause for the Canada-Spain "Turbot War" of 1993. There is some variability in landings by geographical area over time in the western North Atlantic, expanding from an initial focus on deep waters to the east of Newfoundland to now cover the entire range of the species (Fig. 9). The most consistent landings are reported from east of Newfoundland and Labrador and from the Gulf of St. Lawrence.

Reinhardtius provides perhaps a classic case of a fishery developed, especially recently, for political expediency as Canada sought some target for fishermen idled by the cod moratorium (Duthie and Marsden 1995). Bowering and Brodie (1995) first called attention to imminent and serious problems for the fishery, and recent survey data show that the deep-water populations fought over by Canada and Spain are now composed mainly of fish much smaller than the size at maturity (Fig. 10). A major collapse is coming, and the pattern is likely to be very similar to that already revealed in the case of *Coryphaenoides* and the Antarctic nototheniolds.

Pause to reflect

These few examples suggest a reasonably common pattern in many of the deep-water fisheries that have been undertaken in the past few decades. Preliminary exploratory surveys discover large stocks and, shortly thereafter, a high volume but probably low value fishery develops. Very high yields are realised for a few years, but then drop off rather steeply. But the hunt expands, with more countries and to adjacent areas and, where possible, for related species. Even though interest eventually wanes, landings remain very low without any hint that populations may be recovering to their former abundance. Peer-reviewed ecological science only gets involved quite late in the game. This scenario has already taken place in *Coryphaenoides* and other macrourids, and in the notothenioids. *Reinhardtius* shows every sign of heading in the same direction. Deep-water sharks, the oreosomatids, and perhaps even *Aphanopus* may well be next.

Management plans for fishing deepwater species have usually followed the established model used in the management of shelf species. The focus is on individual species data, most especially those relating to growth and population dynamics, and the setting of rough-and-ready quotas (see Atkinson 1995). Deep-water species do not grow fast, they mature late, and they belong to diverse communities where food-web relations are probably well-defined. Because of this diversity, and because of the general problems of deep-water sampling, it is not easy to get information on any one species very quickly. For all these reasons, it is clear that assembling the data needed for conventional management will take a long time, in fact often far longer than the fishery may be expected to last!

A better approach to managing deep-water fisheries would be to consider likely options and scenarios based on a knowledge of the overall ecology and ecosystems of the deep sea. Much is already known, but usually not reported in the fisheries literature, about the deep-sea environment and the fish community generally (e.g. Merrett and Haedrich 1997). Instead of focussing on individual species management, it would be better to focus on ecosystem level knowledge, and work to establish general policies with respect to deep-water fishing. These would include policies, *inter alia*, that recognise the importance of maintaining biodiversity and that rely on the precautionary principle so that the welfare of future generations -- of fish and of fishermen -- is taken into account. Responsibility would then fall on managers to assure that any plans proposed were in line with, and never compromised, the policy guidelines agreed upon. Adopting this approach would be a significant step forward along the path towards ecosystem management (Langton and Haedrich 1997), an area where deep-water fisheries could turn out to be the proving ground.

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Coryphaenoides rupestris, North Atlantic fishery

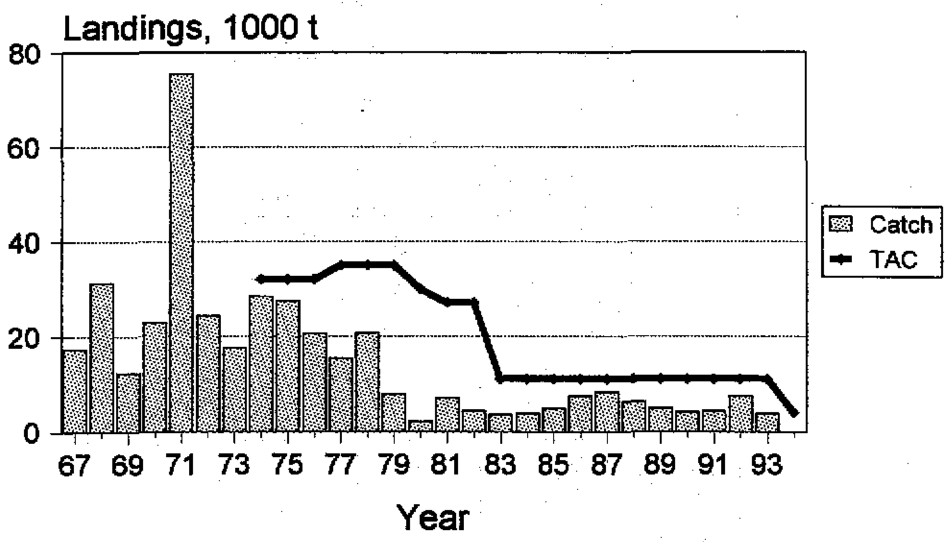

Fig. 1: Haedrich, Merrett & O'Dea, Sept 98 NAFO data

Roundnose Grenadier (*Coryphaenoides rupestris*)

Important Biological Papers and the History of the Fishery

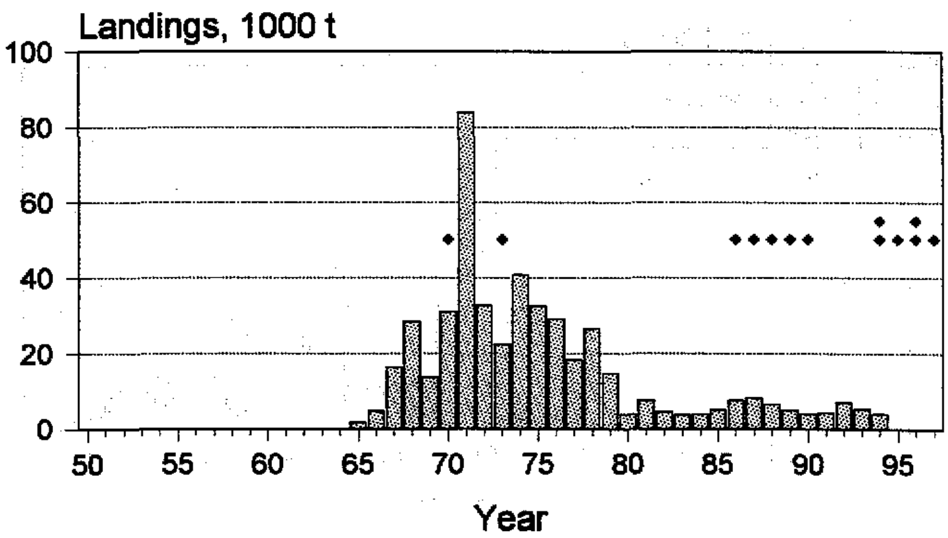

Fig. 2: Haedrich, Merrett & O'Dea, Sept 98 NAFO data

Coryphaenoides

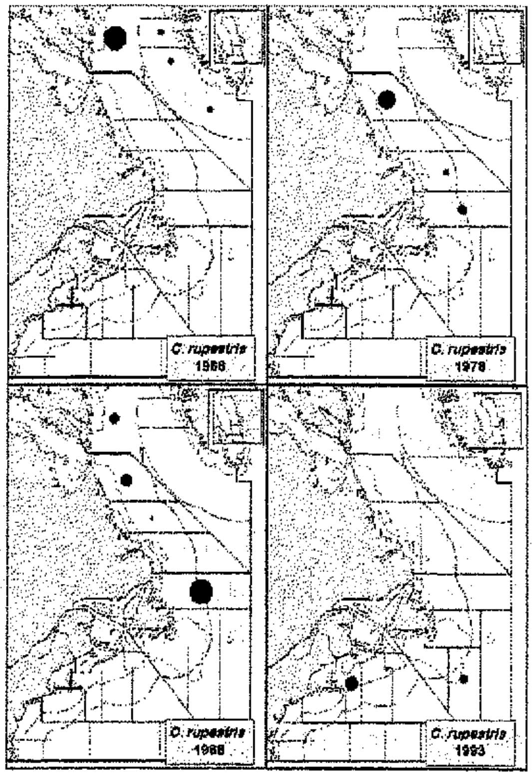

Fig. 3: Haedrich

NAFO data

Deepwater Antarctic notothenioid fisheries

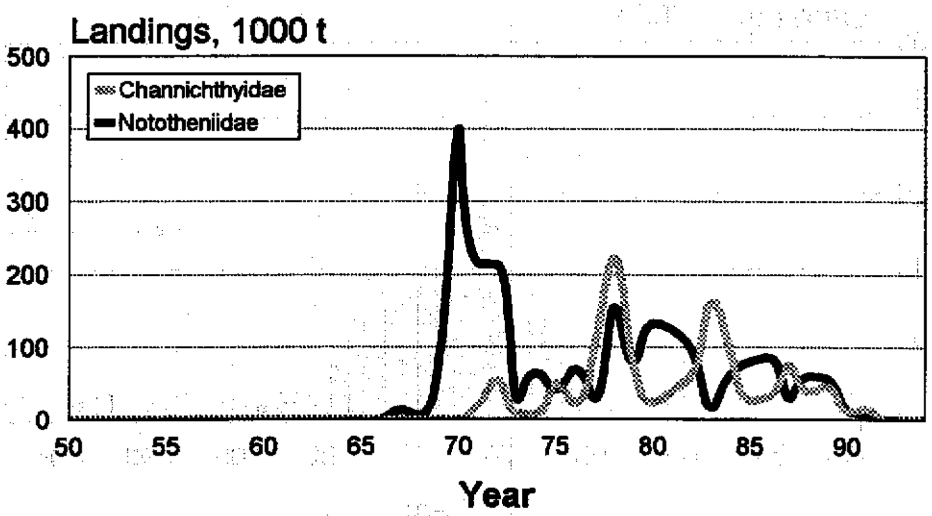

Fig. 4: Haedrich, Merrett & O'Dea, Sept 98

FAO data

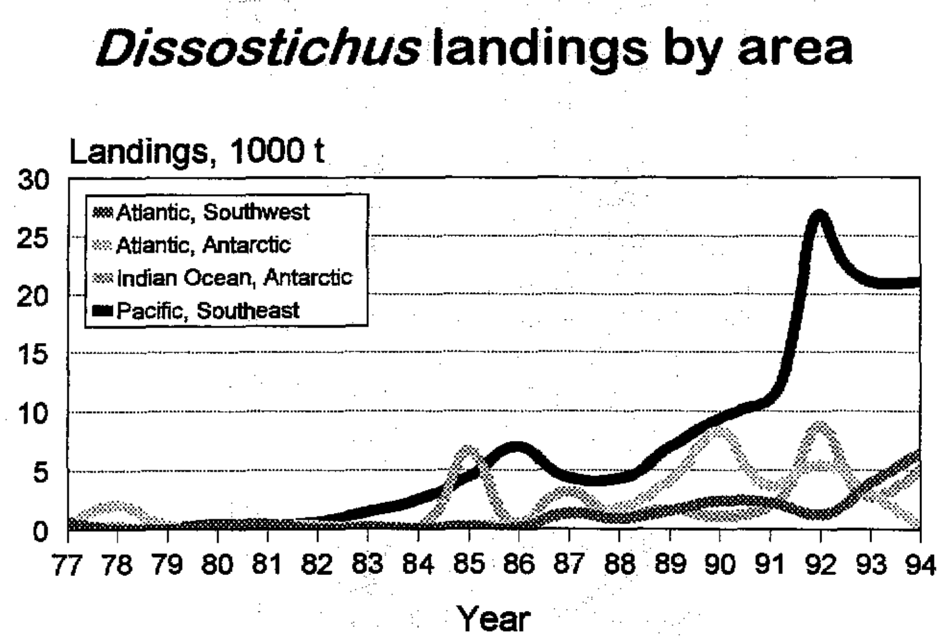

Fig. 5: Haedrich, Merrett & O'Dea, Sept 98 FAO data

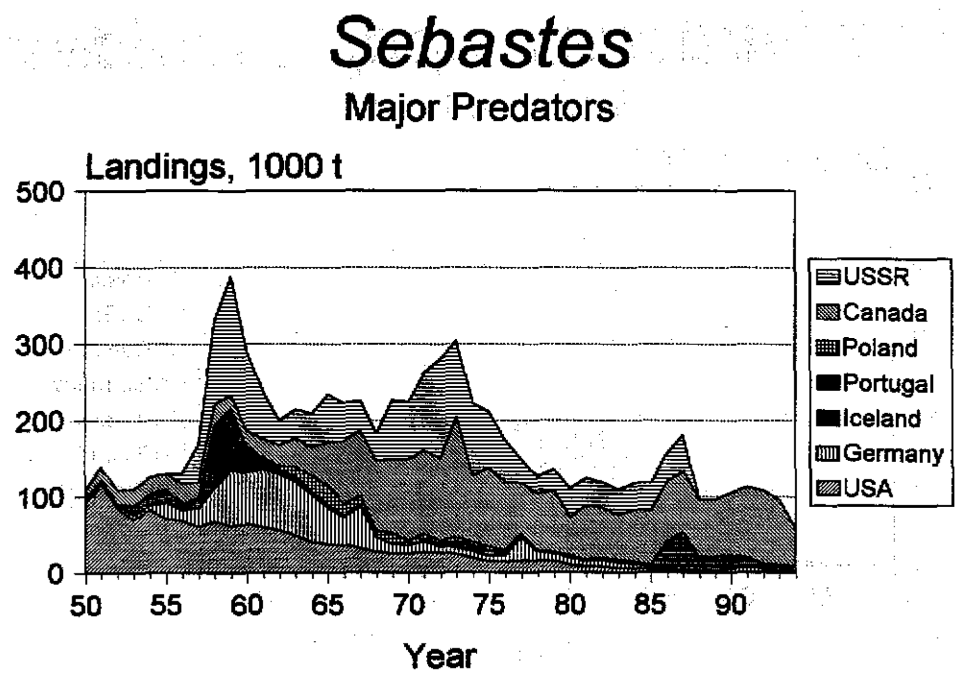

Fig. 6: Haedrich, Merrett & O'Dea, Sept 98 FAO data

Sebastes

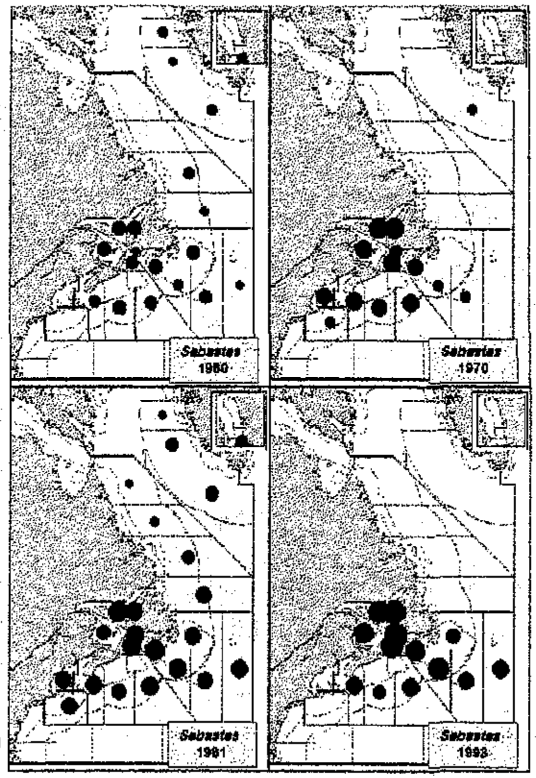

Fig. 7: Haedrich NAFO data

Reinhardtius hippoglossoides

Major Predators

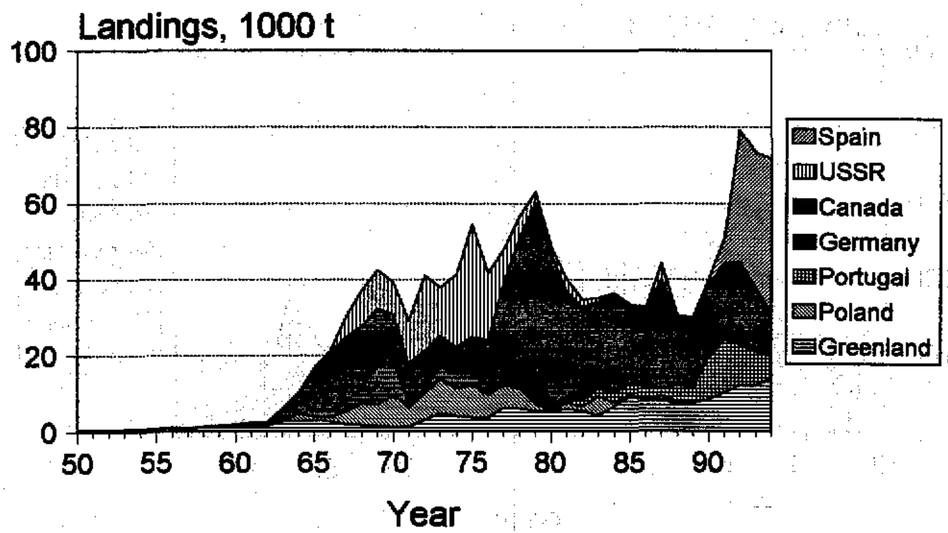

Fig. 8: Haedrich, Merrett & O'Dea, Sept 98 FAO data

Reinhardtius

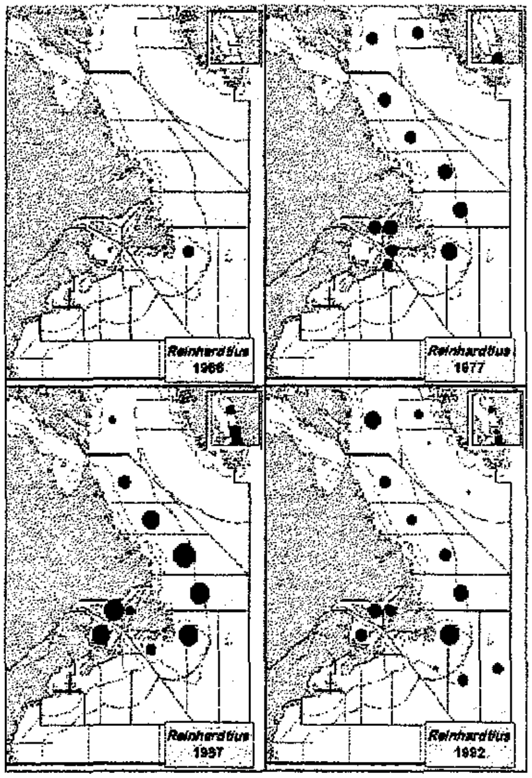

Fig. 9: Haedrich

NAFO data

Reinhardtius now so small the fishery is at risk!

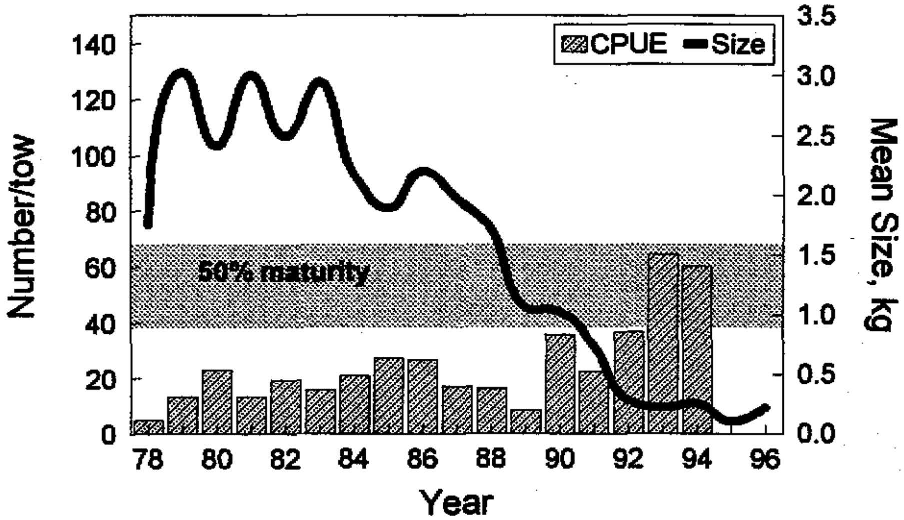

Fig. 10: Haedrich, Merrett & O'Dea, Sept 98

Survey data