Can Ecosystem-Based Deep-Sea Fishing Be Sustained?

Report of a Workshop Held
31 August-3 September 2010

THE UNIVERSITY OF MAINE

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Contents

Executive Summary
Can Ecosystem-Based Deep-Sea Fishing Be Sustained? 1
    Key Findings 2
Can ecosystem-based deep-sea fishing be sustained?
Report of a Workshop held 31 August - 3 Sept. 2010, Neuville-Bosc, France 5
Objectives 6
Background Papers 6
Fishery Case Studies 7
Considerations on the Use of Models 12
Reports on Deep-Sea Fisheries 13
    What is a Deep-Sea Fish? A Phylogenetic and Life History Approach 13
    Sustainability of deep-sea fisheries: Orange Roughy 24
    Orange roughy fisheries in the Northeast Atlantic 26
Applying a basic productivity-susceptibility analysis to a complex deepwater mixed trawl fishery in the Northeast Atlantic 35
Sustainable Deep-Sea Fisheries for Grenadiers 52
Productivity – Susceptibility Analysis of Deep-Sea Fish Species in a Global Context 64
Deep-water fishing in tropical latitudes: the Brazilian experience 67
Habitat Impact of Deep-Sea Fisheries 69
Summary and Conclusions 74
Literature cited 78
Acknowledgements 84

Executive Summary
Can Ecosystem-Based Deep-Sea Fishing Be Sustained?

International scientific workshop
Held 31 August - 3 September 2010

Can there ever be a truly sustainable deep-sea fishery and if so, where and under what conditions? Ecosystembased fisheries management requires that this question be addressed such that habitat, bycatch species, and targeted fish populations are considered together within an ecosystem context.

To this end, we convened the first workshop to develop an ecosystem approach to deep-sea fisheries and to ask whether deep-sea species could be fished sustainably. The workshop participants were able to integrate bycatch information into their framework but found it more difficult to integrate other ecosystem indicators such as habitat characteristics.

For this workshop, "deep-sea" was acknowledged to include ocean depths greater than 200 m, but the fish species of concern were those with adult distributions at depths greater than 400 m. It was understood that the juveniles of some species might occur in the shallower waters off the edge of the continental shelf. Also, the concept that all deep-sea fish are alike was considered and rejected. In fact, a deep-sea fish could be one that has a long evolutionary history in the deep-sea or one that evolved recently from a shelf-dwelling ancestor. A small group of workshop participants evaluated the biological characteristics of a large number of deep-sea species and found that their depth of occurrence correlated most strongly with their life history parameters.

In order to evaluate the potential of deep-sea fisheries for ecosystem-based sustainability, it was originally thought that the relatively simple Lotka-Volterra class of models could be applied, but we soon realized that deep-sea fisheries suffered critical data limitations (i.e. needed information such as life history characteristics, bycatch, or discard rates did not exist) that made the use of quantitative models difficult. An alternative approach, one that allowed the combination of both fish life history data and ecosystem criteria, was to apply a semi-quantitative model (the Productivity – Susceptibility Analysis, PSA) to species routinely caught in deep-sea fisheries. This model subjectively scores species on a scale of 1-3 in terms of their potential productivity (derived from life history data) and susceptibility to overfishing (based on species distribution and behavior, and management practices). The model output is a plot displaying the vulnerability of each species relative to the others analyzed.

In the short time of the workshop, we were unable to fully evaluate all the criteria used in the PSA model by Patrick et al. (2010), but the workshop participants were able to agree on a list of objective productivity criteria (maximum size and age, estimated natural mortality, measured fecundity, breeding strategy, age at maturity, and mean trophic level). On the other hand, identifying criteria that reflected the susceptibility of species to overfishing was more problematical. Some of these criteria -for example area and vertical overlap with the fishery- are imprecise because they are based on information that is not necessarily available, while others such as whether a management plan is currently in place, does not account for the history of the fishery. As a result, some deep-sea species such as black scabbardfish and roundnose grenadiers were rated as not very susceptible to overfishing even though their populations over the past decade have severely declined. These results create a misleading impression of the vulnerability of deep-sea species in some cases.

The PSA vulnerability plot is essentially a risk analysis, but it does not address the question of sustainability directly. However, with further refinement of the susceptibility criteria, and with the addition of habitat criteria, it could be used to identify particularly vulnerable species within an ecosystem context and suggest possible management strategies.

Long-term and broadly based scientific study of the deep-sea presents a picture of a realm where life proceeds at a slow pace. Species are slow growing, long-lived, late to mature and of low fecundity, but diversity is very high, especially at upper bathyal depths (200 – 2000 m). Since all deep-sea fisheries also occur at these depths, the characteristics of the deep-sea fauna have led scientists, governments and NGOs to become concerned about the sustainability of deepsea fisheries and their impact on biodiversity and habitat. Governments have been responding to this growing concern, and in 2002 the United Nations General Assembly entered a process of negotiation that culminated in the adoption of UNGA resolutions 61/105 in 2006 and additional provisions in 64/72 in 2009 to ensure the long-term sustainability of deep-sea fish populations and the preservation of vulnerable marine ecosystems. Recognizing that deep-sea fish species are vulnerable to overexploitation, and that particular fisheries result in habitat damage, the European Commission has also set fishing quotas which have been regularly reduced since 2003, and imposed some area closures within which no bottom tending gear can be used. However, deep-sea fisheries are still harvested outside safe biological limits and cannot be said to be conducted sustainably.

States have an obligation to ensure the long-term sustainability of targeted fish stocks as well as bycatch species, prevent significant adverse impacts on deep-sea ecosystems through the conduct of environmental impact assessments prior to fishing, and close areas to bottom fishing where vulnerable ecosystems occur.

This workshop examined three deep-sea fisheries using the semi-quantitative PSA model and considered environmental consequences of using trawl vs. long-line gear in some. Following the workshop, further analysis and writing proceeded for two months, during which general patterns and rules came to light, enabling us to draw what we have named "lessons" that should be understood by managers as golden rules whose implementation is essential to ensure long-term ecosystem-based sustainability of deep-sea fisheries.

Key Findings

Lesson 1:
No deep-sea bottom fishery can ever be considered sustainable if it involves significant bycatch or habitat impacts.

LESSON 1: NO DEEP-SEA BOTTOM FISHERY CAN EVER BE CONSIDERED SUSTAINABLE IF IT INVOLVES SIGNIFICANT BYCATCH OR HABITAT IMPACTS.

It is well-established, from research in the North Atlantic as well as the Southern Pacific assessing the impacts of fishing on seamounts, ridges, and continental slopes, that bottom trawl gear removes virtually all large non-target species, disturbs the upper layers of sediment (the doors themselves can leave furrows up to a meter deep in soft sediment environments) and generally results in a biomass and species-poor habitat. All trawls are non-selective collectors of organisms, but deep-sea trawls are also extremely heavy and are hauled across the bottom with considerable force and for long distances. The deep sea is generally a quiescent environment, where current flow is gentle, storms have little influence, and organisms are lightly built but can grow to large sizes in the absence of strong physical forces. Deep-sea organisms are therefore no match for the weight and speed of bottom trawls.

The only way for a deep-sea fishery to be sustainable in an ecosystem context is for it to have a slight ecosystem impact. Bottom trawls are non-discriminatory and do irrevocable damage to the ecosystem, and the workshop participants felt that no bottom trawl fishery could ever adequately satisfy the international objectives of fish stock sustainability and habitat preservation. Avoiding deep-sea bottom trawls under all circumstances could act as an overarching rule for all deep-sea fisheries. One possible solution might be to replace bottom trawls with more selective gear, such as traps and longlines. However, longlines can also be indiscriminate catchers of fish species, especially deep-water sharks, and cause habitat damage; therefore, it is important that all bottom gears, including longlines, be deployed in the least vulnerable ecosystems.

Lesson 2:
A few deep-sea fisheries could be operated sustainably under specific conditions.

LESSON 2: A FEW DEEP-SEA FISHERIES COULD BE OPERATED SUSTAINABLY UNDER SPECIFIC CONDITIONS.

Most deep-sea fish stocks suffer from a lack of information about critical life history parameters, so they cannot be modeled in the same way as many shallow water stocks. However, it is possible, using a conceptual model such as the recently developed Productivity-Susceptibility Analysis (PSA), to determine the extent to which a deep-sea fish species might be more susceptible to overfishing. The workshop applied PSA to a series of fish species under several different scenarios. In particular, the species taken in the Northeast Atlantic deep-sea mixed trawl fishery and species of grenadiers taken both in the Atlantic and Pacific were considered. Additional criteria, such as limiting the depth at which fish can be taken and changing fishing method from trawls to longlines, were applied in an attempt to more fully understand the effect of dramatic changes in these fishing practices to deep-sea ecosystems.

Deep-sea grenadiers turn up in virtually all trawl or longline fisheries conducted on continental slopes worldwide, and all are susceptible to overfishing. However, the littlefished,but relatively abundant, giant grenadier population of the North Pacific has the potential to become a sustainable fishery, and because the population numbers are so high, a small percentage could be taken from that presently large biomass on a long-term basis.

The figures below show that black scabbardfish and greater forkbeard are on the less vulnerable end of the PSA plot and bluntnose, sixgill, leafscale, gulper and other sharks are on the most vulnerable end, especially due to their very low productivities. A focus on efforts to reduce the bycatch of species susceptible to overfishing such as sharks would lower the habitat impact and enhance the fisheries potential for sustainability. The workshop participants felt that PSA held promise for assessing the state of deep-sea fisheries in an ecosystem context. While PSA does not directly assess sustainability, it can act as a useful tool to suggest where efforts at improving management might best be directed.

LESSON 3: THEORETICALLY, ALL DEEP-SEA FISHERIES COULD HAVE BEEN CONDUCTED SUSTAINABLY.

Lesson 3:
Theoretically, all deep-sea fisheries could have been conducted sustainably.

Most commercially important deep-sea fisheries were well underway, and some had even already collapsed, before the details of their population characteristics were known. Historical catch levels were much too high to allow the populations to replenish themselves.

Among the many species of commercial interest that had potential for long-term sustainability, the workshop participants analyzed the fishery for orange roughy. Exploitation of the species in the Atlantic has reduced the stock size to only 30% of what it once was, and even under a "no catch" scenario, it is likely to take over 100 years for the population to recover. Orange roughy is an especially long-lived species, mature females do not spawn until they are older than most other fish, little is known about the early life history of the species, and the fisheries are promulgated on spawning aggregations. Thus, the orange roughy is an example of a species whose population characteristics suggest it could only have been fished sustainably by taking very small proportions of the population, which did not happen in the North Atlantic, and does not seem to be happening in the South Pacific. Instead, the history of the fishery is one of serial depletion of stocks in most areas of the ocean where the species is fished.

LESSON 4: DETAILED DIRECTED SCIENCE AND INCREASED MONITORING , CONTROL, AND SURVEILLANCE MUST BE A PART OF ANY DEEP-SEA FISHERY.

Lesson 4:
Detailed directed science and increased monitoring, control, and surveillance must be a part of any deep-sea fishery.

In cases where deep-sea fish species have population characteristics that would allow for a small percentage of the biomass to be taken each year, the fishery needs to be conducted using very selective gear, and needs to be closely monitored to assure that the standing stock biomass of target species or bycatch species does not exceed scientifically recommended levels. Extensive monitoring, control, and surveillance, as well as considerable new scientific study of associated bycatch and habitat alteration, would be required to assure the fishery is conducted sustainably.

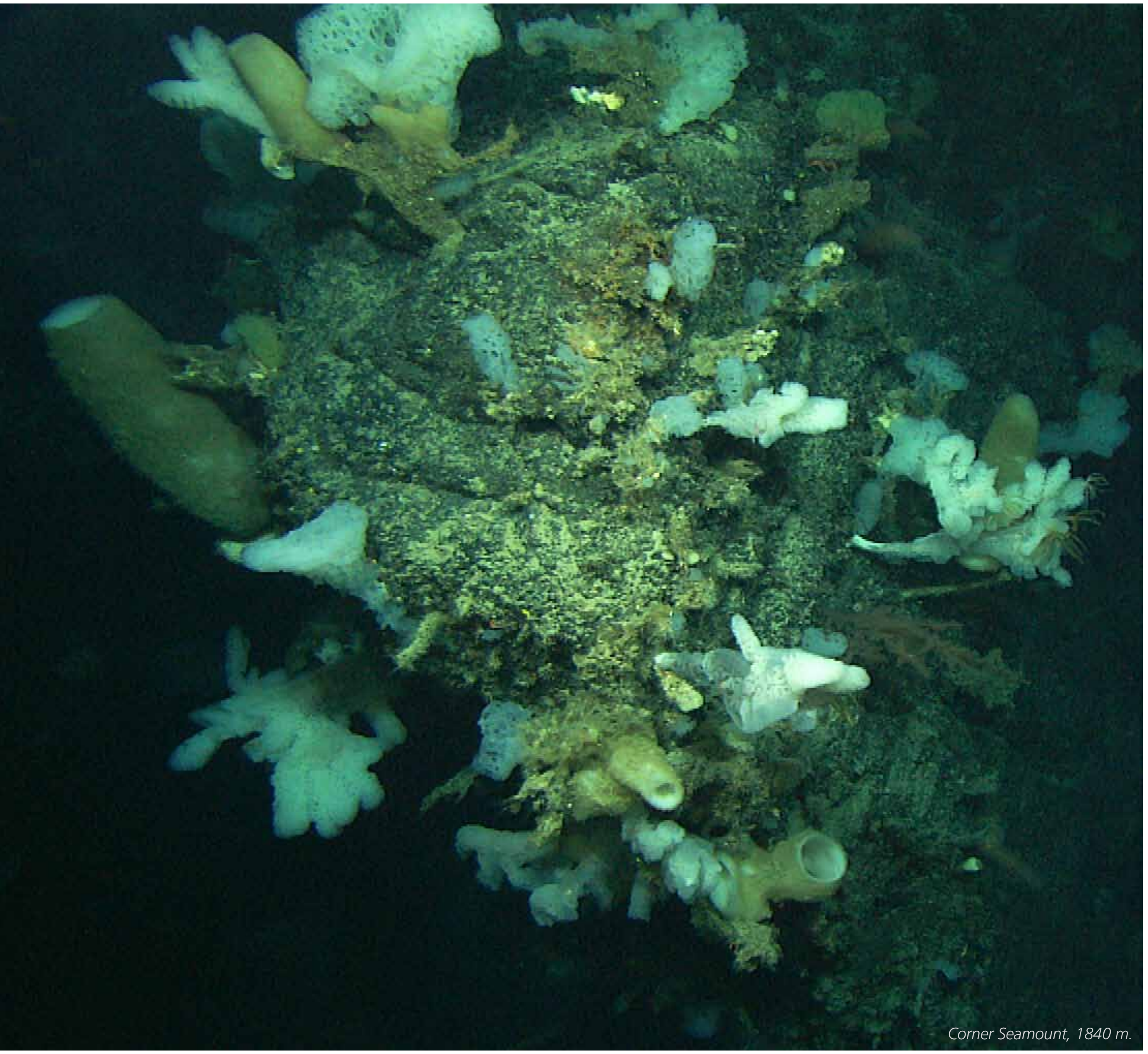
Some species, more closely related to more productive shallow water species, and with depth distributions that are shallower than many other deep-sea species, such as black scabbardfish, greater forkbeard, and blue ling, have high fecundity and relatively short generation times, and so might be candidates for a sustainable fishery. Here too, however, the fishery should be conducted in concert with the biological features of these species and associated bycatch species, and in a way to minimize habitat impacts. For example, blue ling tends to form mating aggregations that have been targeted by the fishing industry. It is highly unlikely that such a practice can be managed sustainably as it would require intensive monitoring and expensive adaptive management. (ICES) the International Council for the Exploration of the Sea currently has restricted fishing in known blue ling spawning areas largely for this reason.
As an alternative, fishing could be suspended during the time of year when mating aggregations are present. In contrast, black scabbardfish is a species whose juveniles range far from the place where they were born, and over their lifespan, seem to wander throughout the Northeastern Atlantic. Fishing heavily on the spawning adults or taking juveniles when they are at the northern end of their range has to be monitored to be sure that the population stays stable over the whole region. All these species can be taken with more selective gear, such as bottom longlines, so efforts should be made to drastically reduce bycatch and habitat impact throughout the North Atlantic.

Key Findings cont.

Lesson 5:
Deep-sea fisheries should be economically viable.

LESSON 5: DEEP-SEA FISHERIES SHOULD BE ECONOMICALLY VIABLE.

We know from the previous lessons that deep-sea fisheries, to be considered sustainable, have to drastically reduce habitat and non-target species impacts and can remove only very small amounts of biomass. We also know from historical records that by-and-large deep-sea fish biomasses have been substantially reduced. Therefore, future yields will never equal what has been taken in the past, and with the notable exception of giant grenadier, there seems to be no commercially important species with potentially important virgin biomasses. While the workshop participants did not have the competence to address economic considerations directly, it was clear from the discussions that some attention needed to be paid to the idea of whether a fishery could be conducted sustainably and be economically viable, especially in light of the added cost of adequate scientific assessment and monitoring. In view of these considerations, the cost to habitat from deep-sea bottom trawling, and the very long times for these habitats to recover, workshop participants repeatedly questioned the economic viability of a truly ecosystem-based and scientifically supported sustainable deep-sea fishery.



Corner Seamount, 1840 m.

Can ecosystem-based deep-sea fishing be sustained?

Report of a Workshop held 31 August - 3 Sept. 2010, Neuville-Bosc, France

But can there ever be a truly sustainable deep-sea fishery and, if so, where, and under what conditions?

The record of decline of continental shelf fisheries is well-known (Pauly *et al* 2002; Worm *et al* 2009). As a consequence, over the past 40-50 years, fisheries have expanded into the deep sea with the result that these ecosystems and fish populations are globally under threat, both within and outside areas of national jurisdiction. During this time, fisheries and environmental scientists have been struggling to obtain sufficient data to determine whether such fisheries can be sustainable and to determine the habitat consequences of those fisheries. Unfortunately, too often critical information is not gathered until the target fisheries have peaked and collapsed (Haedrich *et al*. 2001).

Various legal processes (EU and UN) now require the industry to demonstrate before a fishery begins that deep-sea fishing operations can be conducted sustainably and with little environmental harm. In 2006 the United Nations General Assembly adopted resolution 61/105 calling explicitly for fishing nations to ensure the long-term sustainability of deep-sea fish stocks. That resolution was followed by a negotiated set of guidelines, adopted in 2008, for the management of deep-sea fisheries. Strict measures were laid out concerning environmental impact assessments of existing and proposed fisheries, the characterization and identification of vulnerable marine ecosystems, and rules to be adopted when such ecosystems were encountered.

Between October and December 2010, the EU Council of Fisheries Ministers met in Brussels to discuss their deep-sea fisheries. Quota and Total Allowable Catch (TAC) allocations for deep-sea stocks are set only every other year, as opposed to annually for shallow-water species. The European Commission highlights the fact that deep-sea stocks are harvested outside safe biological limits and, therefore, has regularly implemented quota reductions and even closures. Between September and November 2011, a UN review of the implementation of GA Resolutions 61/105 and 64/72 will occur in New York. In both processes, the EU and the member States of the UN have an obligation to ensure and/or achieve sustainable management of fish stocks under the provisions of international agreements, but with regards to deep-sea fish stocks, they cannot, as of now, define what constitutes a sustainable level of exploitation.

But can there ever be a truly sustainable deep-sea fishery and, if so, where, and under what conditions? Ecosystem-based fisheries management requires that this question be addressed such that habitat, bycatch species, and targeted fish populations are considered together within an ecosystem context.

Therefore, we thought it timely that scientific knowledge and perspectives be synthesized and updated in order to feed into these important international processes and fill the gaps that limit the efficacy of negotiated regulations. Scientists with expertise on deep-sea fish and ecosystems could provide advice on the status of populations and habitats, and assess, using the best available science, whether any of these populations could be sustainably and ecologically exploited and, if so, under what conditions.

To this end, we convened a workshop to review the available scientific information and prepare a synthesis report to inform policy makers about the likelihood that a deep-sea fishery could be sustainable in the framework of ecosystem-based management.

1. In this report, "deep sea" is acknowledged to include depths greater than 200 m, but the fish species of concern have adult distributions at depths greater than 400 m. It is understood that the juveniles of some species may occur in the shallower waters off the edge of the continental shelf.

Objectives

The primary objective of the workshop was to:

- Produce a clear, unified scientific assessment of the sustainability of deep-sea fisheries from an ecosystem-based management point of view that includes an explicit appraisal of the conditions necessary for sustainability.

The workshop sought to cover the following:

- Achieve a practical definition of sustainability in deep-sea ecosystems.
- Examine conditions of deep-sea life and note the differences from those on continental shelves.
- Apply conceptual, empirical and quantitative models.
- Understand the reliability of population parameters, fishing methods, fishery-based and scientific assessments, bycatch species, and habitat impacts of fishing.
- Examine three case studies, (1) the orange roughy fishery (global but with low by-catch), (2) the Northeast Atlantic mixed trawl fishery (black scabbardfish, blue ling, and deep-water sharks), and (3) the grenadier fisheries of the North Atlantic and North Pacific Oceans.
- Provide a synthesis and recommendations.

Background Papers

The workshop began with a series of presentations whose main points are summarized below. The presentations themselves can be viewed in the form of pdfs downloadable from the web site: www.bloomassociation.org.

Are deep-sea fisheries sustainable? The UN General Assembly and the precautionary approach and ecosystem approach to deep-sea fisheries

M. Gianni

The United Nations General Assembly over the past several years has responded to international concerns over the unsustainable nature of many deep-sea fisheries in the high seas

The United Nations General Assembly over the past several years has responded to international concerns over the unsustainable nature of many deep-sea fisheries in the high seas and the damage caused by bottom fishing to benthic biodiversity associated with seamounts, deep-sea corals and other types of ecosystems found in the deep-sea. As a result of a process of negotiation, involving both nations engaged in high seas bottom fisheries and those that are not, the General Assembly in 2006 agreed to a set of measures for the management of deep-sea fisheries in areas beyond national jurisdiction which calls on States and regional fisheries management organizations to protect deep-sea ecosystems from the harmful impacts of bottom fisheries through conducting prior impact assessments of bottom fisheries, manage the fisheries to prevent 'significant' adverse impacts to benthic and deep-sea ecosystems, close areas to fishing where vulnerable ecosystems are known or likely to occur unless harmful impacts of fishing in those areas could be prevented, and to ensure the long-term sustainability of the species targeted or taken as bycatch in these fishers (UNGA 2007).

A set of International Guidelines for the Management of Deep-Sea Fisheries in the High Seas was subsequently negotiated under the auspices of the UN Food and Agriculture Organization (FAO) to elaborate a set of criteria for conducting impact assessments and provide more detailed guidance to States on the identification of vulnerable deep-sea ecosystems and species and determining the level of impact from fishing. The UN General Assembly endorsed these Guidelines in a resolution adopted in 2009 which both reinforced and strengthened the 2006 resolution (UNGA 2010). The measures and criteria set out in both the UN General Assembly resolutions and the UN FAO Guidelines establish fall within the context of the general principles for fisheries conservation and management and the application of the precautionary approach established under international law, in particular the 1995 UN Fish Stocks Agreement. The UN Fish Stocks Agreement establishes a number of obligations for the management of fisheries (for so-called straddling stocks and highly migratory fish stocks), including a requirement to assess the impacts of fishing on target stocks and other species belonging to the same ecosystem, minimize the impacts of fishing on associated or dependent species, in particular endangered species, prevent or eliminate overfishing, and protect habitats of special concern (UN FSA 1995).

What are models for?

M. Dunn

Models are favored by fisheries managers because models produce numbers, which are more easily evaluated with respect to management targets and standards. Models can be used to test hypotheses, and if they are good enough, can make evaluations of stock status and the predictions required by fishery managers. Models need to be as complicated, or realistic enough, to answer the questions posed, for example, if a requirement is to evaluate the effect of changing the size of fish captured, then fish size clearly needs to be included in the model. Demographic stock assessment models have relatively high complexity, requiring, for example, input of data on historical catches (including discards; both normally in terms of biomass), stock productivity (including parameters describing fish growth, maturity at age, natural mortality, the relationship between stock and recruitment, and recruitment variability), vulnerability to fishing by length or age group, and an index or indices of stock biomass, and/or absolute stock biomass estimates. Production models are less complex, with stock productivity and vulnerability terms being effectively summarized in the single population growth parameter 'r'. Production models take the simple form of 'biomass next year = biomass this year + population growth – catch."

In some cases, such as orange roughy, stock assessment models can be uncertain and/or biased to the point that they are not considered credible and useful.

Using several stocks in the New Zealand fishery as an example, it was shown that demographic models predicting rebuilds of orange roughy biomass have conflicted with real-world observations, which have suggested a continued decline. The mismatch between model prediction and reality has several possible explanations but the true cause remains obscure, and is largely due to a poor understanding of productivity, and what the observational data actually represent. The problem may be because orange roughy is fished sequentially from one area to another, or that stocks are spatially structured and the nature of the structure is not yet sufficiently understood, or that there have been extended periods of recruitment failure. Thus, in some cases, such as orange roughy, stock assessment models can be uncertain and/or biased to the point that they are not considered credible and useful. Where the fit of quantitative models to the observed data is poor, this is an indication that one or more of the underlying model assumptions is probably incorrect and the model must be treated with caution. For some fisheries, the recognition that models were highly uncertain and/or biased may have come too late. In the end, it may be that a more conceptual modeling approach will be just as useful: one that will allow management rules to be developed and implemented that are robust to uncertainties (an approach often referred to as Management Strategy Evaluation).

Deep-sea fisheries: management at the population level

J. Devine

Because the deep sea is perceived to be homogeneous over large geographic areas, it is thought that there will be weak or no obvious genetic population structure over these large areas. For example, the deep-sea redfish, *Sebastes mentella*, which ranges from near Svalbard in the northeast Atlantic to the Gulf of St. Lawrence in the west, *The factors producing these separate stocks operate at temporal and spatial scales that are different from the scales over which management operates*

comprised three genetic stocks off the eastern coast of Canada. The factors producing these separate stocks operate at temporal and spatial scales that are different from the scales over which management operates. Management decisions made today will influence the population dynamics of this species for at least a decade into the future.

It was also noted that the genus *Sebastes* is currently divided into four species, *S. mentella, S. fasciatus, S. marinus,* and *S. viviparus*, but it most likely comprises six genetically distinct species. Even though speciation in the open sea is considered to be low due to the lack of physical boundaries, speciation can also result from persistent oceanographic features, discontinuities in required habitat features, etc., and in the North Atlantic, to changes in available habitat space with the progression and retreat of the North Atlantic ice sheet which when coupled with life history characteristics such as assortative mating, larval retention and homing behaviour results in low gene flow. Roundnose grenadiers and black scabbardfish were also seen to be made up of several sub-populations that need to be managed separately. It was noted that there were three mis-matches between fisheries management and stock structure: 1) stock structure is complex and dynamic but management tools are static; 2) there is a discrepancy between management tools and the aims of fishery management, which seem to be directed toward the species as a whole rather than individual stocks; and 3) management occurs at a scale that is different from the scale of the population sub-units.

Bioenergetic requirements of deep-sea fish and deep-sea productivity

J. Drazen

Growth is an energetic parameter of particular importance to fisheries managers

Demersal deep-sea fish live in an environment with relatively low food availability. Do environmental conditions in the deep sea then select for energetic strategies that differ from those in shallow water? Should data for shallow water species be used to estimate energetic requirements of deep-sea species? Growth is an energetic parameter of particular importance to fisheries managers. Data on age for shallow water vs deep water gadiform and rock fishes show that deep water species grow much more slowly than their shallow water counterparts. Metabolism is an energetic parameter linked to growth and overall capacity for activity. Plots of metabolic rate with depth of occurrence also showed a general tendency to slow with depth, a trend verified by examining metabolic enzyme activity. Some fish may also lower their overall energetic costs by reproducing less frequently, perhaps every other year. Thus, a simple estimate of fecundity may overestimate reproductive output. At the level of the individual, then, most deep-sea fishes have lower metabolism, growth, and reproductive output that their related shallow-water species.

The carrying capacity of a system is useful to know when evaluating the current biomass of an exploited fish species to potential virgin levels. Previous studies on shallow water regions have related primary production in the world ocean to fish production. We now have estimates of flux of organic matter to the seafloor, and we can estimate the ecological efficiencies of energy transfer from lower to higher trophic levels Pauly and Christensen (1995) estimated ecological efficiency across a broad range of habitats to be about 10%. Using this information and the trophic level of the catch, one can estimate how much primary production is required to produce the annual fish catch. For shelves and upwelling regions, it seems likely that 24-35% of primary production is required to support the historic fish catch. No such estimates exist for deep-sea species or regions but they could be derived. For deep-sea fishes, the food-web might be more complicated because phytoplankton can arrive fresh on the bottom and be ingested by one or more potential prey, or traverse a pelagic food web, passing through zooplankton and micronekton, before being ingested by the fish. In any case, knowledge of food supply and relative proportions of benthic versus vertically migrating micronektonic prey, together with an ecological efficiency of approximately 10%, could be used to estimate the carrying capacity of a deep-sea region for demersal fishes.

Fishery Case Studies

As a prelude to the workshop, a series of fact sheets were prepared for selected target fish species. Information on these fact sheets included aspects of life history, available databases, literature, and opinions in the form of e-mails concerning abundance, catch history, distribution etc. Fact sheets for black scabbardfish, blue ling, deepwater sharks, giant grenadier, orange roughy, Pacific grenadier, roughhead grenadier and roundnose grenadier are included in the Annex to this report.

In addition, short presentations were given for each of these target species. These presentations reviewed the history of each fishery, including its successes and failures, as well as problems arising in attempts at management. Short summaries of each presentation are given below. The presentations themselves can be viewed in the form of pdfs downloadable from the web site: www.bloomassociation.org.

Orange Roughy *(Hoplostethus atlanticus)*

G. Menezes

The species is one of the longest-lived of all deep-sea fish

The orange roughy fishery is truly global in scope, with fish being caught in the North Atlantic, off SW Africa, on the Southwest Indian Ridge, in the southern Indian Ocean, off South Australia, around New Zealand, and on the seamounts of the Louisville Ridge southeast of New Zealand. The species is one of the longest-lived of all deep-sea fish, living more than 100 years and reaching maturity at 20-40 years. They form dense aggregations around seamounts, hills, and drop-offs in water more than 500 m depth which are targeted by the fishery. The fish are characteristically caught using very large bottom trawls which can result in bags of more than 25 tonnes of fish. Environmental impacts on seamounts and other underwater features being fished can be severe. Because of its widespread nature and deep-sea habit, obtaining fishery-independent data for this species is difficult and expensive. s a result, there is still considerable uncertainty about some life history parameters, and the status of many stocks is unknown. In summary, catch limits have been lowered by all governmental organizations responsible for the management of this fishery, and many stocks have been closed to fishing. For the EU, the total allowable catch is currently zero.

Blue Ling *(Molva dipterygia)*

F. Neat

Blue ling is an aggregating fish, forming spawning aggregations around seamounts and banks

Blue ling is also an aggregating fish, forming spawning aggregations around seamounts and banks as well as on the slope off Scotland, Norway, and eastern Canada. Maximum age is about 17 years, with maturity reached at about 6 years. Growth rate is relatively fast and fecundity is high. The stock structure is poorly defined, seemingly divided into northern and southern stocks. Estimates of exploitable biomass and landings per unit effort have been steadily decreasing. ICES WGDEEP recommends no directed fishery for this species and that measures should be taken to minimize its take as bycatch in mixed species fisheries. Blue ling is susceptible to sequential depletion because it forms spawning aggregations that can easily be exploited. It is possible, due to its reproductive output, that the species could recover if spawning aggregations are left alone.

Black Scabbardfish *(Aphanopus carbo)*

I. Figueiredo

Population dynamics and management differ from most other deep-sea species exploited in the North Atlantic

The population dynamics and management regime for black scabbardfish differ from most other deep-sea species exploited in the North Atlantic. The species grows to about 130 cm in length, and becomes mature at about 106 cm. It appears that the population can be divided into northern and southern stocks. The northern stocks west of the British Isles do not appear to be mature and are caught primarily with trawl gear. In the southern area, ripe individuals are caught off Madeira and are taken using long lines. Otolith microchemistry suggests a single population extends from the west of the British Islas to west of Portugal, Madeira, and the Azores. The best model for this species suggests that it spawns in the southern area, with eggs and juveniles being carried northward. After some time, the juveniles migrate to the south for reproduction. While landings have declined in the northern area, catches have remained moderately steady in the southern area.

Deepwater Sharks Batoids, and Chimaeras

(Class Chondrichthyes)

P. Kyne

About 17 species of sharks are fishery targets, and most are depleted or collapsed

Almost half of the known chondrichthyans are deep-sea species, but most of these belong to the groups squaloid dogfishes, scyliorhinid catsharks, skates, and holocephalans. The bulk of our knowledge of deep water chondrichthyans comes from only a handful of species. The literature on chimaeras is limited. For species where data are available, productivity and rebound potential decrease with depth of occurrence. For a suite of deep-sea species studied, their productivity was on average less than half that of shelf and pelagic species. At present, about 17 species of sharks are fishery targets, and most are depleted or collapsed. On the other hand, some shelf sharks, such as houndsharks and sharpnose sharks might be fished sustainably since they are more productive than most deep-sea shark species. The major issues in assessing the status of deep-sea shark stocks include lack of time series data, lack of species-specific data, poor understanding of stock structure, and the unresolved taxonomy of several groups.

Grenadiers of the North Atlantic

K. Baker

Recovery times in the NW Atlantic could be more than a century

Two species of grenadiers make up most of the North Atlantic fishery, roundnose grenadier *(Coryphaenoides rupestris)* and roughhead grenadier *(Macrourus berglax)*. Roundnose grenadiers appear to consist of three distinct populations, two in the northeast Atlantic and one west of the Mid-Atlantic Ridge. This species grows very slowly and matures at 10-14 years. It is a batch spawner, each female producing 4000 to 68000 eggs per batch. In the northwest Atlantic the species has undergone a precipitous decline in catch, being near zero as of 1997, but increasing slightly in more recent years. Similarly, in the eastern Atlantic stock biomass estimates have shown dramatic declines but are currently thought to be stable at low levels. Using life table analyses, recovery times for this species in the NW Atlantic could be more than a century, assuming no damage to required habitat. This latter factor is important since *C. rupestris* has recently been found to be a typical community member of large coral habitats off the Grand Banks of Newfoundland. Roughhead grenadier is also a slow growing species and matures at 13-16 years. Fecundity ranges from 8500 to 80000 eggs. It is an important bycatch species in the Greenland halibut fishery. Population trends have also been steadily downward and recovery times are estimated at more than two centuries assuming no damage to habitat. Both species of grenadiers are considered to be species at risk in Canada, but neither have formal protection.

Giant *(Albatrossia pectoralis)* and Popeye *(Coryphaenoides cinereus)* Grenadiers of the North Pacific

A.M. Orlov

Both species of grenadiers are widespread around the North Pacific, occurring from California in the east to Japan in the west. The giant grenadier lives from 32 to 56 years, while the popeye grenadier seems to be much younger, living about 15 years. Both species are moderately slow growing. Fecundity varies directly with size in both species with the larger giant grenadier producing 65,000 to 330,000 eggs and the smaller popeye grenadier only 3,000 to 17,000 eggs. Catches of grenadiers in the Russian EEZ have been steadily increasing during the last decade, while in the US EEZ, catches have remained steady at 11,000 to 16,000 mt. Biomass estimates of grenadiers from both Russian and US EEZs suggest that both species are not currently being over fished.

The giant grenadier lives from 32 to 56 years

Pacific Grenadier *(Coryphaenoides acrolepis)* of the Eastern North Pacific

G.M. Cailliet

The Pacific grenadier has a distribution similar to the giant and popeye grenadiers, although it occurs deeper than the former species. The size of individuals increases with increasing depth. It was considered a trash fish until the 1990s when a directed fishery for the species was suggested. There is a limited market for its flesh along the west coast of the US. Fecundity is high, in the range seen for the giant grenadier. Published lead-radium age dating of otoliths validated Pacific grenadier longevities to 50-60 years. Within US waters, only the Pacific grenadier is listed in the Fisheries Management Plan. They are not specifically managed but are listed as part of the "other fish" complex. Trawl reports suggest that between 73 and 79% of the grenadier catch is discarded. Relative stock status was determined using the new depletion-based stock reduction analysis (DB-SRA) model. One result was that the overfishing limit for this species was reduced during the past 10 years.

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Considerations on the Use of Models

Quantitative Population Models

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Any consideration of what constitutes a sustainable fishery entails the use of models, and ideally those that are quantitative. Fundamental information required is the present size of a population (the "stock"), its growth rate, and the size it might attain in an unexploited state. Many such models exist and are in common use by fishery scientists and managers. The models tend to be rather complex and very data-dependent, with considerable attention to the statistics of trawl or acoustic surveys (to determine stock trends and size), age-length-weight relationships and numbers at age (to determine productivity parameters), maturity ogives (to predict recruitment and future stock biomass) and fishery catches and effort, along with reference to the time series and history of stock assessments (which provide the estimates of stock size).

In their simplest state, these complex models take the form of the Lotka-Volterra equation of growth: $B_t = B_{t-1} + B_{t-1}r(1- B_{t-1}/K)$
with inputs of initial stock size (B_o), carrying capacity (K), and an inherent population growth rate (r). This quantitative model was available at the workshop but even the minimal data required could not be provided for almost all the deep-sea species considered, and especially so as regards population growth rate. While educated guesses could and were made, the workshop felt more comfortable adopting a differently-focused qualitative approach.

The lack of data on many deep-sea fish stocks is a fundamental problem that restricts the ability of scientists to provide quantitative advice. This seems unlikely to change, in the short-term at least, and it reflects the difficulty and high cost of conducting research in the deep-sea. In general, deep-sea fisheries have developed (and often declined) faster than scientists have been able to collect data, develop effective monitoring programs, and conduct credible quantitative stock assessments. Recent progress in the quantitative stock assessments for orange roughy, probably the best studied deep-sea fish to date, was the subject of one of the workshop break-out groups.

Semi-quantitative models

An example of a semi-quantitative model is that used in a Productivity-Susceptibility Analysis (PSA), which subjectively scores species on three-point scales in terms of their potential productivity (derived from life history data) and susceptibility to over-fishing (based on distribution, behavior and management practices). The model is a plot displaying the relative vulnerability of each species in a fishery. Species with low production and high susceptibility are most vulnerable and those with high production and low susceptibility are least vulnerable. This approach has proven insightful in data-poor situations by providing a snapshot estimate as to where a species might stand relative to others in regard to its vulnerability to over-exploitation.

The PSA vulnerability plot model is essentially a risk analysis, and does not address the question of sustainability directly. Instead it can be used to identify particularly vulnerable species and suggest possible management strategies. Given the paucity of data on deep-sea species suitable for use in even the simplest of quantitative models, the workshop devoted its work in the mixed trawl fishery and the grenadier break-out groups to compiling data for the qualitative PSA model. Those results appear with full discussion in the individual reports that follow.

Reports on Deep-Sea Fisheries

Participants were organized into three groups to discuss the issue of sustainability of the orange roughy, northeast Atlantic mixed trawl, and grenadier fisheries. Each group was asked to consider the following questions:

1. Is it possible that some or all of the species under consideration could be sustainably fished?
2. Is the current fishery being conducted sustainably?
3. What needs to be done to make the fishery potentially sustainable?

In addition, two other small groups met to discuss 1) the issue of life history attributes and phylogenetic relatedness of deep-sea fish species and what that might mean to predicting the consequences of deep-sea fisheries, and 2) how to assess the environmental impacts of fishing methods in the deep-sea with a view to determining whether deep-sea fisheries can be sustainable in an ecosystem context.

What is a Deep-Sea Fish?
A Phylogenetic and Life History Approach

Participants: Jeffrey C. Drazen and Richard Haedrich

INTRODUCTION

Marine fisheries are classified almost exclusively according to their geography i.e. coastal, shelf, high latitude, high seas, and so on. Over the last 50-60 years fishers have increasingly exploited fish stocks in deeper and deeper water (Morato *et al*. 2006b) and the term deep-sea fishery is now commonplace. Some deep-sea species have extreme life history characteristics which make them particularly unproductive and vulnerable to fishing. Great longevity, slow growth and low fecundity are considered regular features of deep-sea fish stocks (Koslow *et al*. 2000; Morato *et al*. 2006a). Indeed, some might say that all deep-sea fish stocks have low productivity. If we were to consider any species living on the continental slope as a deep-sea species then this supposition can quickly be proven false. Species such as hoki and blue ling are captured to depths of 700 and 1200 m respectively yet they grow relatively fast and are highly fecund (Thomas 1987; Schofield and Livingston 1998; Froese and Pauly 2008). This situation clearly illustrates the problems with using broad classifications and begs the questions as to why some deep-sea fishes appear to be productive and others do not.

A taxonomic approach is used in some fisheries, i.e. herring, tuna and cod fisheries, but this is little more than a label of convenience. Phylogenetic classification to reflect the evolutionary history of the species involved could provide some insights for management. This is certainly true for deep-sea fisheries. Andriashev (1953) made the important distinction between what he called "ancient" and "secondary" deepwater taxa. The ancient (also called 'primary') groups are true deep-sea fishes. Their evolution and radiation, as reflected in their numbers of species in the family or order, took place there. Primary deepwater species tend to be found mostly in the more primitive orders of fishes, with Salmoniformes, Aulopiformes, Stomiiformes and Myctophiformes especially important. Many of these are relatively small pelagic fish and therefore of little commercial interest. In the North Atlantic, the orders Gadiformes (with 19% of the species) and Ophidiiformes (12%) are important bottom-living groups (Merrett and Haedrich 1997). Grenadiers are the gadiform family most widely exploited in deep waters globally. Secondary deepwater fishes belong to groups that have evolved and radiated in the shallow seas. Most species in the family or order are found in that environment, but a few representatives have secondarily invaded deeper waters.

Figure 1 shows an interesting phylogenetic divide in commercially important North Atlantic deep-sea fishes. Of the top five species of commercial importance, four (Greenland halibut, blue ling, black scabbardfish and witch flounder) are secondary deepwater species and all have been fished since the 1950s. The next five ranking species in Atlantic deepwater fisheries are all primary, but the landings are considerably less and the fisheries only began in about 1990. The hypothesis suggested is that evolutionary lineage can explain the productivity of deep-sea fisheries.

Not all deep-sea species are equal with regards to productivity because they occupy different depth levels within a gradient of environmental change

While dichotomous categorizations might be a useful approach, another is to consider the environmental and ecological forces acting on a species' biology as a continuum. Features such as metabolism decline exponentially with depth of occurrence (Drazen and Seibel 2007; Seibel and Drazen 2007). With increasing depth many environmental variables change rapidly including light levels, food availability, temperature, pressure, and in some areas oxygen concentration. Thus there is an alternative hypothesis: not all deep-sea species are equal with regards to productivity because they occupy different depth levels within a gradient of environmental change.

Phylogenetic and depth related hypotheses are not mutually exclusive but are a challenge to separate. For instance, most secondary species live shallower on the slope close to their shelf dwelling cousins. Most ancient species live deeper and dominate lower slope and abyssal habitats. To evaluate variations in the life histories and productivities of deep-sea fish stocks we have taken a meta-analysis approach. We assembled data on all of the major commercially exploited deep-sea fishes along with several phylogenetically related shelf dwelling species. This data was evaluated by phylogenetic history and by using depth as a continuous variable.

METHODS

Data on the productivity and life histories of deep-sea fishes were extracted from the peer-reviewed literature and from the online database www.fishbase.org (Froese and Pauly 2008). Data were also used for several shelf dwelling species phylogenetically related to the deep-sea species. Species were classified as ancient or secondary according to the criteria established by Andriashev (1953).

The biological variables used were related to growth and reproduction. Age and growth are standard variables used in fisheries research. Maximum longevity (A_{max}) is related to natural mortality. Age at 50% maturity (A_{50}) is related to growth rate and generation time. Most fisheries scientists use the von Bertalanffy equation to parameterize growth so its k coefficient, which describes the rate of growth, was also used. Annual fecundity characterizes reproductive output. Egg sizes vary inversely with fecundity and deeper living species often have larger egg diameters (Koslow *et al*. 2000) but all the species evaluated are broadcast spawners and none have very large eggs such as those found in demersal egg layers (Sargent *et al*. 1987). Maximum fecundity data (F_{max}) were compiled as the fecundity of the largest females but most individuals do not reach this size. Therefore, we also used the fecundity at the size of 50% maturity (F_{50}). Some productivity variables covary with species size so we also tabulated the maximum size (L_{max}) and size at 50% maturity (L_{50}) using length measurements. Other variables such as natural mortality could have been used but are often derived from and directly related to other variables in the table such as longevity. We did calculate the potential rate of population increase ($r^1 = \ln(F_{50})/A_{50}$) which incorporates both basic metrics of productivity (Jennings *et al*. 1998). This metric has been used for deep-sea fishes before but with a very limited number of species (Clarke 2003).

Depth ranges were tabulated to include the common depths of occurrence rather than occasional captures at extremes, and each species was then categorized into one of 4 depth groups. Shelf species are defined as those living shallower than 300m. Shelf to upper slope species are those that have an upper depth that is on the shelf but their lower depth extent is at least 500m. Upper slope species range from 200-400m extending down slope to usually less than 1000m. Middle slope species have an upper bound of >400m and a lower bound typically to 1500m and as much as 2500m in some cases.

To evaluate the phylogenetic influence on life history parameters, MDS and cluster analysis were performed on the matrix of biological variables with L_{max}, L_{50} and r^1 excluded. Each variable was standardized by the maximum value to bring each variable onto the same 0-100 scale and evenly weight them. A Bray-Curtis similarity matrix was then used for the analyses. SIMPROF was used to establish the significance of nodes in the cluster analysis. The clusters were overlain on the 2-dimensional MDS analysis. This approach produces groups of species which were then evaluated as to whether they best reflected the habitat depth categories or phylogenetic affinity (ancient vs. secondary vs shelf). PRIMER v6 was used for the analyses. To evaluate productivity as a continuous rather than binned function of depth, r^1 and other biological variables were regressed on depth of occurrence.

RESULTS

Biological variables were assembled from various literature sources on 41 species of fishes in 9 orders. This included eight shelf dwelling species which were phylogenetically related to at least one commercially exploited species living on the continental slope. The values are shown in Table 1 and form the basis of the analysis.

The cluster analysis of biological characteristics indicates three statistically significant groups (Figure 2). From the standpoint of phylogenetic composition, the first group includes only ancient deep-sea species - orange roughy, oreos, and giant and pacific grenadiers. These fishes represent three families each in a different order. The second group contains most of the other ancient deep-sea species but also many secondary deep-sea species including rockfishes, Greenland halibut, Dover sole, and Patagonian toothfish. As a result this group represents six orders each with a single family. The third group contains all of the shelf species, several secondary species and also two ancient deep-sea species – the popeye grenadier and alfonsino. The age and growth of the popeye grenadier comes from scale analysis which has been shown to give underestimates of age in many species including grenadiers (Andrews *et al*. 1999). The alfonsino is likely placed in this group because of its very high fecundity (Table 1). The MDS analysis corroborates this grouping in that ancient species occupy the MDS space to the left of the graph and the secondary species in the middle with the shelf species and some secondary species occupy the right (Figure 3). It is also clear that orders and families do not group together.

Categorization by depth group instead of phylogenetic history produces a similar picture. The "ancient" group are all middle slope dwellers (Figure 4). The second group is a mix of species belonging to mostly slope-dwelling species but also those in the shelf-to-slope category. The third group on the right consists of all the shelf species, a few slope and several shelf-to-slope dwellers. The popeye grenadier is the sole middle slope species in this group. Although species living in common depth categories do not group together strictly there is certainly a gradation across the three significant groups from one that is all middle slope dwelling, an intermediate group, and a group that contains all the shelf dwellers and some other shelf-to-slope species.

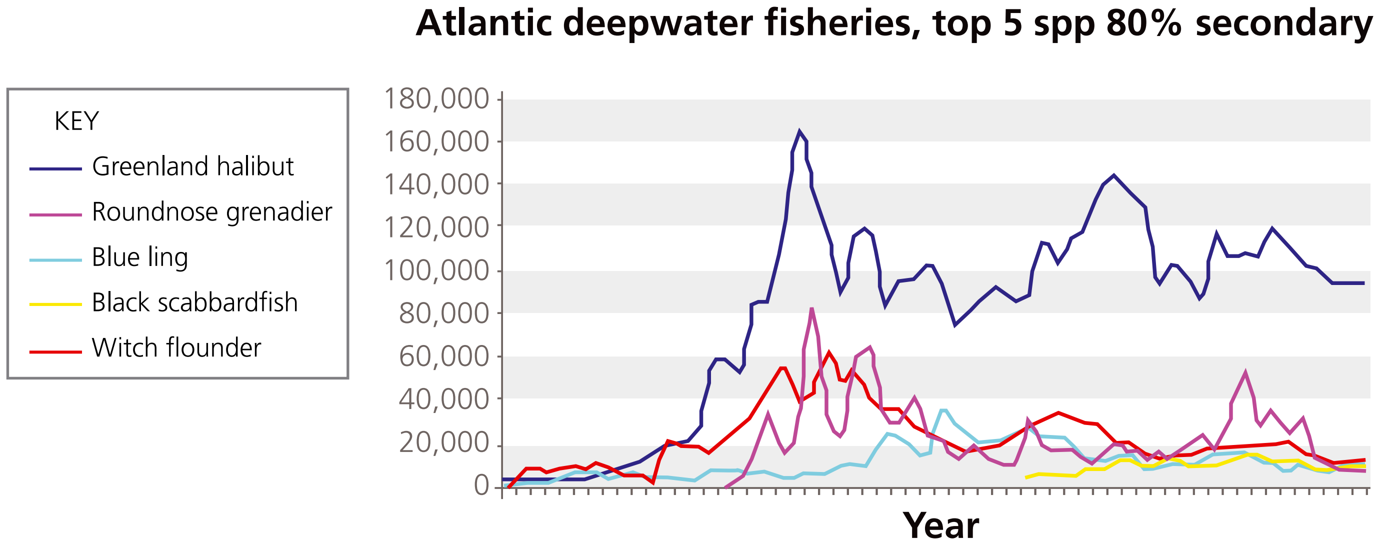
Regressions between minimum and maximum depths of occurrence and the life history attributes yielded several significant relationships. Both metrics of depth were significantly correlated to age at 50% maturity (A_{50}), the von Bertalanffy growth coefficient (k), and potential rate of population increase (r^1; $p<0.05$; Figure 5). Depth explained the greatest amount of variability in the potential rate of population increase ($r^2 = 0.52$), a decline with depth best represented by a negative exponential function indicating greater change in productivity at shallower depths than deeper. The von Bertalanffy growth coefficient k also showed a negative exponential relationship with depth whereas A_{50} showed a positive linear increase with depth. Maximum fecundity showed a weak but significant negative relationship with maximum depth ($p<0.05$, $r^2 = 0.12$) but not minimum depth. The data in Table 1 show that the most fecund fishes are shelf species, a relationship likely driven by the data for Atlantic Cod and other gadids.

Table 1. Life history attributes of 41 species of fishes

Common name	Species	Family	Phy.	min d	max d	Depth category	Amax	A50	VB k	L50	Lmax	F50	Fmax	r1	refs
Order Beryciformes															
Alfonsino	*Beryx splendens*	Berycidae	Anc	400	600	upper slope	23	6	0.10	33	70	240000	675000	2.06	19,33
Orange Roughy	*Hoplostethus atlanticus*	Trachichthyidae	Anc	500	1500	middle slope	149	29	0.06	31	75	35000	180000	0.36	6,12,57
Order Gadiformes															
Atlantic cod	*Gadus morhua*	Gadidae	Shelf	50	200	shelf	25	3	0.20	41	200	300000	9000000	4.20	19,54
Blue ling	*Molva dypterygia*	Gadidae	Sec	350	1200	upper slope	30	6	0.13	80	160	581000	3500000	2.21	19,56
Greater forkbeard	*Phycis blennoides*	Gadidae	Shelf	150	300	shelf	20	4	0.26	33	110		750000		14,19
Giant grenadier	*Albatrossia pectoralis*	Macrouridae	Anc	700	1100	middle slope	58	23	0.02	82	201	35000	231000	0.45	10,50
Pacific grenadier	*Coryphaenoides acrolepis*	Macrouridae	Anc	700	2000	middle slope	73	20	0.02	50	95	23000	150000	0.50	6,41,55
Popeye grenadier	*Coryphaenoides cinereus*	Macrouridae	Anc	500	1200	middle slope	15	5	0.20	32	66	3500	17000	1.63	59
Roundnose grenadier	*Coryphaenoides rupestris*	Macrouridae	Anc	400	1500	middle slope	72	14	0.03	12	29.5	3300	70000	0.58	4,34
Roughhead grenadier	*Macrourus berglax*	Macrouridae	Anc	300	1000	upper slope	25	15	0.04	30	50	19000	80000	0.66	21,45
Ridge-Scaled grenadier	*Macrourus carinatus*	Macrouridae	Anc	500	800	middle slope	37	12	0.08	20	33	15000	57000	0.80	32
Bigeye grenadier	*Macrourus holotrachys*	Macrouridae	Anc	300	1400	upper slope	27	9	0.10	21	37	22000	260000	1.11	32,44
Whitson's grenadier	*Macrourus whitsoni*	Macrouridae	Anc	600	1500	middle slope	55	13	0.06	46	92	9100	41000	0.70	2,38,39
Hoki	*Macrouronus novaezelandiae*	Merluccidae	Sec	200	700	upper slope	25	4	0.17	66	120	500000	3000000	3.28	19,52
Pacific hake	*Merluccius productus*	Merluccidae	Sec	200	700	upper slope	16	3	0.21	34	78	75000	1200000	3.74	19,36
Blue hake	*Antimora rostrata*	Moridae	Sec	750	2200	middle slope	25	13	0.09	42	75				20,37
Order Nototheniiformes															
Patagonian toothfish	*Dissostichus eliginoides*	Nototheniidae	Sec	70	1500	shelf to slope	53	10	0.09	100	240	80000	350000	1.13	23,47
Order Osmeriformes															
Greater Silver smelt	*Argentina silus*	Argentinidae	Sec	150	550	shelf to slope	35	7	0.16	35	70	4478	16284	1.20	13,19
Order Perciformes															
Black cardinalfish	*Epigonus telescopus*	Epigonidae	Anc	300	800	upper slope	104	36	0.04	52	76				58
Pelagic armorhead	*Pseudopentaceros wheeleri*	Pentacerotidae	Sec	200	500	upper slope	7	2	0.30	30	46		100000		9,25
Black scabbardfish	*Aphanopus carbo*	Trichiuridae	Sec	200	1600	upper slope	12	4	0.25	108	151	400000	1000000	3.22	43,46
Largehead hairtail	*Trichiurus lepturus*	Trichiuridae	Shelf	100	350	shelf	15	2	0.32	65	234	4800	160000	4.24	19,30,40
Order Pleuronectiformes															
Rex sole	*Errex zachirus*	Pleuronectidae	Sec	60	500	shelf to slope	29	5	0.28	24	51	6200	238000	1.75	1,24
Witch flounder	*Glyptocephalus cynoglossus*	Pleuronectidae	Sec	50	500	shelf to slope	25	6	0.23	30	61	100000	400000	1.92	19,49

Common name	Species	Family	Phy.	min d	max d	Depth category	Amax	A50	VB k	L50	Lmax	F50	Fmax	r1	refs
Pacific halibut	*Hippoglossus stenolepis*	Pleuronectidae	Shelf	25	300	shelf	42	11	0.10	85	258	220000	3000000	1.12	19,51
Dover sole	*Microstomus pacificus*	Pleuronectidae	Sec	100	1000	shelf to slope	56	7	0.09	33	76	22000	160000	1.43	27,28
Greenland halibut	*Rheinhardtius hippoglossoides*	Pleuronectidae	Sec	200	2000	upper slope	36	10	0.13	67	120	37000	125000	1.05	17,22
Order Salmoniformes															
Baird's slickhead	*Alepocephalus bairdii*	Alepocephalidae	Anc	650	1700	middle slope	38	15	0.07	55	100	2000	7049	0.51	3,5
Order Scorpaeniformes															
Sablefish	*Anoplopoma fimbria*	Anoplomatidae	Sec	10	1000	shelf to slope	114	6	0.20	58	120	210000	450000	2.04	19,26
Pacific Ocean perch	*Sebastes alutus*	Scorpaenidae	Sec	150	450	shelf to slope	100	8	0.14	30	53	15000	505000	1.20	11,35
Splitnose rockfish	*Sebastes diploproa*	Scorpaenidae	Sec	200	600	upper slope	84	8	0.10	19	46	14000	255000	1.19	11,35
Widow rockfish	*Sebastes entomelas*	Scorpaenidae	Shelf	50	250	shelf	60	4	0.16	36	59	95000	1113000	2.87	11,35,48
Acadian redfish	*Sebastes fasciatus*	Scorpaenidae	Sec	130	500	shelf to slope	50	5	0.12	26	44	5200	70000	1.71	19,53
Yellowtail rockfish	*Sebastes flavidus*	Scorpaenidae	Shelf	50	250	shelf	64	6	0.17	40	66	56900	1993000	1.82	11,35,48
Golden redfish	*Sebastes marinus*	Scorpaenidae	Sec	100	1000	shelf to slope	60	10	0.09	38	100	50000	350000	1.08	53
Deepwater redfish	*Sebastes mentella*	Scorpaenidae	Sec	300	700	upper slope	75	11	0.08	26	50	5200	70000	0.78	53
Shortspine thornyhead	*Sebastoloblus alascanus*	Scorpaenidae	Anc	200	1500	upper slope	80	10	0.02	22	80	11906	1000000	0.94	16,29,31
Longspine thornyhead	*Sebastoloblus altivelis*	Scorpaenidae	Anc	500	1500	middle slope	45	16	0.07	21	39	17571	50000	0.61	16,29,31
Order Zeiiformes															
Black oreo	*Allocyttus niger*	Oreosomatidae	Anc	500	1300	middle slope	153	27	0.04	27	47	9000	62000	0.34	15,18,42
Smooth oreo	*Pseudocyttus maculatus*	Oreosomatidae	Anc	900	1100	middle slope	86	31	0.05	21	68	10000	84000	0.30	15,18,42
John dory	*Zeus faber*	Zeidae	Shelf	50	150	shelf	12	4	0.30	36	90		170000		19

1 *(Abookire 2006)*
2 *(Alekseyeva et al. 1993)*
3 *(Allain 1999)*
4 *(Allain 2001)*
5 *(Allain and Lorance 2000)*
6 *(Andrews et al. 1999)*
7 *(Andrews et al. 2009)*
8 *based on Zenopsis nebulosa*
9 *(Bilim et al. 1978)*
10 *(Burton et al. 1999)*
11 *(Cailliet et al. 2001)*
12 *(Clark et al. 1994)*
13 *(Clarke 2003)*
14 *(Cohen et al. 1990)*
15 *(Conroy and Pankhurst 1989)*
16 *(Cooper et al. 2005)*
17 *(Cooper et al. 2007)*
18 *(Doonan et al. 1997)*
19 *(Froese and Pauly 2008)*
20 *(Fossen and Bergstad 2006)*
21 *(Fossen et al. 2003)*
22 *(Gregg et al. 2006)*
23 *(Horn 2002)*
24 *(Hosie and Horton 1977)*
25 *(Humphreys 2000)*
26 *(Hunter et al. 1989)*
27 *(Hunter et al. 1990)*
28 *(Hunter et al. 1992)*
29 *(Jacobson and Vetter 1996)*
30 *(Khan 2006)*
31 *(Kline 1996)*
32 *(Laptikhovsky et al. 2008)*
33 *(Lehodey et al. 1997)*
34 *(Lorance et al. 2003)*
35 *(Love et al. 2002)*
36 *(McFarlane and Saunders 1997)*
37 *(Magnusson 2001)*
38 *(Marriott et al. 2003)*
39 *(Marriott et al. 2006)*
40 *(Martins and Haimovici 2000)*
41 *(Matsui et al. 1990)*
42 *(McMillan et al. 1997)*
43 *(Morales-Nin and Sena-Carvaalho 1996)*
44 *(Morley et al. 2004)*
45 *(Murua 2003)*
46 *(Neves et al. 2009)*
47 *(Nevinskii and Kozlov 2002)*
48 *(Pearson and Hightower 1991)*
49 *(Rideout and Morgan 2007)*
50 *(Rodgveller et al. 2010)*
51 *(Schmitt and Skud 1978)*
52 *(Schofield and Livingston 1998)*
53 *(St-Pierre and De Lafontaine 1995)*
54 *(Stares et al. 2007)*
55 *(Stein and Pearcy 1982)*
56 *(Thomas 1987)*
57 *(Tracey and Horn 1999)*
58 *(Tracey et al. 2000)*
59 *(Tuponogov et al. 2008)*



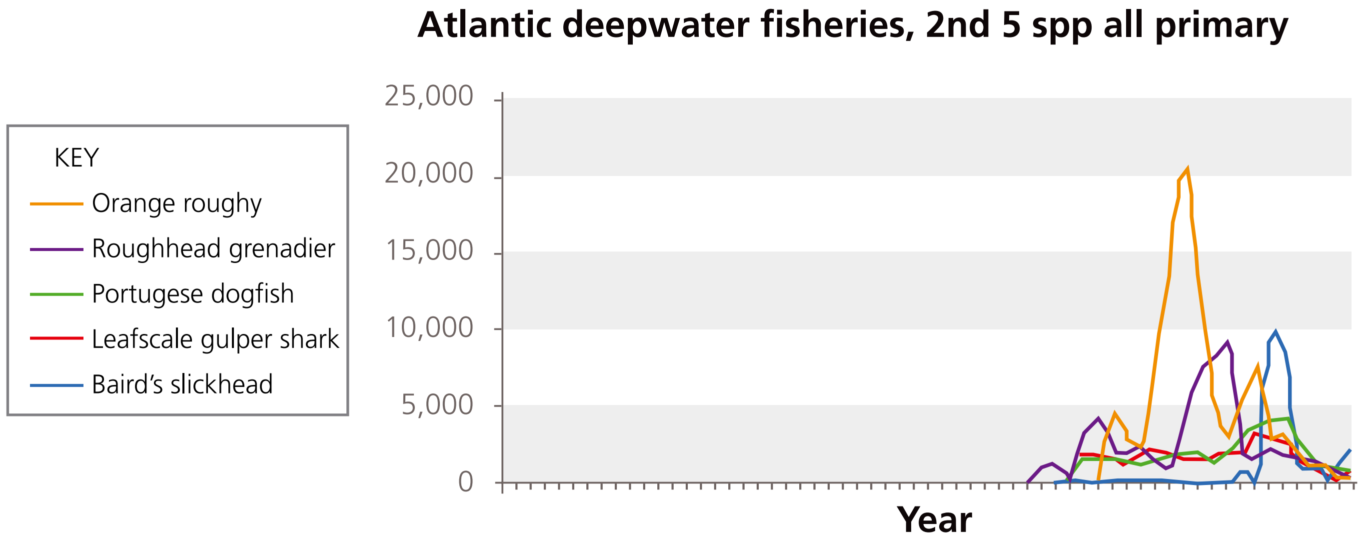


Figure 1. Times series of landings of major deep water fish stocks in the North Atlantic for A) secondary and B) ancestral deep-sea species. Note that in A) the ancestral roundnose grenadier is included.

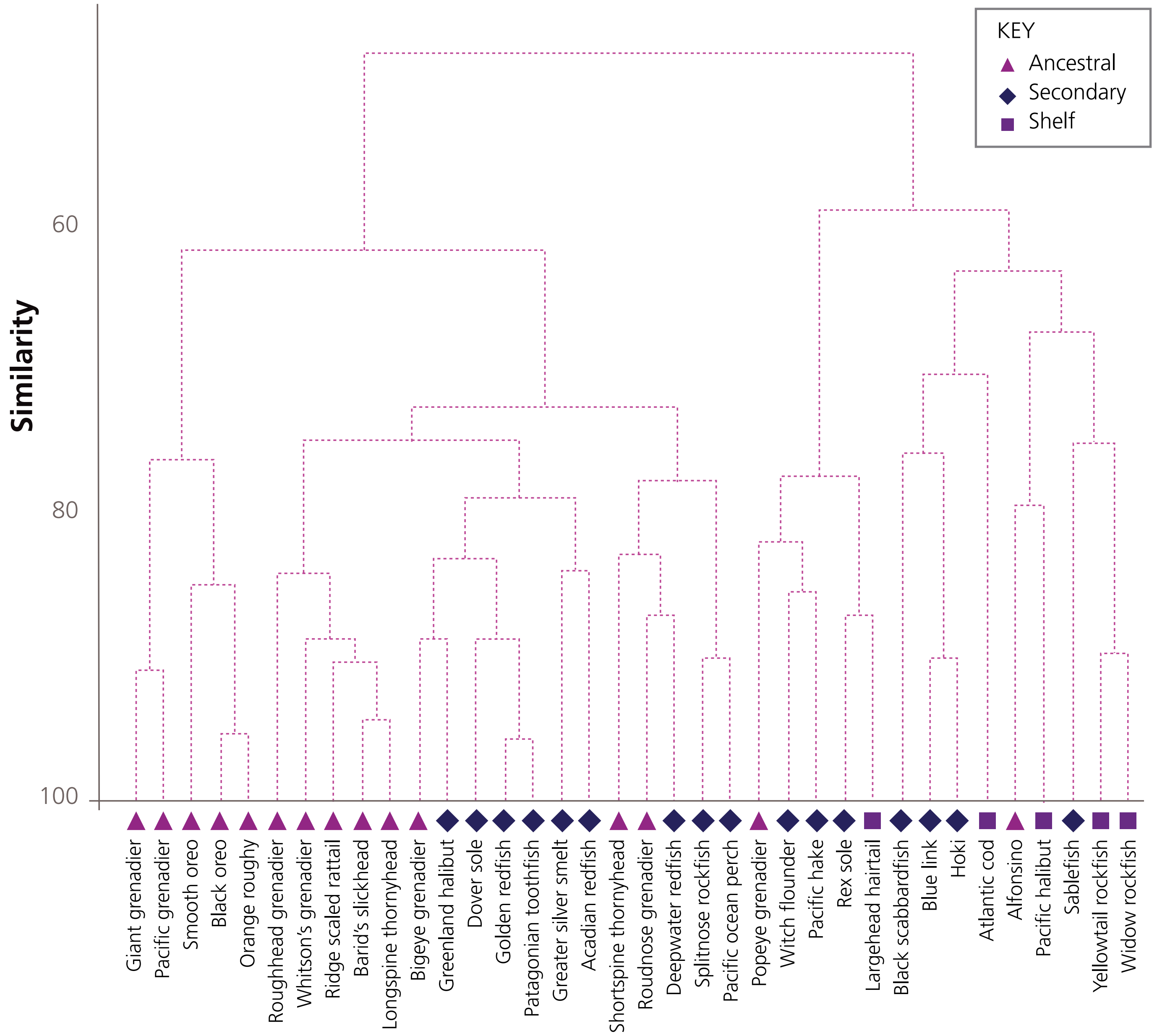
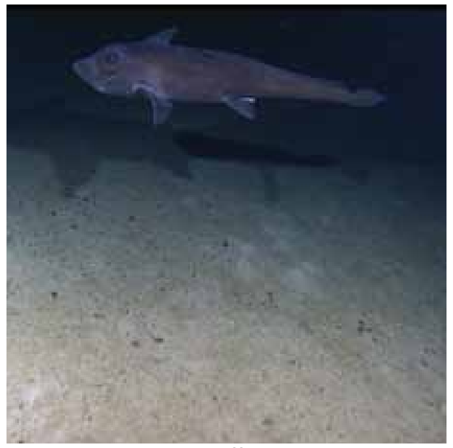


Figure 2. Cluster analysis of growth and fecundity variables. For each species the colored label corresponds to its phylogenetic affinity (green – from ancestral deep-sea group; blue – species that has secondarily evolved to live in the deep sea; red – species which are shelf living and come from shallow water families). Statistically significant groups are denoted by sharing red lines.


Chimaera, Hydrolagus pallidus


Chimaera, Hydrolagus affinis


Roundnose grenadier, Coryphenoides rupestris


Chimaera, Hydrolagus pallidus


False boarfish, Neocyttus helgae


Grenadier, Nezumia sp.

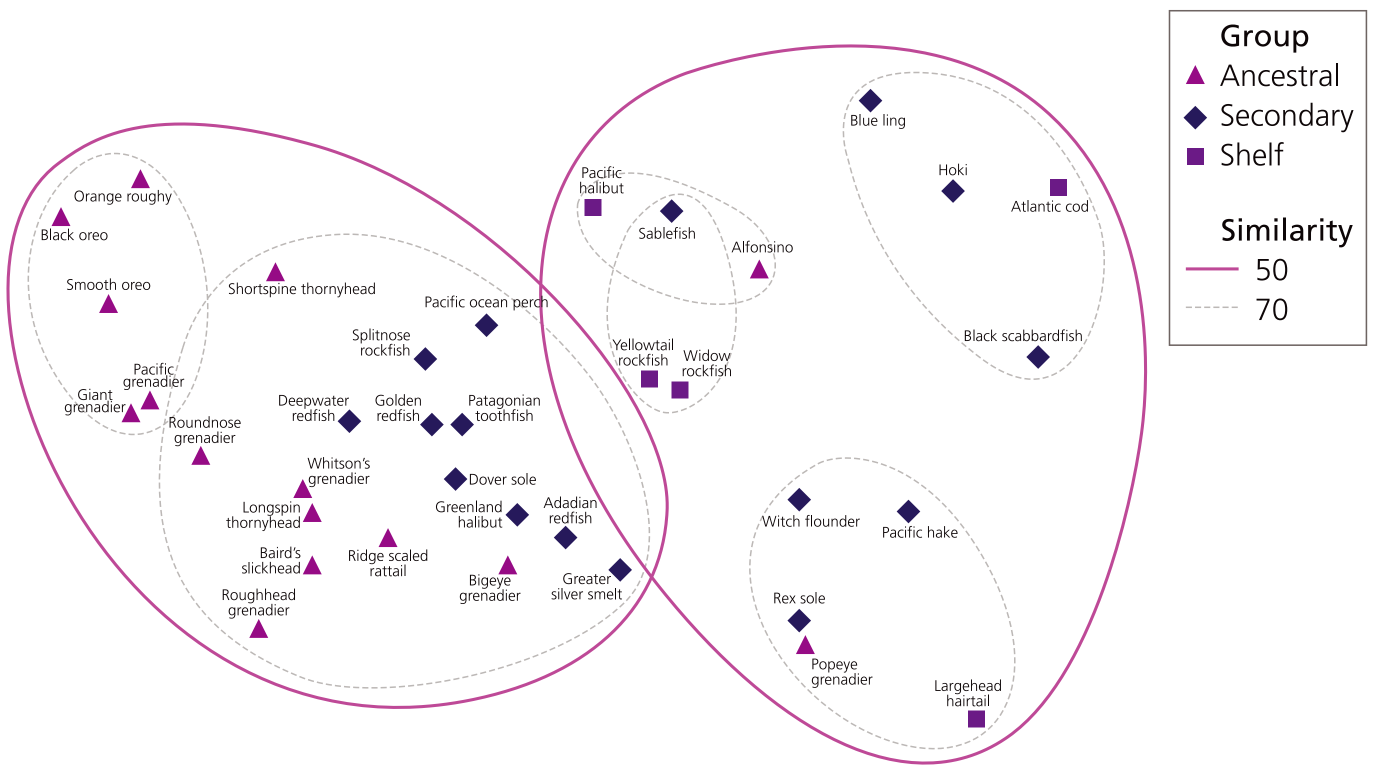


Figure 3. MDS analysis of growth and fecundity variables. Symbols as in Figure 2. The clusters shown are based on the cluster analysis in Figure 2. Thus the green cluster on the left and the blue and green cluster to its right represent the statistically significant clusters.

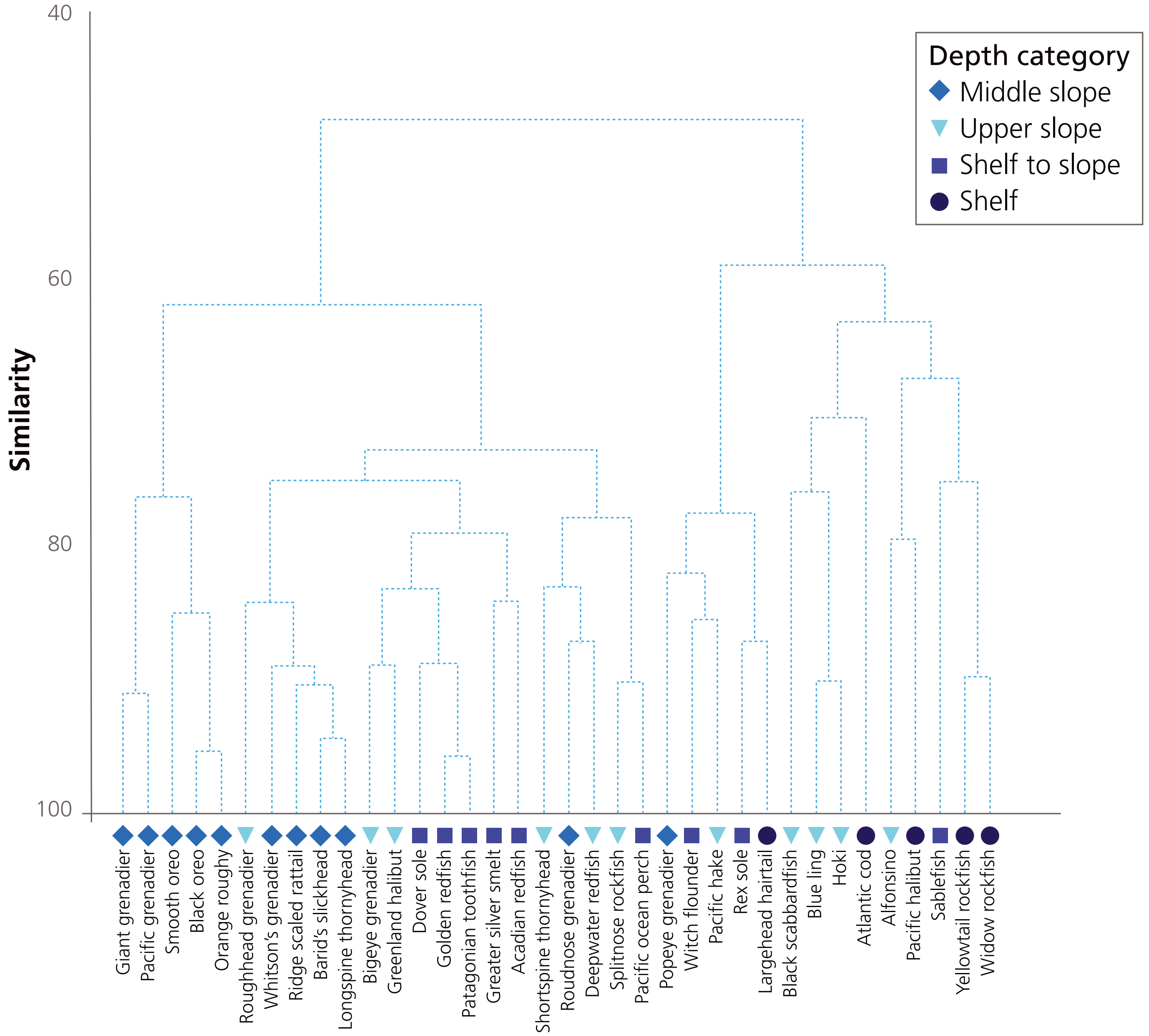
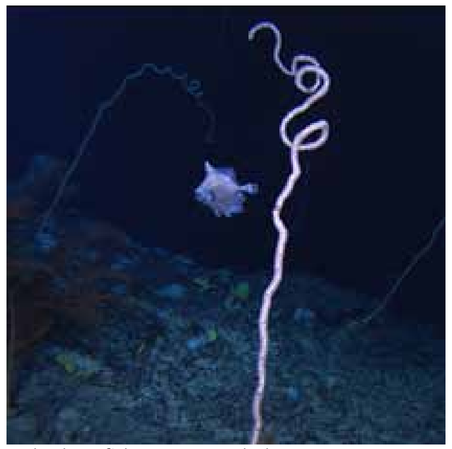


Figure 4. The same cluster analysis as in figure1 but labeled by depth category of each species.



False boarfish, Neocyttus helgae with bamboo whip

Hydrolagus pallidus

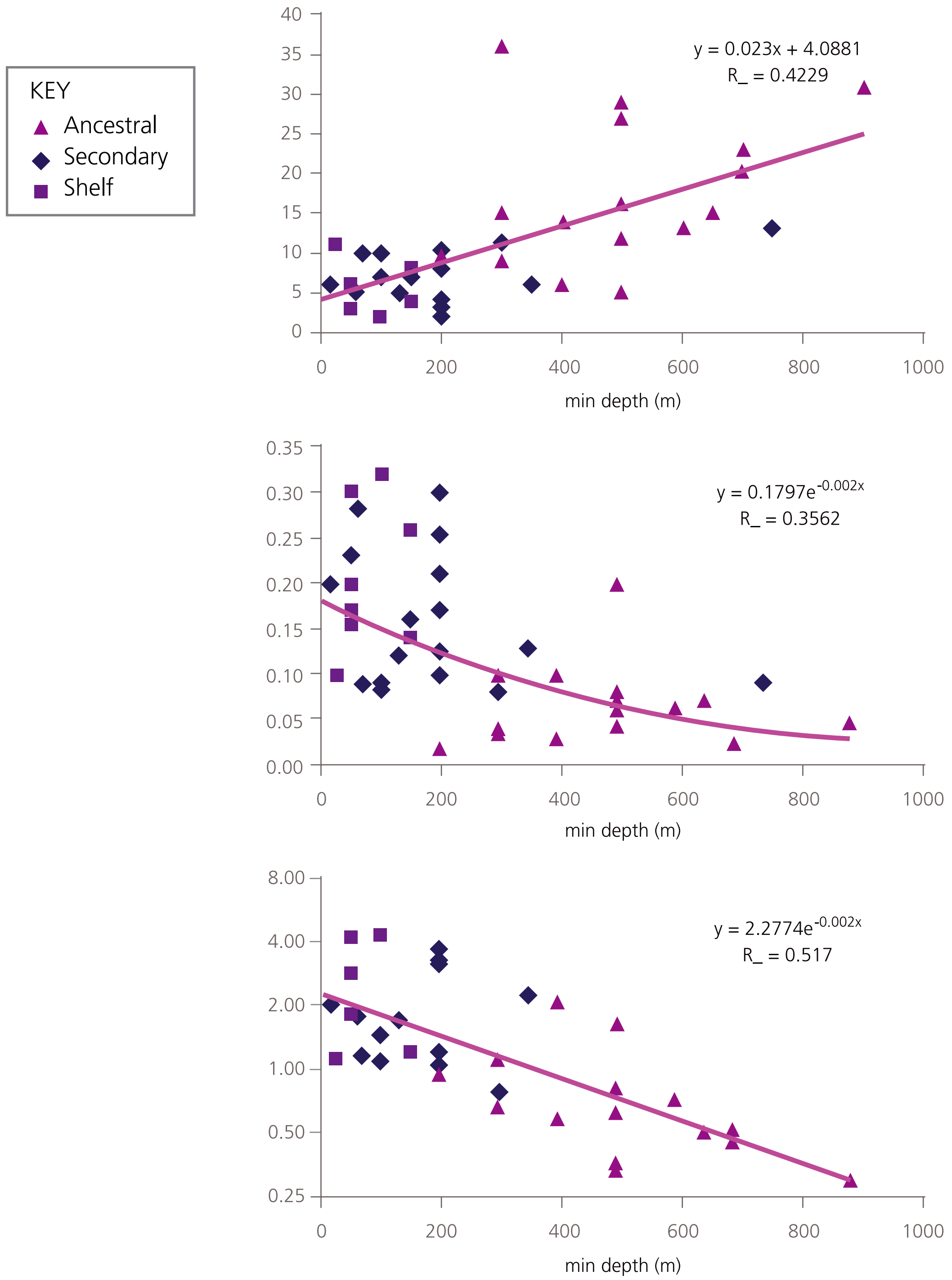
Muddy arrowtooth eel, Ilyophis brunneus

Ophidiid cusk eel, Lamprogrammus sp.

unidentified sea pen and shrimp

Enallopsammia sp.

Figure 5. Life history attributes as a function of minimum depth of occurrence.




unidentified sponges and black coral


unidentified sponge


comatulid crinoids on dead sponge

Discussion

The phylogenetic approach very broadly explains the groups generated using growth and reproductive variables. Ancient species group together and shelf species do too, but the fishes which have secondarily moved into the deep-sea are more problematic. Some are more similar to shelf species and others to ancient species in terms of productivity characteristics. The phylogenetic approach is confounded by covariation of basic evolutionary patterns and depth ranges. Most of the ancient species are the middle slope dwellers with a few on the upper slope (Figures 2 and 3). Secondary species generally do not live as deep (Zenkevitch and Birstein 1960). Grouping the fishes into depth zones does not perform any better than phylogeny to explain the clusters. Middle slope species tend to cluster together and so do the shelf species but there is a great mixing of species with different habitat depth preferences (Figure 4).

Depth of occurrence explains a great deal of the variability in life history attributes

Most studies have focused on comparing deep-sea to shelf species as groups (Koslow *et al*. 2000; Clarke 2003; Morato *et al*. 2006a; Drazen 2008) and have found the now well-documented distinctions in terms of longevity, time to maturity and natural mortality. Our analysis shows that if species are not grouped a priori, the they do not naturally fall into two clear groups but range along a continuum of life history attributes.

Depth of occurrence explains a great deal of the variability in life history attributes, specifically age at 50% maturity, growth rate, maximum fecundity and the potential rate of population increase (Figure 4). In the ocean the strongest environmental gradients exist across depth: pressure increases, light levels and temperature decrease, food availability and biomass decrease, and some areas have oxygen minimums at mid slope depths (Gage and Tyler 1991). Deep-sea fishes are adapted physiologically to these changes in a variety of ways (Somero and Hochachka 1984; Somero 1992; Seibel and Drazen 2007; Samerotte *et al*. 2007) and their life histories also should change as a result of depth-related gradients.

Several environmental factors could be responsible for patterns observed in life history attributes, including temperature (Russell *et al*. 1996; Clarke and Johnston 1999; Gillooly *et al*. 2001; Seibel and Drazen 2007), reduction in predation pressure as a consequence of reduced megafaunal density (Haedrich and Rowe 1977; Lampitt *et al*. 1986) and food availability. The latter has very clear affects on the growth rates of animals (Jobling 1982; Fonds *et al*. 1992; Persson and De Roos 2006), and we note that many secondary species display shallow minimum depths because of ontogenetic migration (i.e. sablefish; Jacobson *et al*. 2001); with access to food-rich shallow waters early in life those species grow and mature relatively quickly. Intraspecific fecundity varies with ration level in culture (Ma *et al*. 1998; Coward and Bromage 1999), and in the field between fish in good versus poor nutritional condition (Rideout *et al*. 2005; Rideout and Morgan 2007).

In our results growth rate and age at maturity showed strong trends with depth but longevity did not. Greater longevity has a variety of life history advantages such as longer reproductive lifespan and a more stable population structure (Musick 1999), both attributes of many deep-sea fishes. Cailliet *et al* (2001) did find a significant trend with longevity for rockfishes in the NE Pacific, but this is not surprising since rockfishes comprise a single coherent family as opposed to the 9 orders we examined.

Slow rates of growth may be the result of metabolic limitation. The metabolic rate of pelagic fishes declines exponentially by an order of magnitude with depth (Drazen and Seibel 2007). The data for demersal deep-sea fishes is sparse but for some groups such as macrourids and morids, deeper living species have up to a 10-fold reduction in metabolic rate compared to shallow water species. Data using metabolic enzyme activities as proxies of metabolic capacity show an exponential decline with increasing depth (Drazen and Seibel 2007; Drazen, unpub data). In other words the greatest change in metabolic capacity occurs between the shallowest living fishes and those that inhabit depths of 200-500m in a pattern similar to what we found for growth rate and potential rate of population increase. The visual interactions hypothesis states that reductions in metabolic capacity are linked with light levels and locomotory capacity rather than food supply (Childress 1995; Seibel and Drazen 2007).

Depth explains at most ~50% of the variation in the productivity variables so other important factors remain to be elucidated. Reproductive biology is often constrained by phylogeny as in sharks that produce few but very large advanced stage offspring (Musick 1999). Previous meta-analyses of deep-sea fish fecundity, one of the biological attributes we include in our analysis, have found variation between orders. Gadiformes typically have greater maximum fecundities than most other orders containing deep-living representatives (Merrett and Haedrich 1997).

All of the environmental factors mentioned could be important and act in concert. For fisheries managers the reasons for the declines in productivity with depth are perhaps not as important as the general trend. Past studies have repeatedly shown that deep-sea fishes are not as productive as species from the continental shelves (Moore 1999; Koslow *et al*. 2000; Roberts 2002; Devine *et al*. 2006; Morato *et al*. 2006b). By analyzing a suite of fishes from the shelves to the middle slope the present analysis has moved beyond simple dichotomies to show that depth of occurrence correlates with several life history attributes and the potential rate of population increase. The relationship suggests some level of predictive power in understanding the potential response of species to fishing pressure in the absence of detailed life history information. But this rule appears only generally true. Still the most effective management must of necessity be based on detailed knowledge of the particular characteristics of the species in question as well as a similar level of understanding for species involved incidentally in the fishery as bycatch.

Sustainability of deep-sea fisheries: Orange Roughy

Participants:
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ABSTRACT

In this report, the main challenges of managing orange roughy fisheries are outlined, as well as lessons learned that could be applied in the future to fisheries for this species (and others like it) which in some cases may allow for an ecologically sustainable, albeit limited, commercial fishery. The term ‘sustainable’ or ‘sustainable fishery’ in this context is defined as a fishery which meets the objectives established by the UN General Assembly and through the UN FAO with regard to the management of deep-sea fisheries in areas beyond national jurisdiction. We consider whether any orange roughy fisheries currently do, or could, satisfy the UN and FAO guidelines, and what characteristics these fisheries might have. We consider the nature and impact of the fishery, the management framework, and the ability of science to inform management. Where one or more of these components are lacking, we conclude that a sustainable fishery is not possible. There is potential for a sustainable orange roughy fishery; most likely one that exploits spawning aggregations on flat ground, with accompanying monitoring using acoustic methods, and catch limits set using a demonstrable robust harvest rule. Such fisheries are likely to be very few in number, and provide catches that are much lower than historical, including recent, levels.

SUSTAINABLE ORANGE ROUGHY FISHERIES

The orange roughy *(Hoplostethus atlanticus)* has many biological characteristics (e.g. high longevity, late age of maturity, slow growth, predictable aggregation behaviour) that generally suggest it as a poor candidate for sustainable commercial exploitation (Branch 2001; Clark 2001; Francis & Clark 2005). It is perhaps the best studied example of what can go wrong when such a species is commercially exploited, as borne out historically in a string of boom-and-bust fisheries worldwide (e.g., Branch 2001; Clark 2001; Lack *et al*. 2003; Paya *et al*. 2005; Sissenwine & Mace 2007; ICES 2010). That said, in a few locations, such as Chatham Rise New Zealand, the sheer numbers of individuals can provide the species with a certain amount of resilience to fisheries exploitation, because larger stocks prolong the fishery and so provide more time for the development of scientific research and fishery management (Sissenwine & Mace 2007). In such places, where there are large numbers of individuals, and where there is an existing management structure for assessment, monitoring, control and surveillance, it is conceivable that a small proportion could be taken from the biomass such that a fishery is both commercially and biologically sustainable. Historically, this has not happened, however. Surviving fisheries in their current form are almost all substantially depleted and are, or have been, ecologically damaging, requiring an alteration in both management and fishing practices.

The orange roughy (Hoplostethus atlanticus) has many biological characteristics (e.g. high longevity, late age of maturity, slow growth, predictable aggregation behaviour) that generally suggest it as a poor candidate for sustainable commercial exploitation

INTERNATIONAL POLICY CONTEXT DRIVING A CHANGE IN FISHING PRACTICES

The United Nations General Assembly over the past several years has responded to international concerns over the unsustainable nature of many deep-sea fisheries in the high seas, and the damage caused by bottom fishing to benthic biodiversity associated with seamounts, deep-sea corals and other types of ecosystems found in the deep-sea. As a result of a process of negotiation, involving both nations engaged in high seas bottom fisheries and those that are not, the General Assembly in 2006 agreed to a set of measures for the management of deep-sea fisheries in areas beyond national jurisdiction. This calls on States and regional fisheries management organizations (RFMOs) to protect deep-sea ecosystems from the harmful impacts of bottom fisheries through conducting prior impact assessments of bottom fisheries, manage the fisheries to prevent ‘significant adverse impacts’ to benthic and deep-sea ecosystems, close areas to fishing where vulnerable ecosystems are known or likely to occur unless harmful impacts of fishing in those areas could be prevented, and to ensure the long-term sustainability of the species targeted or taken as bycatch in these fisheries (UNGA 2007).

A set of International Guidelines for the Management of Deep-Sea Fisheries in the High Seas was subsequently negotiated under the auspices of the UN Food and Agriculture Organization (FAO), to elaborate a set of criteria for conducting impact assessments and provide more detailed guidance to States on the identification of vulnerable deep-sea ecosystems and species, and determining the level of impact from fishing (FAO 2009). The UN General Assembly endorsed these Guidelines in a resolution adopted in 2009 which both reinforced and strengthened the 2006 resolution (UNGA 2010). The measures and criteria set out in both the UN General Assembly resolutions and the UN FAO Guidelines both fall within the context of the general principles for fisheries conservation and management and the application of the precautionary approach established under international law, in particular the 1995 UN Fish Stocks Agreement. The UN Fish Stocks Agreement establishes a number of obligations for the management of fisheries (for so-called straddling stocks and highly migratory fish stocks), including a requirement to assess the impacts of fishing on target stocks and other species belonging to the same ecosystem, minimize the impacts of fishing on associated or dependent species, in particular endangered species, prevent or eliminate overfishing, and protect habitats of special concern (UN FSA 1995).

The orange roughy aggregations discovered in the North Atlantic have been in areas usually associated with seamounts or other topographical features (e.g. pinnacles or slopes), and have also been found on the flat grounds of the continental slope (ICES 2010). Although there may be wide-scale low level mixing of orange roughy populations (White *et al*. 2009), it is unknown whether or not these aggregations represent independent stocks, although it is known that these features have historically been sequentially depleted by the fishery (ICES 2010).

The northeast Atlantic has supported the largest orange roughy fishery in the northern hemisphere. In the late 1980s, catches of many deep-water species, including orange roughy, increased in the northeast Atlantic (Gordon *et al*. 2003). Since the early 1990s about 37 000 t of orange roughy have been landed in total, about 80% from ICES subareas VI and VII, and most by French trawlers. In 2003, a catch quota of 88 t was introduced for orange roughy in Sub-area VI, and this remained until 2006. After the virtual collapse of the fishery in the ICES subarea VI, the main fishery moved to Subarea VII, before this was closed in 2008. In addition to a catch quota, a number of orange roughy protection areas were introduced in 2005 (ICES 2010). These included areas around the Azores where an exploratory survey had indicated high catch rates could be made (Melo & Menezes 2002).

Little or no fisheries-independent data exist on which to determine abundance, length and age composition, or recruitment (ICES 2010). Most of the existing data were obtained from the commercial fishery and from fishery observers, and mainly collected before 2008. The data describe the geographical distribution of the catch, fish length distributions, and catch and effort data mainly for the French fleet. New fish length frequency data were made available to ICES in 2010 from the Irish and Scottish deepwater trawl surveys, sampling flat grounds along the continental slope in areas VI and VII from 2006 to 2009 (ICES 2010). Data on age composition and maturity were obtained from commercial trawlers operating on the Porcupine Bank in 2003, 2004 and 2005 (ICES 2010). These recent data have not yet been used for quantitative stock assessment (ICES 2010), the key input to which is a credible relative biomass index or absolute biomass estimate.

ICES assessments for orange roughy have relied on time-series of catch-per-unit-effort (CPUE) from commercial fisheries. Both Shaefer production and Delury depletion stock assessment models have been applied for ICES Subarea VI and VII (ICES 2010). Both methods estimated a pre-fishery stock biomass (the carrying capacity; K) of about 6000 t (95% confidence limits; 5500–7300 t). Stock biomass in 1998 was estimated to be about 1800 t; i.e. 30% of the carrying capacity. The maximum sustainable yield (MSY) was estimated to be about 300 t (95 % confidence limits; 100–480 t), and therefore about 5% of carrying capacity. The biomass estimates, combined with a history of rapid and sequential depletion of local aggregations, and the comparatively low total catch from the fishery, indicates that the natural abundance of orange roughy in the Northeast Atlantic is much lower than found in Australian and New Zealand waters. Efforts to find orange roughy aggregations in the North Atlantic, comparable to the ones found in the Southern Hemisphere, have not been successful (Merret & Haedrich, 1997). According to ICES (2010) there are many areas of the Mid-Atlantic Ridge where aggregations of this species occur, although there are no estimates of biomass. The terrain of the Mid-Atlantic Ridge is very difficult for trawlers, which may have precluded the development of orange roughy fisheries in this area.

In 2010, the ICES deepwater working group reported that "….due to its very low productivity, orange roughy can only sustain very low rates of exploitation. Currently, it is not possible to manage a sustainable fishery for this species." The working group also recommended "..no directed fisheries for this species, and bycatches in mixed fisheries should be as low as possible. […] Management measures should be developed to ensure that there is no bycatch of this species."

At present, orange roughy catches are not allowed in the Northeast Atlantic in all ICES areas (catch quotas are zero), except in one of the North East Atlantic Fisheries Commission's (NEAFC) regulatory areas encompassing the international waters south of Iceland, but restricted to vessels of NEAFC Contracting Parties having participated in fishery for orange roughy in the NEAFC Regulatory Area in areas other than V, VI and VII prior to 2005. However the annual total catches of any Contracting Party shall not exceed 150 tonnes (NEAFC 2010).

Problems with orange roughy fisheries

ECONOMICS

Economic sustainability of any fishery hinges on balancing the costs of fishing and the costs of management against the size and value of the total catch commensurate with the long-term biological sustainability of the stocks.

Orange roughy stocks are often far offshore, and provide the best fishing opportunities during winter (when spawning aggregations form) when seas can be rough, and therefore they are typically fished using vessels which are relatively large and expensive to operate (trawlers and factory trawlers). The global orange roughy fishery has been characterized by a series of boom-and-bust fisheries and, as a result, there is generally an overcapacity to fish whatever stocks remain. Other species that can be targeted by the orange roughy vessels are also prone to overexploitation, e.g. oreos, southern boarfish, alfonsino, cardinalfish, bluenose (Clark *et al*. 2007). Preferred options on how this capacity can be reduced will vary from jurisdiction to jurisdiction, including high seas regions under different RFMOs, but will not be discussed here.

Different management approaches will affect the costs of assessing the fish stocks, as well as the costs of monitoring, control and surveillance (MCS) required to ensure compliance. Even in the best case scenarios, long term catches of species such as orange roughy, which exhibit the classic characteristics of many unproductive deep sea species, will be limited to small proportions of the total biomass. Hence, even more so than in continental shelf fisheries, there is a need to seek out MCS options that are both relatively inexpensive and that ensure robust long term ecological sustainability (discussed below). The remoteness of deep sea fisheries can make MCS an especially challenging problem, and in some cases this cost factor alone may not justify assessing or managing a given fish stock.

The ecological sustainability of prosecuting orange roughy fisheries will depend upon finding strategies to keep target populations at biologically sustainable levels, whilst minimizing damage to habitat and other species

ECOLOGICAL SUSTAINABILITY

The ecological sustainability of prosecuting orange roughy fisheries will depend upon finding strategies to keep target populations at biologically sustainable levels, whilst minimizing damage to habitat and other species; in particular, preventing significant adverse impacts to Vulnerable Marine Ecosystems (VMEs) and threatened species. Additionally, likely wider interactions from fishing orange roughy should be factored in (e.g., the effects via the food web to other species). Each sub-section below considers these elements in greater detail.

Managing orange roughy stocks at biologically sustainable levels

The basic data requirements to ensure the long-term biological sustainability of a fish stock are: 1) knowledge of the catch, 2) knowledge of the production potential, and 3) an ability to evaluate and monitor the stock biomass. For orange roughly, these have generally been difficult to accurately estimate and hence have hampered stock assessments based on conventional approaches. Below we explain some of the issues that have been encountered to date, and outline an alternative approach.

KNOWLEDGE OF THE CATCH

The most basic information required is knowledge of the catch, including both the landings and the discards. Catch information must be associated with data on fishing effort and its location. This requires rigorous MCS. Knowledge of historical catches is relatively poor for the high seas and northeast Atlantic (Box 1), and relatively good for areas such as Australia and New Zealand (Ministry of Fisheries 2010), even though some catch misreporting does still occur (e.g., Ministry of Fisheries 2007). FAO catch reporting is on too large a spatial scale relative to the localised distribution of orange roughy stocks and fishing grounds. Hence to enable effective stock assessment, detailed tow by tow records need to be kept by national and RFMO agencies.

KNOWLEDGE OF THE PRODUCTION POTENTIAL

The production potential of orange roughy stocks is known to be especially low (e.g., Branch 2001; Clark 2001; Francis & Clark 2005; Sissenwine & Mace 2007). A low average level of recruitment relative to stock size is a consequence of high longevity, and orange roughy is probably the longest living commercially exploited marine fish found to date (Andrews *et al*., 2009; Clark 2009). The relatively slow individual growth rate and late maturity of orange roughy means that stock dynamics are slow, and any recruitment or growth compensation as a result of stock depletion may not be observed for several decades (Clark & Tracey 1994; Clark *et al*. 2000; Hilborn 2010). High longevity may be an adaptation to infrequent favourable conditions for reproduction, leading to highly intermittent recruitment (Longhurst 2002; Francis & Clark 2005). Nevertheless, fishing for orange roughy is relatively easy because they form predictable aggregations that are vulnerable to trawlers (Clark 1999; Branch 2001). The aggregating behaviour of orange roughy may lead to hyperstability of catch rates, where good catch rates are maintained, potentially along with a perception that the stock is not at risk, despite low stock levels or continued stock decline (Harley *et al*. 2001). The combination of high vulnerability, and especially low and uncertain productivity and slow stock response times, is what has made management of orange roughy stocks especially difficult (Sissenwine & Mace 2007; Clark 2009).

The largest and most persistent orange roughy fisheries in the world have taken place around New Zealand. In New Zealand, stock assessment models with what was thought to be suitably low and deterministic productivity assumptions have predicted biomass rebuilds following catch reductions that have failed to happen (e.g., Field & Francis 2001; Dunn 2007a,b; Sissenwine & Mace 2007; Ministry of Fisheries 2010). Instead, the biomass indices for these stocks have remained low or continued to decline, indicating the assumed productivity was too high, or that the assumption of deterministic recruitment was incorrect. The deterministic recruitment assumption was simply used because of a lack of convincing information to the contrary (Francis & Clark 2005; Francis 2006). Knowledge of recruitment variability remains poor for orange roughy because of the low precision of age estimates, a consequence of the difficulty in interpreting growth zones on otoliths (Francis 2006; Andrews *et al*. 2009). As a result, ageing studies have been few and of limited use, and it is not clear whether highly intermittent recruitment events take place. Extended periods of low recruitment are quite possible, and fisheries could therefore develop and deplete a stock in between recruitment events (Longhurst 2002; Francis & Clark 2005). In the gaps between recruitment events, average recruitment (productivity) would be lower than expected, and as a result, intermittent recruitment is perhaps the most obvious explanation for the failure of models to fit the observations (although others exist). The risk of recruitment overfishing, as a result of targeting and substantial depletion of spawning plumes during the early years of many fisheries, has not yet been confronted because of the high age of recruitment relative to the short history of the fisheries, but remains an obvious possibility (Francis & Clark 2005; Dunn 2007a). Indeed, recent trawl surveys have suggested there may be imminent recruitment failure for the largest and most persistent orange roughy stock, on east and south Chatham Rise, that would have originated from about the time the spawning plumes were initially fished down (Dunn *et al*. 2008; Ministry of Fisheries 2010). Knowledge of individual fish growth is reasonably good for orange roughy (Tracey & Horn 1999), such that growth overfishing is less of a concern.

Experience has shown that caution is needed when estimating stock status from models that assume deterministic recruitment, as they could overestimate recruitment levels, and therefore predict a slower decline in stock size than actually occurs

Experience has shown that caution is needed when estimating stock status from models that assume deterministic recruitment, as they could overestimate recruitment levels, and therefore predict a slower decline in stock size than actually occurs. Therefore, if a deterministic recruitment assumption is used, then an attempt must

be made to validate that assumption. Previous stock assessment models using un-validated deterministic recruitment assumptions should be treated with caution (Hilborn *et al*. 2006). Understanding the true nature of orange roughy recruitment variability is only likely with long-term monitoring of pre-recruits, for example using annual trawl surveys, or with large improvements in ageing precision (Francis & Clark 2005). In the interim, fishery management strategies should be employed which are robust to getting the productivity assumptions wrong.

The veracity of a given stock monitoring method depends on the behaviour of the fishes, the habitat, and the survey technique used

ABILITY TO MONITOR THE STOCK BIOMASS

The veracity of a given stock monitoring method depends on the behaviour of the fishes, the habitat, and the survey technique used (Clark 1996; Branch 2001, Clark 2005). Orange roughy occur in a variety of deep sea habitats. Around New Zealand, juveniles are most abundant on flat areas of the continental shelf, and tend to occur in low densities, shallower than the adults (Dunn *et al*. 2009). It is possible that juveniles may occur deeper than the adults in the North Atlantic (Shephard *et al*. 2007). Adults are also found dispersed in low densities on flat areas, but also form aggregations near underwater features, such as seamounts, hills, ridges and canyons (Clark 1999; Branch 2001). Winter spawning aggregations, known as “plumes”, have been found in association with seamounts and other features, and on flat areas of the continental slope. Spawning plumes are usually relatively predictable, stable, and large monospecific aggregations. These characteristics make spawning plumes amenable to acoustic surveying, when done using methods to estimate relative biomass, or with knowledge of fish acoustic target strength, to estimate absolute spawning biomass. Sources of variability and bias in the acoustic technique, from the assumed target strength (Branch 2001; Ryan *et al*., 2009), the mix of species (McClatchie & Coombs 2005), and the extent of the acoustic dead zone (Ona & Mitson 1996), are minimized for spawning plumes on flat ground, although remain a substantial problem for aggregations over hills and other features. Problems associated with species mix are so great for dispersed orange roughy on flat grounds that such surveys are not credible (Clark 2005).

The main problems for acoustic surveys of aggregations over hills are the substantial acoustic dead zone, within which fish cannot be seen acoustically, and a greater potential for dense aggregations of more than one species (Tracey *et al*. 2004). The acoustic dead zone can be reduced by using acoustic systems towed at depth rather than mounted on the ship’s hull (Branch 2001; Clark 2005). Species mix on features cannot necessarily be sampled reliably using trawls because of the variable species catchability and often limited tow paths available over rough ground, but multifrequency acoustic techniques (Kloser *et al*. 2002) and moored camera systems (O’Driscoll, NIWA, pers.comm.) offer potentially less biased estimates. For dispersed orange roughy aggregated over features, further developments in technology, and in the understanding of orange roughy behaviour, are required to achieve biomass estimates that are credible and precise enough for reliable stock monitoring.

Off Namibia, it has been observed that differences in acoustic spawning plume biomass estimates from a fishing ground between years could not be accounted for by the commercial catch, and it was hypothesised that the spawning aggregations form only intermittently or were disturbed by fishing, with fish returning to spawn in some years but not others (e.g., Butterworth & Brandao 2005). In this situation, acoustic surveys of spawning plumes will not track stock biomass. A time series of surveys, and/or additional wide-area surveys, are then required to understand the occurrence of spawning aggregations.

Egg production surveys to estimate spawning biomass were attempted in Australia and New Zealand, but have proven unreliable, and were abandoned (Branch 2001, Clark 2005). Research trawl surveys are not suitable for monitoring aggregated biomass, where catches may be hit-or-miss and gear saturation can occur, but are suitable for monitoring the relative abundance of dispersed fish on flat grounds (Clark

1996). Trawl surveys are potentially unreliable on features, because of the variability in trawl performance caused by the rough ground. Commercial catch-per-unit-effort (CPUE) requires minimal research cost and is often used as a biomass index, but suffers similar problems to research trawl surveys, with short tows, large catches, and gear saturation. Commercial CPUE is also much more susceptible to spatial and temporal bias (Dunn *et al*. in press). Changes in CPUE can give an indication of the general changes and trends in abundance, but are not reliable or sufficiently robust to uncertainty to be recommended as a primary method for monitoring stock biomass for use in stock assessments (e.g., Dunn *et al*. in press).

Due to the issues outlined above, a time-series of surveys combining acoustic and trawl survey components currently offers the most robust monitoring method, where the absolute biomass of aggregations over flat grounds is measured using acoustics, and a trawl survey is used to monitor relative abundance in surrounding areas. The latter is important to verify that fluctuations in the aggregation biomass are not caused by changes in the distribution of the fish (e.g., related to changes in the timing of the aggregation, or changes in the proportion in the aggregation). Such surveys would have to take place over a relatively short time period, such that biases caused by fish movement are minimised. This would be easiest if the aggregations formed in the same place and at the same time every year: as a result, the surveys would best be completed on spawning plumes. The fisheries on many stocks have increasingly focused on spawning plumes following depletion, as these provide the best catch rates (Anderson & Dunn 2008). As a result, it might be practical to complete such surveys from industry vessels in between (or preferably prior to) commercially fishing (O'Driscoll & Macaulay 2005).

AN ALTERNATIVE QUOTA ASSESSMENT APPROACH

The standard approach to providing scientific advice on catch limits for orange roughy stocks has used population models fitted to observed data, to estimate unfished and current biomass, and sustainable yields (e.g., McAllister & Kirchener 2001; Wayte & Bax 2007; ICES 2010; Ministry of Fisheries 2010). However, as described above, recent experience with age-structured models in New Zealand has found a deterministic recruitment assumption is not reliable. Further, models assuming stochastic recruitment have often provided poor fits to the (admittedly uncertain; Francis 2006) age frequency observations (e.g., Dunn 2005, 2006; Wayte & Bax 2007).

The acoustic estimation of absolute biomass of orange roughy spawning plumes allows the application of an alternative, simple, and transparent assessment and management approach, where the catch limits are set at an agreed proportion of the current estimated absolute biomass. Although it comes with scientific uncertainties of its own, this approach has shown itself to be more readily understood and accepted by the fishing industry in New Zealand, allowing for potentially better adaptive management. Previous stock assessments were complex and harder to understand and explain (Hilborn 2003), and so generally faced greater opposition, especially when numbers were continually being revised and catch quotas reduced.

Under this alternative paradigm, the catch quota is set as some proportion of the current estimated mature (or spawning) biomass. For the East and South Chatham Rise stock off New Zealand, since 2008-09 the target catch limit has been set at the natural mortality rate (M) multiplied by an estimate of recent absolute mature biomass (i.e., setting fishing mortality, F, equal to M) (Ministry of Fisheries 2010). The mature biomass is the spawning plume absolute biomass, as estimated from acoustic surveys, with an allowance added for spawning fish outside of the main plume, scaled up to allow for a proportion of non-spawning adults. The benefits of this approach are a relatively transparent science and management process, in that the acoustic survey has a clear and direct link to the catch quota, and that the burden of proof is reversed, in that catch increases can only occur if the biomass is estimated to have increased, based on actual survey data. Key uncertainties in this method concern the estimate of spawning biomass itself, particularly the fish target strength, the allowance for fish outside of the plume (spawning and non-spawning), and the validity of the harvest rule; i.e. the proportion of the observed biomass that is allocated to the catch quota. The efficacy of the harvest rule might be tested through Management Strategy Evaluation (MSE) simulations (Butterworth & Punt 1999, Sainsbury *et al*., 2000). In an MSE, a range of potential management rules would be evaluated using a range of population models ("operating models": having a range of assumptions, e.g., different recruitment schedules, or intermittent spawning aggregation behaviours, or different levels of stock depletion), given the likely errors and biases in the monitoring method, and performance measured against set criteria (e.g., catch size, stock size, rebuild rate). This process would not rely upon a single operating model that has been convincingly fitted to real observational data (especially as few, if any, exist), but would use simulations that deliberately included some extreme cases. The MSE would aim to determine which harvest rule performed best across the range of operating models.

Whilst this assessment and management paradigm still provides scientific challenges, it would be simpler and more transparent than the prevalent stock assessment model paradigm, and could allow a fishery management system consisting of relatively robust stock monitoring, with catch limits set using a management rule demonstrated to produce sustainable fisheries despite uncertainties. One potential problem is variable catch limits as a result of varying biomass estimates, but the harvest rules evaluated via MSE might specify a maximum rate and frequency of change for the catch limits. The paradigm shows promise, and has been applied in the main New Zealand stock on the East and South Chatham Rise since 2008–09 (Ministry of Fisheries 2010). However, it still needs to be fully evaluated and proven as a suitable management technique.

Managing the impact on benthic habitat

We have identified spawning plumes above flat grounds as being easiest to monitor scientifically. On the flat areas where these plumes occur, the bottom habitat may be less likely to harbour vulnerable marine ecosystems (VMEs) than would seamounts or other underwater features (Rowden *et al*. 2010). Because of a pronounced "dive flight" behaviour in response to potential threats by orange roughy, it is almost always necessary to trawl on the seabed. Although fishing with midwater trawls through large spawning plumes on Chatham Rise has been successful, with large catches taken up to 40 m above the seabed (Clark 1995), this has only been done during one survey and midwater trawling is not currently used for commercial orange roughy fishing. It would therefore appear that orange roughy cannot be currently fished with alternative gears that would have minimal or no contact with the seabed. If the fishery only targeted the spawning plumes, the high catch rates achieved when fishing on large aggregations would allow bottom contact time by the trawl gear to be minimized. Fishery independent, prior bottom impact assessments would be required to ensure that VMEs did not occur in the areas or that, if they did occur, the fishery could be managed to prevent significant adverse impacts on VMEs (e.g. spatial restrictions on the areas open to fishing, and/or the direction or duration of the tows in relation to contact with the seabed).

It would therefore appear that orange roughy cannot be currently fished with alternative gears that would have minimal or no contact with the seabed

Managing impacts on non-target species

Some orange roughy may be caught as part of a mixed species fishery, where the additional target species may include, for example, alfonsino (Beryx spp.), cardinalfish (*Epigonus telescopus*), or deep-sea oreos (Oreostomatidae). A fishery targeting orange roughy spawning plumes, however, would only target orange roughy at that time, and in such a fishery we would expect the bycatch of other species to be low (Anderson 2009). Despite the low bycatch, where this bycatch consisted of species with biological characteristics which made them highly vulnerable to fishing induced mortality (e.g. deep-sea sharks), the impact of the catch would need to be assessed, and reduced or eliminated altogether. To achieve this, temporal or spatial restrictions on the extent of the fishery may need to be applied, e.g. prohibiting the fishery in specific locations or times where highly vulnerable species are known to occur, and/or establishing a trigger mechanism which requires a vessel to cease fishing when a certain level of bycatch species is caught, and/or establishing an overall vulnerable bycatch limit which would apply to all vessels fishing in a given biogeographic region.

Minimizing trophic level perturbations/ deep-sea community structure

It is reasonable to assume that a widespread and (originally) abundant species such as orange roughy played a widespread and important role in the food webs of a given bioregion (Rosecchi *et al*., 1988; Bulman & Koslow 1992). However, there is little research to elaborate upon or revise this assumption, because fish stocks in most areas were depleted before such studies could begin. It would appear reasonable to assume that if a biologically sustainable catch level (one that was robust to the uncertainties of orange roughy life history) was correctly ascertained, then it would probably be small relative to the stock biomass, such that the associated trophic effects might be absorbed by the bioregional ecosystem without significant adverse impact. However, in the case of orange roughy stocks that have been substantially depleted, it is reasonable to expect that significant adverse impacts are likely to have already occurred to the wider ecological community, and the productivity of the orange roughy stock may have been modified. Rebuilding the orange roughy stock would benefit not only the fishery, but also its associated ecological communities.

Characteristics of a sustainable orange roughy fishery

Orange roughy fisheries generally fall into one of four variations: fisheries on persistent aggregations on features; fisheries on small or transient aggregations on features; fisheries on dispersed orange roughy on flat grounds; or fisheries on spawning aggregations on flat ground. As outlined above, to sustainably manage the fishery, it will be necessary to properly estimate the spawning or stock biomass. However, as we discuss below, currently only one, or potentially two, of these four fishery variations lends itself to such measurement.

PERSISTENT AGGREGATIONS ON TOPOGRAPHIC FEATURES

Some orange roughy fisheries on seamounts, hills and other features have quickly crashed while others have lasted for many years, indicating in the latter case that persistent aggregations have occurred (e.g., Anderson & Dunn 2008; Wayte & Bax 2007). Reliably estimating absolute orange roughy biomass above hills, with a reasonable degree of certainty, has not been possible to date. Until better technology becomes available, sustainable catches cannot be accurately estimated, and as a result such fisheries cannot be easily deemed sustainable unless a highly precautionary approach is taken. If the biomass could be reliably estimated, an environmental impact assessment would still be required to identify VMEs, as the incidence of VMEs on such features is likely to be higher (Rogers *et al*. 2008; Clark 2009), which should then need to be protected. Whether a fishery would be allowed to persist on areas previously impacted, or whether such areas would be closed to allow recovery, would likely need to be determined on a case-by-case basis. However, recovery of the benthos on seamounts after fishing is likely to be a slow process, at least of the order of decades (Williams *et al*. 2010). An example of a potentially sustainable fishery on an aggregation is that on Cascade Plateau, Australia, where vessels target spawning aggregations over a large rocky seamount (Wayte & Bax 2007). The Cascade fishery has persisted since 1990, and although monitoring remains problematic, the stock biomass in 2009 was estimated to be about 64% of pre-fishery levels (S.Wayte, pers.comm.). The Cascade Plateau may have avoided overexploitation because the aggregation was reasonably large (the pre-fishery biomass would have been 30,000 t or larger; Wayte & Bax 2007), the area is offshore, rough and difficult to fish, the aggregations have not always been predictable and, in particular, the catches were restricted from the early days of the fishery.

Many orange roughy fisheries, such as those on high seas seamounts and other features, have shown strong patterns of sequential fishing and depletion

SMALL OR TRANSIENT AGGREGATIONS ON TOPOGRAPHIC FEATURES

Many orange roughy fisheries, such as those on high seas seamounts and other features, have shown strong patterns of sequential fishing and depletion (Clark *et al*., 2010), which is an indication that large and persistent aggregations of orange roughy were not found; i.e. that these aggregations have been small and perhaps transient. The absence of a persistent large aggregation precludes the regular direct measurement of absolute biomass, and therefore precludes the best possibility of ensuring a sustainable fishery. The sequential depletion of aggregations on features effectively precludes the use of CPUE as a reliable stock biomass index (Clark *et al*., 2010), and to date no fishery-independent biomass estimates have been made for fisheries on the high seas; as a result, the status of the high seas orange roughy fisheries remains unknown. Sequential fishing of features is also known for several other orange roughy fisheries, including the non-spawning component of fisheries for the many orange roughy stocks (e.g., Clark 1999; Anderson & Dunn 2008; ICES 2010; Mormede 2010). The occurrence of VMEs on topographic features is likely to be relatively high (e.g., Tittensor *et al*. 2009), and combined with the practice of sequential fishing of features, this is likely to result in substantial benthic and ecosystem impacts over the life of the fishery (e.g., Althaus *et al*. 2009, Clark & Rowden 2009). Fisheries on small or transient aggregations on topographic features, therefore, cannot be considered sustainable.

DISPERSED STOCKS ON FLAT GROUND

Fisheries on dispersed orange roughy on flat grounds have occurred, but only after the associated aggregations were substantially depleted (e.g., Clark & Tracey 1994). These fisheries are likely to be economically suboptimal. The absolute biomass of widely dispersed orange roughy on flat grounds cannot be measured with a reasonable degree of certainty, but credible relative biomass estimates are possible from trawl surveys. Monitoring of the stock would therefore be possible. Nevertheless, the longer trawl tows needed to achieve reasonable commercial catches could have high benthic and ecosystem impacts (particularly bycatch) relative to the amount of orange roughy caught. Because of the substantial ecosystem impact of such a fishery, it cannot be considered ecologically sustainable.

SPAWNING AGGREGATIONS ON FLAT GROUND

Fisheries on spawning aggregations on flat ground provide the best opportunity for sustainable fisheries. Credible estimates of absolute spawning biomass are possible, although estimating mature biomass does present problems. Therefore, an assessment and management paradigm that was informed by spawning rather than mature biomass estimates would be most credible. A fishery targeting spawning aggregations on flat ground would achieve high catch rates, minimising bottom contact, with minimal bycatch. Flat grounds would also be less likely to harbour VMEs (Rogers *et al*. 2008). The only remaining challenge for this approach is to determine a harvest rule for setting catch limits that is shown to be robust, and result in a sustainable stock. In the longer-term, it would also be necessary to determine whether fishing on spawning aggregations reduced spawning success, and how any impact could be avoided or minimised. There are few fisheries worldwide that could support this approach; examples include the stocks on Challenger Plateau and East and South Chatham Rise, both off New Zealand (Ministry of Fisheries 2010), and possibly stock(s) in the north

Atlantic (ICES 2010). However, although managed using this approach since 2008–09 (albeit with an untested harvest rule), the East and South Chatham Rise is substantially depleted and biomass has continued to decline (Dunn *et al*., 2008; Ministry of Fisheries 2010). The Challenger Plateau stock has been closed since 1998, but has recently shown signs of rebuilding (Ministry of Fisheries 2010).

EFFECTIVE MCS

Effective MCS is an integral part of a sustainable fisheries management regime, and the best approach needs to be determined for any fishery. The size, fishing capacity and economics of the fleet will influence the MCS regime. Orange roughy fisheries are generally characterized by small fleets of large vessels which logistically are easier to monitor, and can better accommodate observers; however, for fishing to be economically feasible for such vessels, they require large catches which can threaten the long-term sustainability of orange roughy fish stocks at a given location. With relatively smaller vessels, the economic imperatives may be more compatible with catch levels consistent with long-term sustainability, but monitoring the greater numbers of vessels to ensure compliance (e.g. catch, bycatch, area closures, gear deployment etc.) is more costly. For any new fishery, expansion would need to be carefully controlled in order to avoid overcapitalisation (Boyer *et al*. 2001; Bax *et al*. 2005; Paya *et al*. 2005; Clark 2009). In any event, small individual catches would only remain economically viable if the market value was high, or if orange roughy could be prosecuted as one component of a sustainable multi-species fishery. Given current market value of the catch, the cost of a management regime exclusively for sustainable orange roughy fisheries is likely to be high relative to the economic value of the fishery (as measured by ex-vessel value of the catch). This is particularly the case when fishing on depleted stocks that are being managed to ensure rebuilding. The increasingly restrictive market for orange roughy may also ultimately negatively impact market value (e.g., Greenpeace 2009; Anon 2010). That said, a fleet that is characterized by cooperative behaviour, including cooperative data-gathering, will be much less costly to manage than one characterized by animosity or indifference towards fisheries regulation. Hence, associated MCS costs can vary greatly from region to region, and need to be carefully considered. MCS might even prevent a sustainable fishery from commencing or continuing on purely economic grounds, especially if there are no direct or indirect subsidies.

Conclusions and recommendations

Fishing for orange roughy requires bottom trawls, impacting vulnerable low productivity deep-sea benthic fauna, and as a result the ecosystem impact of orange roughy fishing can be substantial. Sustainable orange roughy fisheries must therefore operate in a way that minimises bottom contact.

Orange roughy stocks have proven to be particularly difficult to understand and assess, and monitoring remains difficult. Sustainable orange roughy fisheries must therefore focus on stocks where credible monitoring and assessment can take place.

Finally, there must be a management system, and a will, to operate orange roughy fisheries in a sustainable way, complete with appropriate MCS.

The majority of the orange roughy fisheries have not operated in this way, and have not been sustainable. Nevertheless, there remains the potential for a sustainable orange roughy fishery, and one which could achieve the FAO guidelines (FAO 2009). The most likely fishery is one that exploits spawning aggregations on flat ground, with accompanying monitoring using acoustic methods, and catch limits set using a demonstrably robust harvest rule. Such fisheries are likely to be very few in number, and provide catches that are much lower than historical, including recent, levels (Clark 2009). Because of the high economic overheads of deep-sea fishing, orange roughy from such fisheries might need to be marketed as a “boutique” product.

Applying a basic productivity-susceptibility analysis to a complex deepwater mixed trawl fishery in the Northeast Atlantic

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Introduction

To the west of the United Kingdom a mixed species trawl fishery operates on the mid to upper continental slope to maximum depths of around 1500 m. Species such as blue ling *(Molva dypterygia)*, roundnose grenadier *(Coryphaenoides rupestris)* and black scabbardfish *(Aphanopus carbo)* are targeted with deep-water sharks taken as bycatch. The fishery began in the mid 1970s (Gordon, 2001; Gordon *et al*., 2003), but management of the fishery via TACs was not introduced until 2003. Most landings are made by France with a smaller proportion made by Spain, UK and Ireland. TACs have declined since 2003 and for some species (e.g. deepwater sharks) there is now no TAC or bycatch allowance. It is estimated that species such as roundnose grenadier and black scabbardfish have declined by 50 %, blue ling by approximately 75 %, and the deepwater sharks by over 90 %. There are reliable fisheries-independent data available for this area and over the past ten years it appears many species, such as the grenadiers, have remained stable but are showing little sign of recovering to former levels (Neat & Burns, 2010).

The fishery is mainly concentrated on the muddy habitat of the continental shelf slope and therefore, it is unlikely to impact vulnerable marine ecosystems (VMEs) such as coldwater coral reefs. It may, however, be in an area of importance for fauna such as sea pens, sponges and anemones. There are steeper sections of the slope as well as the seamounts and banks in the region that are important sites for VMEs. It is not clear to what extent these areas are fished. Some have been protected, but others remain vulnerable to fishing impacts. The fishery is also associated with high discards of both undersized target species and so- called ‘trash’ species such as smoothheads and chimaeras. There is likely to be 100 % mortality of discards due to the length of trawl duration and the depth from which these species are brought to the surface.

There is insufficient information on these species to undertake formal stock assessments, although this year an attempt was made to benchmark the status of a few species for which reasonable levels of information were available (ICES WGDEEP). For most deepwater species the evaluation of the biological status of their stocks (levels of abundance and of exploitation) is commonly made following simple approaches, such as the direct estimation of indices of abundance either from survey or from fishery-dependent data. The application of more complex modeling approaches to deepwater species, although desirable, has not been implemented due mainly to the data-poor status of most species in conjunction with their high level of vulnerability to exploitation. Attempts to use Ecopath models also suffer from the scarcity of data (Heymans *et al*., 2010) and high levels of uncertainty. A new approach is clearly needed.

To remedy these shortcomings meta-analytical approaches applied within a Bayesian context are gaining popularity. The development and application of ecological risk assessment methods to fisheries has provided a rapid technique to evaluate the *relative* vulnerability of an individual species to fishing activities, or the *relative* risk posed to individual species from fishing activities. Milton (2001) and Stobutzki *et al.* (2001; 2002) concurrently developed a qualitative ecological risk assessment approach for Australia’s Northern Prawn Fishery (NPF), which considers vulnerability to be dependent on two factors: 1) the productivity (or recovery potential) of a species, and 2) the susceptibility of a species to a fishery. This technique is considered to be simple, robust and repeatable; it is particularly valuable in data poor situations, making it an effective assessment tool for bycatch species for which there is often little information available (Griffiths *et al*., 2006; Stobutzki *et al*., 2001; 2002; Zhou & Griffiths, 2008).

Since its development and initial application to Australian trawl fisheries, the method has been modified, expanded and utilised elsewhere, including application to U.S. fish stocks (e.g., Patrick *et al*., 2010). Termed ‘productivity-susceptibility analysis’

(PSA) (following the terminology of Patrick *et al*. 2010), the method considers the 'productivity' of a species to be based on its biological attributes, which determine its ability to sustain exploitation or to recover after depletion, and the 'susceptibility' of a species to be dependent on the level of interaction of that species with the fishery. This analysis assigns a productivity rank and a susceptibility rank to each species, the combination of which highlights those species most at risk or alternatively, most vulnerable to the fishing activity (Milton, 2001; Stobutzki *et al*., 2001; Stobutzki *et al*., 2002). It thus allows species-specific information on productivities to be incorporated into an assessment of fishing impacts.

The aim of this analysis was to apply the PSA technique to assess the relative vulnerability of a group of target and bycatch species in the Northeast Atlantic Mixed Trawl Fishery by 1) assessing the productivity of each species, 2) assessing the susceptibility of each species to the fishery, 3) combining productivity and susceptibility to illustrate the overall vulnerability of species to the fishery, 3) using susceptibility scores to highlight potential management options to achieve more sustainable fisheries, and 4) testing how vulnerability (or 'risk') changes under various management scenarios. In our application of this method we broadly followed (with some modifications, outlined in the methodology) a recent application of this method by Patrick *et al*. (2010). Our objective was not to assess all species recorded in the fishery, but to perform this analysis at the most basic level for a rapid assessment of vulnerability for 16 key species, comprising the key target and bycatch teleost fishes (5 species) and the key bycatch chondrichthyan species (11 species: 10 sharks and one chimaera). This latter group includes species of conservation concern in the mixed species group 'deepwater sharks'.

We subsequently highlighted data requirements needed to manage the Northeast Atlantic Trawl Fishery sustainably.

Materials and Methods

An ecological risk assessment approach (productivity-susceptibility analysis) was applied to the 16 key species taken as either targeted species or bycatch in the Northeast Atlantic Mixed Trawl Fishery in order to determine their relative vulnerability to the fishery. Application of the technique closely followed Patrick *et al*. (2010), which was based on methodology initially developed by Milton (2001) and Stobutzki *et al*. (2001; 2002) but which expanded the number of attributes used particularly in relation to management factors (see Patrick *et al*. 2010 and references therein). For each species, its productivity and its susceptibility to the fishery were ranked by assigning scores or 1, 2 or 3 against a series of attributes which define each of 'productivity' and 'susceptibility'. Whilst broadly following Patrick *et al*. (2010) we, however, utilised the PSA in its most basic form as we required a rapid assessment tool to rank only a subset of species recorded in the fishery in order to determine their relative vulnerability. We wished to firstly identify how the fishery was impacting these species, and secondly to investigate how management options may alter the sustainability landscape. As such, we used a very simple method of the PSA, selecting key attributes from Patrick *et al*. (2010), ranking these attributes and using an additive approach to arrive at the average ranking of a species against 1) productivity attributes, and 2) susceptibility attributes, without assigning weightings to individual attributes (as is standard practice in the PSA method; see Milton 2001, Stobutzki *et al*. 2001, 2002, Patrick *et al*. 2010).

An explanation of the productivity and susceptibility attributes used and their synthesis in the PSA method follows. See Patrick *et al*. (2010) for a more detailed explanation and justification of each attribute.

PRODUCTIVITY

Seven attributes relating to the biology of a species were used to assess productivity (selected from 10 attributes used by Patrick *et al*. 2010):

1. Maximum size
2. Maximum age
3. Estimated natural mortality
4. Measured fecundity
5. Breeding strategy
6. Age at maturity
7. Mean trophic level

Each species is ranked against each attribute on a scale of 1 (low productivity) to 3 (high productivity).

Each species is ranked against each attribute on a scale of 1 (low productivity) to 3 (high productivity)

Justification: Younger, earlier-maturing and more fecund species (i.e. more productive species) have a greater ability to recover from population depletion than older, later-maturing and less fecund species (i.e. less productive species) (Camhi *et al*., 1998; Smith *et al*., 1998).

Data sources: Data on the size, reproductive biology, age and diet (to estimate trophic level) were gathered from the published literature as well as author's unpublished data. Natural mortality *(M)* was estimated using the method of Jensen (1996) which determines M from the relationship with the von Bertalanffy growth parameter k ($M = 1.6k$). For the selection of biological data for the assessment of productivity, regional data were used if available in preference to data from elsewhere.

Productivity attributes and rankings are outlined in Table 2 (attributes based on Patrick *et al*. 2010). For each productivity attribute, the minimum and maximum values of the data for the 16 species examined were log-transformed. The range of these data was then divided into thirds and back-transformed to provide reference points for the determination of ranks, which resulted in the productivity attribute ranking rules outlined in Table 2. Total length (L_T) was used as the standard size measurement of all species.

In cases where species-specific data were lacking (mostly relating to age and growth data for some of the chondrichthyans), a ranking was applied for a particular attribute based on known data from similar species (i.e. congeners or species from the same family). Some previous PSA-type analyses have instead used a precautionary approach when species-specific data are lacking. This approach assigns a low productivity ranking for missing data, however this approach tends to overestimate vulnerability, and it is more realistic to make inferences from related species.

SUSCEPTIBILITY

Seven attributes relating to the level of interaction between a species and the fishery were used to assess susceptibility (selected from 12 attributes used by Patrick *et al*. 2010):

1. Areal overlap
2. Vertical overlap
3. Seasonal migrations
4. Schooling, aggregations, and other behaviour responses
5. Morphological characteristics affecting capture
6. Survival after capture and release
7. Management strategy

Each species was ranked against each attribute on a scale of 1 (low susceptibility) to 3 (high susceptibility).

Justification: Species whose geographic and bathymetric distribution overlaps considerably with the fishery, whose migration and behavioural patterns increase their overlap with the fishery, whose morphology increases their likelihood of capture when encountered by the fishery, whose survival after capture as a result of the fishery is low, and those that have no management measures directed at them, will be more susceptible to the fishery.

Data sources: Data on distributions were obtained from the literature while expert knowledge and available information on the operation of the fishery were used to assess all other susceptibility attributes.

Susceptibility attributes and rankings are outlined in Table 3. Note that we modified the attribute 'vertical overlap' as we were dealing with a demersal fishery; we considered vertical overlap as bathymetric range.

CALCULATION OF OVERALL PRODUCTIVITY AND SUSCEPTIBILITY RANKINGS FOR EACH SPECIES

Previous analyses have used the weighted average method developed by Milton (2001) and Stobutzki *et al*. (2001; 2002) to calculate overall susceptibility and recovery for each species assessed. It should be noted that there are two commonly used approaches to calculate overall susceptibility, the weighted average method, and the multiplicative approach. In the latter, if one attribute has a low rank, then the species is considered not at risk, and thus the multiplicative approach has a tendency to underestimate susceptibility. When using multiple attributes, emphasis should not be placed on one attribute; it is more balanced to average all values.

To calculate the final productivity score of each species, the average of each of the seven productivity attribute rankings was taken. To calculate the final susceptibility score of each species, the average of each of the seven susceptibility attribute rankings was taken. As previously mentioned, individual attributes were not weighted as is usually done in PSA methods (e.g. in Patrick *et al*. 2010). Due to the rapid nature of the assessment, weighting was avoided, and furthermore the working group felt that chosen attributes were of roughly equal importance for the aims of this assessment.

The final susceptibility and recovery rankings were plotted on a productivity-susceptibility plot (also referred to as a sustainability plot or a vulnerability plot) developed by Stobutzki *et al*. (2001) and modified by Patrick *et al*. (2010) where the x axis represents productivity and the y axis represents susceptibility. The productivity axis scales from 3.0 to 1.0, with the left hand side of the axis (3.0) representing high productivity (i.e. less vulnerable) and the right hand side of the axis (1.0) representing low productivity (i.e. more vulnerable). The susceptibility axis scales from 1.0 (low susceptibility) to 3.0 (high susceptibility). Therefore, the most vulnerable/least sustainable species (highest risk) have a relatively low rank on the productivity axis and a relatively high rank on the susceptibility axis, and will fall on the top right-hand corner of the plot. In contrast, the least vulnerable species (lowest risk) have a relatively high rank on the productivity axis and a relatively low rank on the susceptibility axis, and will fall on the bottom left-hand corner of the plot.

The assessment was first performed for the current management scenario and the results examined to pinpoint other potential management scenarios. The assessment was performed on two additional management scenarios to highlight changes in the vulnerability. For each scenario, productivity rankings for each species remained the same (these are the intrinsic biological parameters and cannot be changed through management of the fishery). However, for each scenario, susceptibility rankings for certain species were altered to reflect changes to a species' susceptibility under a different management scenario. For each management scenario a separate table of susceptibility rankings and a separate productivity-susceptibility plot was produced.

For each management scenario a separate table of susceptibility rankings and a separate productivity-susceptibility plot was produced

Management scenarios tested were
- Management scenario 1:
  the current management situation within the fishery ('current management')
- Management scenario 2: banning all trawling at depths >1000 m ('1000 m ban')
- Management scenario 3: banning trawling during the blue ling spawning season ('blue ling spawning ban')

Results and Discussion

Table 4 outlines the life history data used for ranking the productivity attributes: maximum size (available for all 16 species), maximum age (available for 11 species), natural mortality (available for 12 species), fecundity (available for 15 species) and female age at maturity (available for 13 species).

Productivity rankings ranged from 1.00–2.71 (possible range of rankings: 1.00–3.00) (Table 5). Species with the highest rankings (high productivity) were the teleosts greater forkbeard *Phycis blennoides* (ranking of 2.71) and black scabbardfish *Aphanopus carbo* (2.43), and the shark blackmouth catshark *Galeus melanostomus* (2.43). Another group with rankings of 2.29 consisted of blue ling Molva dypterygia, great lanternshark *Etmopterus princeps* and velvet belly *Etmopterus spinax*. A group with rankings of 2.14 consisted of roundnose grenadier *Coryphaenoides rupestris*, Baird's smoothhead Alepocephalus bairdii and black dogfish Centroscyllium fabricii. The rabbitfish *Chimaera monstrosa* had a ranking of 2.00, and those species with rankings below 2.00, in order of decreasing productivity were longnose velvet dogfish *Centroselachus crepidater* (1.43), Portuguese dogfish *Centroscymnus coelolepis* (1.29), birdbeak dogfish *Deania calcea* (1.29), leafscale gulper shark *Centrophorus squamosus* (1.14), kitefin shark *Dalatias licha* (1.14) and bluntnose sixgill shark *Hexanchus griseus* (lowest possible ranking of 1.00) (Table 5).

MANAGEMENT SCENARIO 1

Under management scenario 1 (current management) susceptibility rankings ranged from 1.57–2.29 (Table 6). Species with the lowest rankings (least susceptible) were black scabbardfish *Aphanopus carbo* and roundnose grenadier *Coryphaenoides rupestris* (ranking of 1.57). A group with susceptibility rankings of 1.71 consisted of greater forkbeard *Phycis blennoides*, blackmouth catshark *Galeus melanostomus*, velvet belly *Etmopterus spinax* and Portuguese dogfish *Centroscymnus coelolepis*. A group with susceptibility rankings of 1.86 consisted of birdbeak dogfish *Deania calcea*, kitefin shark *Dalatias licha*, black dogfish *Centroscyllium fabricii* and great lanternshark *Etmopterus princeps*. A group with susceptibility rankings of 2.00 consisted of longnose velvet dogfish *Centroselachus crepidater*, bluntnose sixgill shark *Hexanchus griseus*, Baird's smoothhead *Alepocephalus bairdii*, rabbitfish *Chimaera monstrosa* and leafscale gulper shark *Centrophorus squamosus*. The highest ranking (most susceptible) was for blue ling *Molva dypterygia* (2.29). The vulnerability plot for productivity and susceptibility under management scenario 1 (current management) is shown in Figure 6.

Large deep sharks, intermediate sharks and chimaeras. The large deep sharks are not considered to be potentially sustainable. Combinations of large size, high age at maturity, slow growth and low fecundity mean they are highly unproductive. They are currently at < 10 % of their initial biomass estimates. There is no fishery for them, but even bycatch may prevent recovery. The intermediate sharks and chimaera are less vulnerable, but still not sufficiently so to be considered potentially sustainable.

Reducing mortality of these sharks could possibly be achieved by:

1) increasing survival probability by reducing trawl duration;
2) restricting trawling to depths shallower than 1000 m to minimize *C. ceololepis* catch;
3) increasing research to assess age and spatio-temporal distributions;
4) developing research into technical conservation measures to allow sharks to escape.

Baird's smoothhead and roundnose grenadier. These species have medium fecundity and growth. There is potential for sustainable fisheries, but the bathymetric overlap between nursery grounds and adult grounds is a strong conservation concern.

Possible means of increasing sustainability include the following:

1) identify and protect nursery grounds and areas of high juvenile density;
2) restrict trawling to a shallower depth range, thereby reducing vertical overlap;
3) rebuild biomass (maintain strict TACs and closely monitor populations).

Blue ling. Blue ling has potential to be fished sustainably, but due to its aggregating behaviour at spawning is vulnerable to overfishing. It is currently depleted, but showing signs of recovery.

Potential measures to move toward a sustainable fishery include the following:

1) close all spawning grounds to fishing during the spawning season;
2) rebuild biomass (maintain strict TACs and monitor recovery).

Greater forkbeard and black scabbardfish. These species are intrinsically productive and could be exploited sustainably. Black scabbardfish is depleted, but abundance is unpredictable.

The impact of this fishery could be reduced by using the following measures:

1) focus effort during certain times of the year when black scabbardfish is concentrated in non-spawning aggregations;
2) rebuild biomass (maintain strict TACs and monitor recovery).

MANAGEMENT SCENARIO 2

Under management scenario 2 (1000 m depth ban) susceptibility rankings ranged from 1.43–2.14 (Table 7). This management scenario removed three shark species (Portuguese dogfish *Centroscymnus coelolepis*, black dogfish *Centroscyllium fabricii* and great lanternshark *Etmopterus princeps*) from the PSA because they live predominately below this depth. It also reduced the susceptibility ranking of black scabbardfish *Aphanopus carbo* from 1.57 to 1.43, that of velvet belly *Etmopterus spinax* from 1.71 to 1.43, that of Baird's smoothhead *Alepocephalus bairdii* from 2.00 to 1.86, and that of blue ling *Molva dypterygia* from 2.29 to 2.14. The susceptibility for greater forkbeard *Phycis blennoides* increased from 1.71 to 1.86, since a restriction on maximum depth would increase effort on the upper slope where this species predominates. The vulnerability plot for productivity and susceptibility under management scenario 2 (1000 m depth ban) is shown in Figure 7.

MANAGEMENT SCENARIO 3

Under management scenario 3 (blue ling spawning ban) susceptibility rankings ranged from 1.57–2.00, representing a relatively narrow range (Table 8). This management scenario shifted the susceptibility ranking of blue ling *Molva dypterygia* from 2.29 down to 1.75. The vulnerability plot for productivity and susceptibility under management scenario 3 (blue ling spawning ban) is shown in Figure 8.

By closing the fishery during March-May, fishing is reduced at the time of year that blue ling is susceptible to the fishery. The susceptibility of blue ling to the fishery is decreased considerably since rankings for the 'seasonal migration' and 'behaviour' (aggregation) attributes are reduced. The modeled effect is restricted to blue ling, and wider changes are difficult to predict. If the fishery operates with the same effort, but over a shorter period, the susceptibility attributes of the other species will likely remain unchanged. Alternatively, this management option would free up the fleet for the period of the temporal closure and may allow them to fish elsewhere, increasing in a broader context, overall effort.

MULTIPLE MANAGEMENT SCENARIOS

Multiple management scenarios should be combined. For example a combination of management scenarios 2 & 3 (i.e. fishing banned deeper than 1000 m and only permitted from June-February) would release 3 species of sharks from fishing, be beneficial to species such as roundnose grenadier, black scabbardfish, velvet belly, and Baird's smoothhead and protect blue ling in such a way as to make them much less vulnerable to being overexploited. An optimal range of alternative scenarios that provide the greatest benefit to the largest number of species and assures the most vulnerable species are protected must be found. This will result in the closest possible approximation of a multi-species sustainable fishery.

An optimal range of alternative scenarios that provide the greatest benefit to the largest number of species and assures the most vulnerable species are protected must be found.

THE PSA MODEL

Benefits of the methodology:

- The method is suitable in data-poor situations where data for traditional stock assessments are lacking (it is based on qualitative data).
- The outputs (vulnerability plots) provide a visual tool for examining the relative vulnerability of a suite of species to a particular fishery.
- The method can be tailored to the data availability and state of knowledge of species and fisheries by carefully selecting productivity and susceptibility attributes which both represent the breadth of knowledge of species/a fishery, and account for characteristics of those species (with regards to their productivity) and the operating environment of the fishery.
- The method is rapid and is based on previously developed, tested and published protocols, and has a history of application as a risk assessment method in fishing.

Limitations of the methodology:

- This method only provides an assessment of relative risk, that is, species x is more at risk (higher susceptibility to the fishery and lower ability to recover from fishing) than species y. In this assessment species are ranked relative to each other. If more species were included (i.e. shelf fishes caught as bycatch), many of the species in the current analysis could be shifted to a higher, relative vulnerability.
- The analysis is only what it appears – a vulnerability analysis – and should not be used to prove or disprove the sustainability of a fishery. The results do not translate directly into "sustainability", and drawing such a conclusion for any species should be avoided. Instead, it should be used as a tool to highlight potential management strategies, vulnerable species, and areas where particular attention should be paid.
- This assessment is fishery-specific, as susceptibility rankings are specific to a species' interaction with the fishery in question. Because the analysis is fishery specific, it ignores the potential susceptibility outside the limits of the fishery and therefore in other fisheries. Other fisheries and cumulative impacts can have far-reaching consequences. Whenever possible, fishery-specific in combination

with global (such as that conducted in the 'Sustainable deep-sea fisheries for grenadiers' section of this report) or population-specific analyses could be completed for a more holistic view of vulnerability.

- The results are only as strong as the attributes included. There are many more attributes that increase or decrease a species' susceptibility or recovery potential. Attributes should be added or removed based on the fishery and as more information becomes available.
- The method lacks ecosystem context. It primarily focuses on the individual fish species and not the broader ecosystem. To help counter this effect, management decisions should be evaluated in relation to their consequences on the ecosystem. For example, banning fishing below 1000 m would protect some fragile gorgonian corals and other unique habitat features, but do nothing to protect *Lophelia pertusa* reefs. Prohibitions against fishing during the spawning season of blue ling could greatly mitigate overfishing and sequential depletions of this species, but do little to protect VMEs.

DATA REQUIREMENTS

The UNGA resolution calls for assessments to determine if significant adverse impacts are likely. Particular data are required to ensure fisheries are managed sustainably and do not produce these types of impacts. Table 8 outlines key data that must be assessed to manage the fishery before it can be deemed sustainable.

For many deep-sea fishes, the size structures of specific life stages are still unknown and even less is known about age structure. For example, maximum age was only known for half of the sharks evaluated in our analysis. These data are required to ensure that the fishery is managed on appropriate time scales and with suitable catch restrictions. Knowledge of temporal and spatial distributions is essential for any fishery to be managed sustainably and spatio-temporal distribution knowledge of particular age and maturity classes will further enhance fishery management. With this knowledge, fishers can avoid fishing at particular times of the year or areas where concentrations vulnerable to fishing exist.

The known and potential locations of VMEs must be identified and used in the spatial management of this fishery. Research must also be undertaken to determine the potential for recovery in areas not currently considered VMEs to ensure that impacts are in fact only temporary.

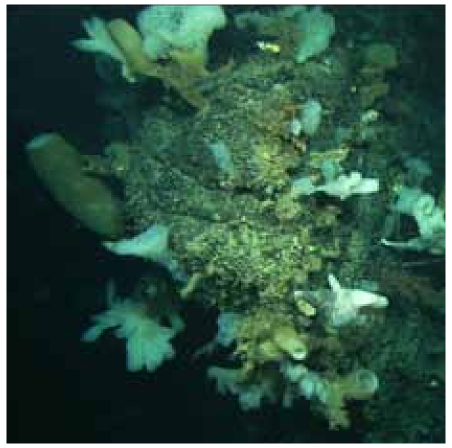
Of course, knowledge of these attributes is useless unless it is used to manage the fishery appropriately. For example, VMEs and spawning aggregations must be closed to any destructive fishing practices and catch limits based on populations must be used in conjunction with appropriate feed-back (control) measures, especially for those species known to be exceptionally vulnerable.

CONCLUSIONS

- The PSA analysis is a useful tool for data-poor fisheries and thus works well in the deep-sea context.
- This analysis does not determine if a fishery is sustainable, but instead highlights vulnerable species within the fishery and potential reasons for susceptibility.
- Our analysis showed that strong attention should be paid toward the intrinsically vulnerable sharks caught in the mixed trawl fishery of the Northeast Atlantic.
- A wide-range of management options should be considered and integrated.
- Before a fishery is deemed 'sustainable' certain data are required and management decisions to minimize significant adverse impacts (based on reliable data) must be made and enforced.

Table 2. Productivity attributes and their rankings. Attributes and definitions modified from Patrick *et al*. (2010).

		RANKING		
Productivity attribute	Definition	High (3)	Moderate (2)	Low (1)
Maximum size	Maximum size is correlated with productivity, with large fish tending to have lower levels of productivity.	<151 cm L_T	152–270 cm L_T	>270 cm L_T
Maximum age	Maximum age is a direct indication of the natural mortality rate (M), where low levels of M are negatively correlated with high maximum ages.	<15 years	15–33 years	>33 years
Estimated natural mortality (M)	Natural mortality rate directly reflects population productivity; stocks with high rates of natural mortality will require high levels of production in order to maintain population levels. When more than one estimate was available, the maximum value was chosen.	>0.28	0.13–0.28	<0.13
Measured fecundity	Fecundity (i.e., the number of eggs (or pups) produced by a female for a given spawning event or period) is measured as the mean value when a range of values is possible.	>28844	416–28844	<416
Breeding strategy	The breeding strategy of a stock provides an indication of the level of mortality that may be expected for the offspring in the first stages of life.	Broadcast spawner	Oviparous chondrichthyan	Viviparous chondrichthyan
Female age at maturity	Age at maturity tends to be positively related with maximum age; long-lived, lower productivity stocks will have higher ages at maturity than short-lived stocks.	<8 years	8–16 years	>16 years
Trophic level	The position of a stock within the larger fish community can be used to infer stock productivity; lower-trophic-level stocks generally are more productive than higher-trophic-level stocks.	Mixed diet; small prey size	Piscivorous; small prey size	Piscivorous; large prey size



Corner Seamount, 1840 m

Octocoral, Paragorgia johnsoni

Octocoral, Acanella arbuscula

Table 3. Susceptibility attributes and their rankings. Attributes and definitions modified from Patrick *et al*. (2010).

		RANKING		
Susceptibility attribute	Definition	Low (1)	Moderate (2)	High (3)
Areal overlap	The extent of geographic overlap between the known distribution of a stock and the distribution of the fishery.	<25% of stock present in the area fished	Between 25% and 50% of the stock present in the area fished	>50% of stock present in the area fished
Vertical overlap	The extent of overlap between the bathymetric distribution of a species and the depths fished by the fishery	<25% of the depth range of the stock is fished	Between 25% and 50% of the depth range of the stock is fished	>50% of the depth range of the stock is fished
Seasonal migrations	Seasonal migrations (i.e. spawning or feeding migrations) either to or from the fishery area could affect the overlap between the stock and the fishery.	Seasonal migrations decrease overlap with the fishery	Seasonal migrations do not substantially affect the overlap with the fishery	Seasonal migrations increase overlap with the fishery
Schooling, aggregations, and other behaviour responses	Behavioural responses of both individual fish and the stock in response to fishing.	Behavioral responses of fish decrease the catchability of the gear	Behavioral responses of fish do not substantially affect the catchability of the gear	Behavioral responses of fish increase the catchability of the gear
Morphological characteristics affecting capture	The ability of the fishing gear to capture fish based on their morphological characteristics (e.g. body shape, spiny versus soft rayed fins, etc.).	Species shows low susceptibility to gear selectivity	Species shows moderate susceptiblity to gear selectivity	Species shows high susceptiblity to gear selectivity
Survival after capture and release	Fish survival after capture and release varies by species, region, and gear type or even market conditions, and thus can affect the susceptibility of the stock (note: retained individuals have 100% mortality).	Probability of survival >67%	33% < probability of survival <67%	Probability of survival <33%
Management strategy	The susceptibility of a stock to overfishing may largely depend on the effectiveness of fishery management procedures used to control catch.	Targeted stocks have catch limits and proactive accountability measures; nontarget stocks are closely monitored	Targeted stocks have catch limits and reactive accountability measures	Targeted stocks do not have catch limits or accountability measures; nontargeted stocks are not closely monitored


Octocoral, Metallogorgia melanotrichos


brittle star, Ophiocreas oedipus, living on M. melanotrichos


unidentified ceranthid anemone

Table 4. Life history parameters used to assess against productivity attributes for 16 fish species taken in the Northeast Atlantic Mixed Trawl Fishery. Species codes correspond to those used in Figures 1–3.

Species	Species code	Maximum size (cm L_T)	Maximum age (years)	Natural mortality	Fecundity	Age at maturity (years)
Greater forkbeard *Phycis blennoides*	Pblen	84	14	0.24	750,000	3.5
Black scabbardfish *Aphanopus carbo*	Acarb	151	12	0.32	625,000	8
Blackmouth Catshark *Galeus melanostomus*	Gmelo	90	8	0.60	23	4
Blue ling *Molva dypterygia*	Mdypt	160	17	0.26	2,000,000	6
Great lanternshark *Etmopterus princeps*	Eprin	75	NA	NA	NA	5
Velvet belly *Etmopterus spinax*	Espin	60	7	0.47	13	5
Roundnose grenadier *Coryphaenoides rupestris*	Crupe	105	60	0.16	23,000	10
Baird's smoothhead *Alepocephalus bairdii*	Abair	103	38	0.12	3,400	13
Black dogfish *Centroscyllium fabricii*	Cfabr	107	NA	0.47	16	5
Rabbitfish *Chimaera monstrosa*	Cmons	100	26	0.16	7	11
Longnose velvet dogfish *Centroselachus crepidater*	Ccrep	105	54	0.12	6	20
Portuguese dogfish *Centroscymnus coelolepis*	Ccoel	122	NA	NA	14	NA
Birdbeak dogfish *Deania calcea*	Dcalc	122	35	0.12	11	25
Leafscale gulper shark *Centrophorus squamosus*	Csqua	160	70	0.07	8	35
Kitefin Shark *Dalatias licha*	Dlich	182	NA	NA	13	NA
Bluntnose sixgill shark *Hexanchus griseus*	Hgris	482	NA	NA	108	NA

NA, data not available. Assigning of productivity rankings inferred from similar species.


sea spider, Colossendeis *sp.*


octocoral, Iridogorgia fontinalis


octocoral, Acanella arbuscula

Table 5. Productivity. Rankings against the seven productivity attributes and the final productivity ranking for 16 species taken in the Northeast Atlantic Mixed Trawl Fishery.

Species	Productivity attribute							Final Productivity ranking
	Maximum size	Maximum age	Natural mortality	Fecundity	Breeding strategy	Female age at maturity	Trophic level	
Greater forkbeard *Phycis blennoides*	3	3	2	3	3	3	2	2.71
Black scabbardfish *Aphanopus carbo*	2	3	3	3	3	2	1	2.43
Blackmouth Catshark *Galeus melanostomus*	3	3	3	1	2	3	2	2.43
Blue ling *Molva dypterygia*	2	2	2	3	3	3	1	2.29
Great lanternshark *Etmopterus princeps*	3	3	3	1	1	3	2	2.29
Velvet belly *Etmopterus spinax*	3	3	3	1	1	3	2	2.29
Roundnose grenadier *Coryphaenoides rupestris*	3	1	2	2	3	2	2	2.14
Baird's smoothhead *Alepocephalus bairdii*	3	1	1	2	3	2	3	2.14
Black dogfish *Centroscyllium fabricii*	3	2	3	1	1	3	2	2.14
Rabbitfish *Chimaera monstrosa*	3	2	2	1	2	2	2	2.00
Longnose velvet dogfish *Centroselachus crepidater*	3	1	1	1	1	1	2	1.43
Portuguese dogfish *Centroscymnus coelolepis*	3	1	1	1	1	1	1	1.29
Birdbeak dogfish *Deania calcea*	3	1	1	1	1	1	1	1.29
Leafscale gulper shark *Centrophorus squamosus*	2	1	1	1	1	1	1	1.14
Kitefin Shark *Dalatias licha*	2	1	1	1	1	1	1	1.14
Bluntnose sixgill shark *Hexanchus griseus*	1	1	1	1	1	1	1	1.00


scleractinian, *Enallopsammia sp.*


unidentified sponge with crinoids


octocoral, *Acanella arbuscula*

Table 6. Susceptibility under management scenario 1 (current management). Rankings against the seven susceptibility attributes and the final susceptibility ranking for 16 species taken in the Northeast Atlantic Mixed Trawl Fishery.

Species	Susceptibility attribute							Final Susceptibility ranking
	Areal overlap	Vertical overlap	Seasonal migrations	Behaviour	Morphology	Survival	Management strategy	
Black scabbardfish *Aphanopus carbo*	1	3	1	1	1	3	1	1.57
Roundnose grenadier *Coryphaenoides rupestris*	1	1	2	1	2	3	1	1.57
Greater forkbeard *Phycis blennoides*	1	2	2	1	2	3	1	1.71
Blackmouth Catshark *Galeus melanostomus*	1	3	1	1	2	3	1	1.71
Velvet belly *Etmopterus spinax*	1	3	1	1	2	3	1	1.71
Portuguese dogfish *Centroscymnus coelolepis*	1	1	3	1	2	3	1	1.71
Birdbeak dogfish *Deania calcea*	1	2	3	1	2	3	1	1.86
Kitefin Shark *Dalatias licha*	1	2	3	1	2	3	1	1.86
Black dogfish *Centroscyllium fabricii*	1	1	3	1	3	3	1	1.86
Great lanternshark *Etmopterus princeps*	1	1	3	1	3	3	1	1.86
Longnose velvet dogfish *Centroselachus crepidater*	1	2	3	1	3	3	1	2.00
Bluntnose sixgill shark *Hexanchus griseus*	1	2	3	1	3	3	1	2.00
Baird's smoothhead *Alepocephalus bairdii*	1	2	2	1	2	3	3	2.00
Rabbitfish *Chimaera monstrosa*	3	3	2	1	1	3	1	2.00
Leafscale gulper shark *Centrophorus squamosus*	1	3	3	1	2	3	1	2.00
Blue ling *Molva dypterygia*	2	3	3	3	1	3	1	2.29

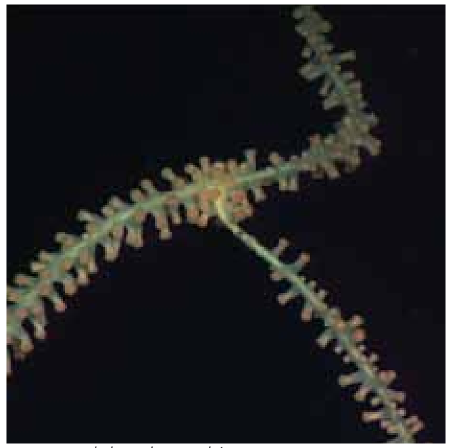

unidentified anemone

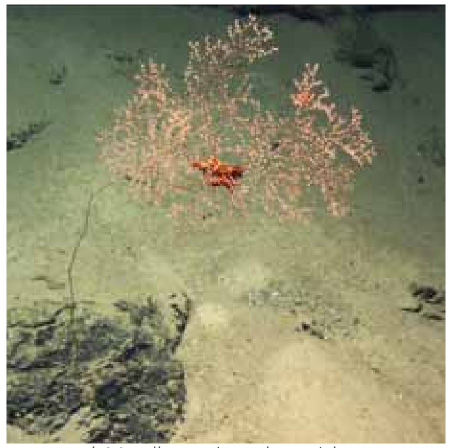

unidentified stalked sponge


the ROV Hercules sampling

Table 7. Susceptibility under management scenario 2 (1000 m ban). Rankings against the seven susceptibility attributes and the final susceptibility ranking for 16 species taken in the Northeast Atlantic Mixed Trawl Fishery.
Red text represents rankings which are altered under this management scenario.

Species	Susceptibility attribute							Final Susceptibility ranking
	Areal overlap	Vertical overlap	Seasonal migrations	Behaviour	Morphology	Survival	Management strategy	
Portuguese dogfish *Centroscymnus coelolepis*	-	-	-	-	-	-	-	-
Black dogfish *Centroscyllium fabricii*	-	-	-	-	-	-	-	-
Great lanternshark *Etmopterus princeps*	-	-	-	-	-	-	-	-
Black scabbardfish *Aphanopus carbo*	1	2	1	1	1	3	1	1.43
Velvet belly *Etmopterus spinax*	1	1	1	1	2	3	1	1.43
Roundnose grenadier *Coryphaenoides rupestris*	1	1	2	1	2	3	1	1.57
Blackmouth Catshark *Galeus melanostomus*	1	3	1	1	2	3	1	1.71
Greater forkbeard *Phycis blennoides*	1	3	2	1	2	3	1	1.86
Baird's smoothhead *Alepocephalus bairdii*	1	1	2	1	2	3	3	1.86
Birdbeak dogfish *Deania calcea*	1	2	3	1	2	3	1	1.86
Kitefin Shark *Dalatias licha*	1	2	3	1	2	3	1	1.86
Longnose velvet dogfish *Centroselachus crepidater*	1	2	3	1	3	3	1	2.00
Bluntnose sixgill shark *Hexanchus griseus*	1	2	3	1	3	3	1	2.00
Rabbitfish *Chimaera monstrosa*	3	3	2	1	1	3	1	2.00
Leafscale gulper shark *Centrophorus squamosus*	1	3	3	1	2	3	1	2.00
Blue ling *Molva dypterygia*	2	2	3	3	1	3	1	2.14


octocoral, bamboo whip


octocoral, Metallogorgia melanotrichos

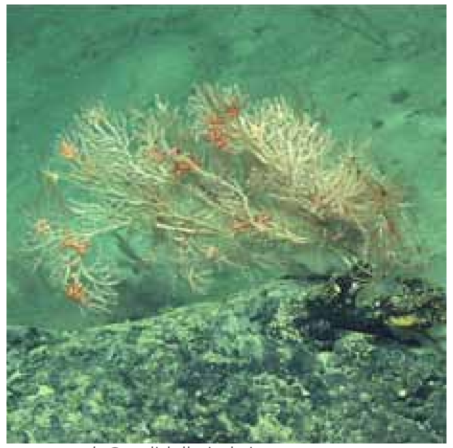

octocoral, Candidella imbricata

Table 8. Susceptibility under management scenario 3 (blue ling spawning ban). Rankings against the seven susceptibility attributes and the final susceptibility ranking for 16 species taken in the Northeast Atlantic Mixed Trawl Fishery.
Red text represents rankings which are altered under this management scenario.

Species	Susceptibility attribute							Final Susceptibility ranking
	Areal overlap	Vertical overlap	Seasonal migrations	Behaviour	Morphology	Survival	Management strategy	
Black scabbardfish *Aphanopus carbo*	1	3	1	1	1	3	1	1.57
Roundnose grenadier *Coryphaenoides rupestris*	1	1	2	1	2	3	1	1.57
Greater forkbeard *Phycis blennoides*	1	2	2	1	2	3	1	1.71
Blackmouth Catshark *Galeus melanostomus*	1	3	1	1	2	3	1	1.71
Velvet belly *Etmopterus spinax*	1	3	1	1	2	3	1	1.71
Portuguese dogfish *Centroscymnus coelolepis*	1	1	3	1	2	3	1	1.71
Blue ling *Molva dypterygia*	2	3	1	1	1	3	1	1.71
Birdbeak dogfish *Deania calcea*	1	2	3	1	2	3	1	1.86
Kitefin Shark *Dalatias licha*	1	2	3	1	2	3	1	1.86
Black dogfish *Centroscyllium fabricii*	1	1	3	1	3	3	1	1.86
Great lanternshark *Etmopterus princeps*	1	1	3	1	3	3	1	1.86
Longnose velvet dogfish *Centroselachus crepidater*	1	2	3	1	3	3	1	2.00
Bluntnose sixgill shark *Hexanchus griseus*	1	2	3	1	3	3	1	2.00
Baird's smoothhead *Alepocephalus bairdii*	1	2	2	1	2	3	3	2.00
Rabbitfish *Chimaera monstrosa*	3	3	2	1	1	3	1	2.00
Leafscale gulper shark *Centrophorus squamosus*	1	3	3	1	2	3	1	2.00


octocoral, Candidella imbricata


C. imbricata *and brittle star* Ophioplinthaca


crab, Chaceon *sp.*

Table 9. Summary of key data requirements for a sustainable ecosystem-based fishery. Each data requirement pertains to not only the target species, but also those regularly caught as bycatch and/or discarded.

Data	Requirement
Size structure of life stages	High
Spatial and temporal distributions	High
Reliable population estimates	High
Location of known and potential VMEs	High
Discards and catch estimates identified to species (full observer coverage)	High
Position and duration of fishing sets	High
Genetic analysis identifying populations	High
Reproductive periodicity	High
Positions and attributes of required habitat	High
Age estimates (maximum, maturity, recruitment, etc)	High
Timing of reproduction	High
Spatial and temporal distributions in relation to age and maturity	Medium
Trophic relationship and diet	Medium
Intrinsic rate of increase	Medium
Fecundity	Medium
Percent survival to maturity	Medium

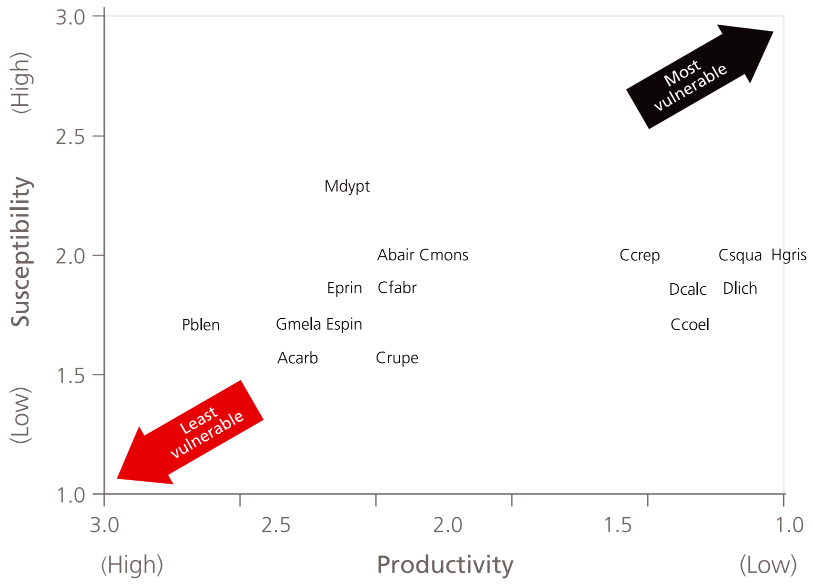


Figure 6. Productivity-susceptibility plot for 16 fish species taken in the Northeast Atlantic Mixed Trawl Fishery under management scenario 1 (current management). Species codes are provided in Table 3.

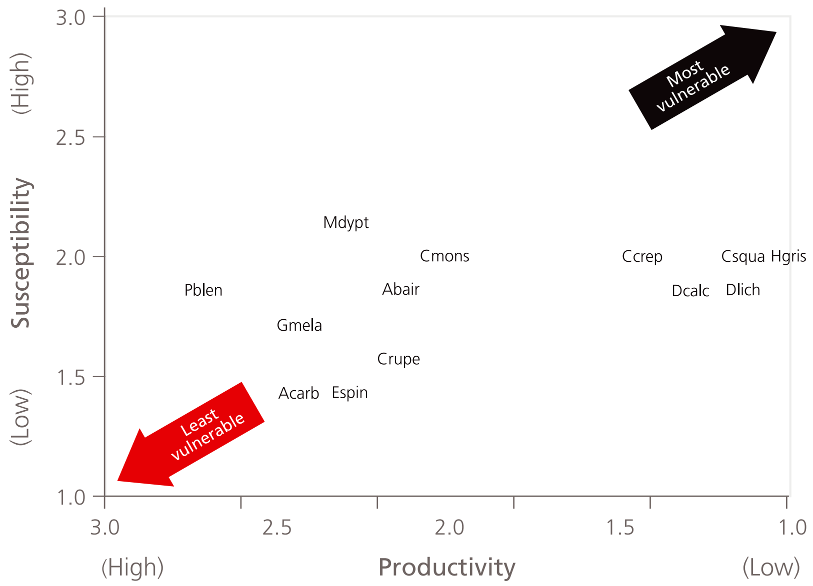


Figure 7. Productivity-susceptibility plot for 13 fish species taken in the Northeast Atlantic Mixed Trawl Fishery under management scenario 2 (1000 m ban). Under this management scenario, three species of sharks are effectively removed from the fishery and so they are no longer 'susceptible' to the fishery. Species codes are provided in Table 3.

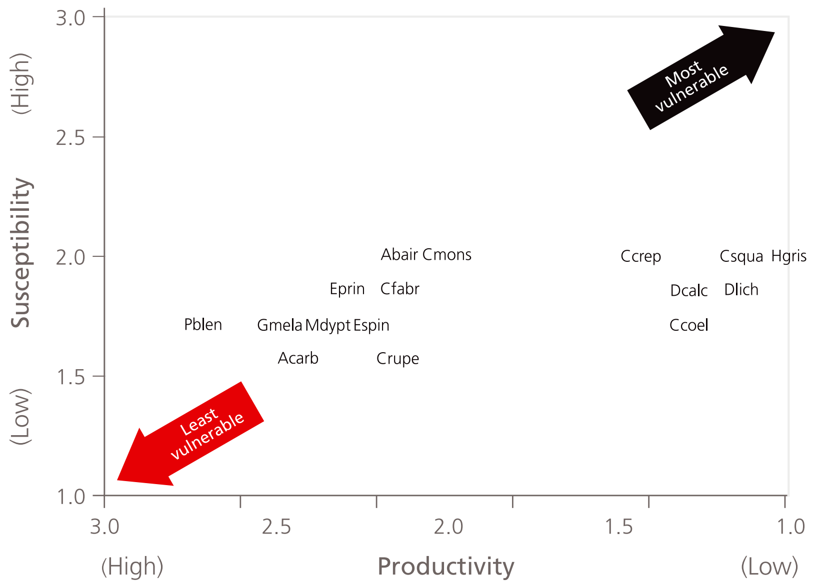


Figure 8. Productivity-susceptibility plot for 16 fish species taken in the Northeast Atlantic Mixed Trawl Fishery under management scenario 3 (blue ling spawning ban). Species codes are provided in Table 3.

Sustainable Deep-Sea Fisheries for Grenadiers

Participants:
G.M. Cailliet,
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SUMMARY

1) Grenadiers are important bycatch of virtually every current deep-sea fishery and of many developing ones, and thus their sustainability is inherently linked with the sustainability of target species.
2) Some directed fisheries for grenadiers may be currently developing.
3) Grenadier history of exploitation does not suggest sustainability at a high harvest level.
4) Currently known grenadier life history attributes suggest great susceptibility to fishing.
5) Many fisheries that include grenadiers are bottom fishing gear based, and thus are potentially destructive to the habitat if the fishing grounds overlap with the distribution of vulnerable marine ecosystems.
6) Given all these criteria, grenadier fisheries will be very hard to manage sustainably.
7) Nevertheless, with the adoption of adequate regulations, coupled with successful management, monitoring and enforcement actions, sustainability might be achieved.
8) Not all grenadier fisheries will be sustainable even with regulatory measures in place.

INTRODUCTION

Grenadiers or rattails (family Macrouridae) are one of the most important components of bycatch in deep-sea fisheries occurring along the upper and middle continental slopes of the world. The group consists of roughly 400 species that are globally distributed across a wide depth range (~200-7000m) (Iwamoto 2008), hence, virtually all deep-sea fisheries around the world capture grenadiers. Data on a few individual grenadier species are available from some Regional Fisheries Management Organizations (RFMOs) (e.g., González-Costas and Murua, 2008). In general, however, when they are recorded, these species are usually aggregated as "grenadiers" in the catch statistics of most nations. Within New Zealand's EEZ, approximately 60 grenadier species are present, some of which are captured as bycatch in large amounts in the deepwater trawl fisheries, such as the hoki *(Macruronus novaezelandiae)* fishery (Ballara *et al*. 2010). Many of the species are small and therefore not directly marketable, but have been and may continue to be processed as fishmeal (Stevens *et al*. in prep.) It is therefore very likely that the catch of grenadiers is underestimated worldwide.

Many grenadier species are taken by fisheries, either as bycatch (most common) or as a target. We have chosen to evaluate a group of relatively larger grenadier species, for which there are well-established or developing fisheries and about which a reasonable amount of information is known. There is also a diverse suite of relatively smaller grenadiers, including *Lepidorhyncus deniculatus, Trachyrhyncus murrayi, Nezumia* spp., and *Coelorinchus* spp., that is taken as bycatch and used as fish meal or discarded, but little is known of their biology or life history characteristics as bycatch statistics are typically not taken. We will not cover those in this report except to mention them.

SPECIFIC GRENADIER SPECIES AND THEIR FISHERIES

Several larger species of grenadier (50-200cm max TL) have more reliable catch statistics. Pacific Grenadier *(Coryphaenoides acrolepis)* and to a lesser extent Giant Grenadier *(Albatrossia pectoralis)* are taken as bycatch in the deep-water groundfish trawl fishery off the west coast of the United States which targeted sablefish, rockfishes, and Dover Sole (Clausen 2008, 2009). This fisheries effort has been significantly reduced by quota restrictions on these species. In the North Pacific, a fishery for Greenland Halibut takes ~20,000 tonnes of giant grenadier and lesser amounts of popeye grenadier *(C. cinereus)* each year (Clausen 2008, Orlov and Tokranov 2008). A similar fishery in the northwest Atlantic along with a deep-water shrimp trawl fishery takes Roundnose Grenadier *(C. rupestris)* and Roughhead Grenadier (*Macrourus berglax*) as bycatch (NAFO, 2010b; González-Costas and

Murua, 2008). Although currently captured only as bycatch, Roughhead Grenadier is becoming an important commercial species in this area. Although NAFO assessments show that the biomass trend of Roughhead Grenadier has been increasing since 1995, and catches have been declining in recent years as a result of a decrease in the fishing effort in the Greenland Halibut fishery (NAFO 2010b), it was listed as a species of 'Special Concern' by COSEWIC (Committee on the Status of Endangered Wildlife in Canada) partially because of large declines in abundance noted in the 1980s and 1990s (COSEWIC 2007). In the northeast Atlantic, these species are commonly taken in mixed deep-water fisheries, both as bycatch and targeted catch species (ICES 2010). In the Southern Ocean, Ridge-scaled Grenadier *(M. carinatus)* are taken in the bycatch of trawl and longline fisheries targeting Patagonian Toothfish, hake and squid (Laptikhovsky *et al*. 2008).

An important question is whether these grenadiers are currently fished sustainably even if the fisheries are not directed towards these species

An important question is whether these grenadiers are currently fished sustainably even if the fisheries are not directed towards these species. Giant and Popeye Grenadiers probably are targeted since they have very high estimates of biomass. For example, 1,273,000-2,491,000 mt were estimated to exist in Russian waters in recent years (Tuponogov *et al*. 2008) and 1,986,000-2,144,000 mt in Alaskan waters in 2008-2009 (Clausen and Rodgveller 2009). They also have very low catch rates. According to published data (Bocharov and Melnikov 2005), recent catches of grenadiers in Russian waters totalled 12,800-16,700 mt annually. In Alaskan waters annual catch varied in recent years from 11,400-18,900 mt (Clausen and Rodgveller 2009).

Pacific Grenadiers may not have always been sustainably harvested. But, largely through restrictions on the mixed trawl fishery off the US West coast, fishing effort has been dramatically reduced. Catches peaked in 1996 at just over 8,000 mt and declined rapidly with catches in 2009 equal to ~750 mt including discards (Dick and McCall 2010). A few biomass estimates are available from the NMFS biannual slope survey. They suggest that in the Vancouver and Columbia (INFPC) statistical areas (from the Canadian border to southern Oregon), there were ~9,000 mt in 1996, and there were 25,865 mt of Pacific grenadier in 1999 along the US west coast (Lauth 1997; Lauth 2000). These estimates come from only the upper half of the depth range from the species.

It is difficult to state if Roundnose Grenadier are considered to be sustainably fished as no reliable estimates of stock size have been made, mainly because the data to assess the stocks have not been continuously collected. In the northeast Atlantic (west of the British Isles), Basson *et al*. (2001) estimated relative biomass of Roundnose Grenadier to be around 15-23% of virgin biomass, while Lorance *et al*. (2008) estimated stocks were at ~30% of virgin biomass. Their estimate of the virgin biomass was ~ 670,000 mt by the swept area method and 130,000 mt using the Schaefer production model; however, both Lorance *et al*. (2008) and the ICES deepwater working group acknowledge that these estimates are highly uncertain and that biomass estimates should only be used as an indication of trends over time. Neat and Burns (2010) found biomass estimates to be stable from 1998 to 2008 during which time TACs were imposed for the species in ICES Division VIa. Roundnose Grenadier is one of several target species in a mixed-species deep-water fishery and is also taken as bycatch in other fisheries (Basson *et al*. 2001; Gordon *et al*. 2003). Catches have declined in recent years as a result of decreased TACs for the grenadier and other deepwater species, but there is fear that this species is misidentified and actual catches are higher than that reported (ICES 2010). High discard levels (approximately 50% by number and 30% by weight) are reported in some areas, although rates around 20% tend to be typical in most fisheries (Pawlowski and Lorance 2009; ICES 2010). A small target fishery existed in the Skagerrak (ICES Division IIIa) until 2007, but now Roundnose Grenadier is taken only as bycatch in extremely small amounts in the deepwater shrimp fishery (ICES 2010). TACs are in place for the remainder of the ICES management areas and also in international waters (ICES 2010).

A few fisheries have targeted grenadiers specifically and these have proven very unsustainable

In the northwest Atlantic, Roundnose Grenadier was listed as endangered by COSEWIC as a result of declines of 98% in adult abundance over a 20-year period (COSEWIC 2008). Roundnose Grenadier was targeted in the 1960s–1990s (Haedrich *et al*. 2001) and moratoriums are currently in place in NAFO Subarea 0 and in Canadian waters of Subareas 2 and 3 (DFO 2010; NAFO 2010b). Catches in international waters outside of NAFO Subarea 0 are unregulated except through mesh sizes for other fisheries (NAFO 2010b). Roundnose Grenadier is captured as bycatch, mainly in the Greenland Halibut fishery, and bycatch estimates since 2000 range from 60–5,400 mt year $^{-1}$ (NAFO 21A STATLANT database, www.nafo.int). Bayesian surplus production models were used to determine the effect of bycatch removals on recovery of roundnose grenadier and levels exceeding 1,250 mt were found to impede recovery (DFO 2010).

It is questionable whether Roughhead Grenadier are sustainably fished. Biomass of Roughhead Grenadier in the northwest Atlantic was estimated to be 75,000 t in 2009 and biomass has been increasing (NAFO 2010b), mainly as a result of decreased fishing mortality (Gonzalez-Costas 2010). However, in 2007, COSEWIC listed the species as threatened in the northwest Atlantic (COSEWIC 2007). One factor that may impede the sustainability of Roughhead Grenadier is the misreporting of catches. Off Greenland (NAFO Subarea 1), catch is often misreported as Roundnose Grenadier (Lyberth 2009). In the northeast Atlantic, Roughhead Grenadier is taken as bycatch in many of the fisheries (Gordon *et al*. 2003) and catch is typically low (100–200 mt annually since 1994), but it is often misidentified as other grenadier species (ICES 2010). The ICES WGDEEP have considered the 'other species' group in both 2009 and 2010, but set no quotas for any of these species in the NEAFC Regulatory Area nor were any included in Appendix I of Council Regulation (EC) No 2347/2002, with the result that vessels are not required to hold a Deepwater Fishing Permit to land these species. Catch of Roughhead Grenadier is therefore not necessarily regulated by EC policies governing deep-water fishing effort.

It is also unknown whether the Ridge-scaled Grenadier is sustainably fished. Currently, it is taken as bycatch in the New Zealand Orange Roughy fishery, but it is not known if the species is landed (Stevens *et al*. in prep.). No biomass estimates exist for this species from New Zealand waters. It is also found on the Patagonian Shelf and the Falkland Islands (Laptikhovsky 2010). Total biomass in this area was estimated to be 40,000 t (Laptikhovsky 2006; Laptikhovsky *et al*. 2008) with an MSY of 3,000-7,000 mt (Falkland Islands Government 2007). A stock assessment in international waters of the Southern Ocean put its biomass at 116,000 – 212,000 mt , but these estimates must be treated with caution because they are based on data from only two research surveys (STECF 2010). Ridge-scaled grenadier can make up 17% of the bycatch in the longline fishery for Patagonian Toothfish, *Dissostichus eleginoides* (van Wijk *et al*. 2003). Catch in the Southern Ocean was extremely low until the 2008 and 2009 fishing years, when it increased to 900 and 1,200 mt, respectively (CCAMLR 2010). It is protected by CCAMLR with a general *Macrourus* TAC and bycatch regulation (see below).

Macrourus whitsoni, another large grenadier, is a commercially important species in the Ross Sea (Marriott *et al*. 2003) with catches ranging from 50-200 tons annually (CCAMLR 2010) and bycatch rates averaging 10% annually in the toothfish longline fishery (Hanchet *et al*. 2003). CCAMLR does manage *Macrourus* species (not species specific) in some areas with a TAC and stipulations that if bycatch in any one haul is equal to or greater than 2 t, the vessel must not fish within 5 n. mi. of that location with that gear for 5 days (Bulman *et al*. 2007).

A few fisheries have targeted grenadiers specifically and these have proven very unsustainable. For a brief time, 1986-1991, Ridge-scaled Grenadier and several others were targeted in the southwest Atlantic by the soviet fleet with initially high catches and then very rapid depletion to less than 25% of initial levels (Laptikhovsky *et al*. 2008). The other directed fisheries for grenadiers occurred in the Skagerrak and in the North Atlantic for Roundnose Grenadier (Gordon 2001; Haedrich *et al*. 2001). The fishery in the Skagerrak is also now closed due to rapid exploitation of the species (ICES 2010), retirement of the sole vessel catching grenadier, and to close a loophole in the regulations. A directed fishery in the northwest Atlantic greatly reduced the stocks to the point that the Roundnose Grenadier population in that area is considered endangered (COSEWIC 2008).

It is highly likely that new directed grenadier fisheries will develop and that their capture as bycatch will continue or even increase. Fishers exploiting greater depths or new regions of the world will always catch these animals because of the large number of species and their global distributions. There are few groups of deep-sea fishes which attain large enough size and sufficient abundance to be of any commercial importance (Merrett and Haedrich 1997). Only fishes in the family Macrouridae and a few species in the order Ophidiiformes fit this category for the middle to lower slope habitats. As an example, Giant Grenadier became recently targeted species by Russian longliners fishing for cod, halibut and rockfishes in some periods. Much of this catch was targeted for sale in China. The Ridge-scaled Grenadier is one of the larger grenadier species found around New Zealand and has the potential to be the target of a small fishery in this region.

LIFE HISTORIES AND VULNERABILITY OF GRENADIERS TO FISHERIES

The life history characteristics of grenadiers are not conducive to commercial exploitation. A review of the available information of the six large species given above indicates high longevity, slow growth, and late age at maturity (Table 10). Even smaller species which are shorter-lived have relatively slow mass-specific growth (Drazen 2008) suggesting that they could be greatly depleted by moderate exploitation rates. Studies have also shown that grenadiers are not very fecund, typically having at most 200,000 eggs per female (Table 10) and often much less (Stein and Pearcy 1982; Murua and Motos 2000; Allain 2001). They have very low metabolic rates (Drazen and Seibel 2007) and an energy budget analysis of the Pacific grenadier suggests that the females may require two or more years to develop adequate energy stores to spawn. Histological examination and time series sampling of gonads suggests a similar situation for *M. carinatus* in the southern ocean (Alekseyeva *et al* 1993). This means that the fecundity estimates are actually two times higher than realized annual reproductive output (Drazen 2008).

To further evaluate the vulnerability of grenadiers to existing fisheries we employed a risk analysis procedure called a productivity-susceptibility analysis (PSA). This technique originated in Australia in the early part of this century (Milton 2001; Stobutzki *et al*. 2001, 2002), and its use has now spread to the eastern North Pacific as described in Patrick *et al*. (2010) and applied to assess the vulnerability of United States fish stocks to overfishing. It has subsequently been used for California near shore finfish species (Fields *et al*. 2010) and for U.S. west coast groundfishes (Cope *et al*. *in press*).

Following Patrick *et al*. (2010) and the Deep-water Mixed Trawl Fishery Group (see previous section), we used a modified version of a productivity and susceptibility analysis (PSA) to evaluate the vulnerability of the grenadier species of interest. We based our evaluation of attributes on published data; where attributes were more subjective, the opinions of an expert group were used. We used several productivity and susceptibility attributes and scales for the grenadier stocks of interest. Similar to Patrick *et al*. (2010), we allowed intermediate scores (e.g., 1.5, 2.5) when the attribute values spanned two categories.

First, we estimated productivity and susceptibility using the attributes and scale outlined in Patrick *et al*. (2010) (also in Field *et al*. 2010, and Cope *et al*. in press) to compare how deep-sea grenadiers compared to several slope and shelf species from the North Pacific (Figure 9). Plotting susceptibility and productivity rankings allows one to characterize, in general, the vulnerability of each species. This is especially true when plotted against shallow-water, shelf, and slope species that may not have the same life history traits as the deeper-dwelling species. We modified one susceptibility attribute: morphology relating to capture was estimated on a fishing method basis (separately for the longline and trawl fisheries) rather than as a whole. This was done because the expert group agreed that susceptibility differed greatly between the two types of fishing methods and that they should not be combined in one index. Several of the attributes either did not apply to the grenadiers or no information existed to evaluate and those were left blank. This treatment was deemed more acceptable than using a median value (2) or treating the attribute as either least productive or most susceptible (i.e., taking the most precautionary stand). The final productivity rankings are an average and leaving the value missing resulted in a slightly more conservative value than if using a median value. Productivity of grenadiers using the Patrick *et al*. (2010) scale ranged from 1.75 for Popeye Grenadier to 1.13 for Giant Grenadier. As expected, none of the species was highly productive. Susceptibility rankings were fairly similar and ranged from 1.9 (Ridge-scaled Grenadier) to 2.38 (Roundnose Grenadier). Cope *et al*. (in press) estimated productivity and susceptibility of Popeye Grenadier from one part of their global range (NE Pacific) to be 1.39 and 2.32, respectively, while values estimated for the global distribution were 1.75 and 2.08 (Table 11, Figure 9). When plotted, it was obvious that the six grenadier species considered were at the more vulnerable end of the plot of susceptibility and productivity scaling, even when compared to other slope species of the eastern North Pacific coast (Figure 9, data come from Patrick *et al*., in press).

Next, productivity of grenadiers (on a global scale) were compared to the deep-water mixed trawl fishery in the northeast Atlantic, using the scaling of attributes established in the previous section. Because grenadiers were not believed to spawn annually (see above), fecundity estimates were halved before applying the deep-water mixed trawl fishery scale for this attribute. Lastly, productivity was estimated by assigning rankings based only on grenadier data (data from Table 10) and susceptibility was estimated using the same attributes and scaling as Cope *et al*. (in press). The PSA scores (Table 12) indicate that the six species of grenadiers we analyzed had quite variable values of both productivity and susceptibility attributes. Productivity rankings, using either scaling, indicated that the Giant, Pacific, and Ridge-scaled Grenadiers were less productive than the Popeye, Roundnose, and Roughhead Grenadiers, respectively. The Popeye Grenadier stood out as the most productive species which may be due, to some extent, to its smaller size. When compared to Productivity of the main deep-water mixed trawl fishery in the northeast Atlantic, grenadiers are much more productive than many of the deep-sea sharks (see Table 5, previous section). Popeye Grenadier shares the same productivity ranking as Greater Forkbeard, the most productive species within that fishery. Globally, roundnose grenadier is slightly more productive than grenadier within this single fishery, indicating other populations within the global range of this species may vary slightly in their productivity. The Susceptibility rankings, were very similar among species, ranging from 1.95 to 2.05, indicating that all six grenadier species analyzed were relatively susceptible to fishing pressure.

When plotted, it was obvious that the six grenadier species considered were at the more vulnerable end of the plot of susceptibility and productivity scaling, even when compared to other slope species of the eastern North Pacific coast (Figure 9, data come from Cope *et al*., in press). Within the six grenadier species and fisheries we analyzed, all appeared to be equally susceptible but varied in their productivity, ranging from the most productive species, the Popeye Grenadier, to the least, the Giant Grenadier (Figure 10).

IMPLICATIONS RELATIVE TO ECOSYSTEM-BASED MANAGEMENT OF GRENADIER FISHERIES

To evaluate fishery sustainability in an ecosystem context, the impacts of the fishery on both target and bycatch species as well as on the habitat must be evaluated. Most of the fisheries which capture grenadiers are bottom gear fisheries that have a variety of deleterious impacts (Bavestrello *et al*., 1997; Roberts *et al*., 2000; Krieger, 2001; Fosså *et al*., 2002; Reed, 2002; Hall-Spencer *et al*., 2002; Davies *et al*, 2007) on benthic habitats when the fishing grounds overlap with the distribution of vulnerable marine ecosystems (VMEs) (FAO, 2009). In recent years, the issue of protecting VMEs in the deep-sea fisheries of the high seas has been extensively debated in the United Nations General Assembly and in the Regional Fisheries Management Organizations (Rogers and Gianni, 2010). As an example, in fishing grounds of the northwest and northeast Atlantic where grenadiers are captured, VME distributions in relation to deep-sea fisheries have been mapped (Durán Muñoz *et al*., 2009; Hall-Spencer, *et al*, 2009; Murillo *et al*, 2010) and extensive areas have been closed to bottom fishing in order to protect cold-water corals and sponges (EC, 2009; NAFO 2010c; NEAFC, 2010). Moreover, some grenadiers are captured with longlines and such fisheries can cause incidental seabird mortality (Brothers *et al*., 1999; Furnes, 2003). Seabird protection measures (EC, 2004) have been implemented in many of these fisheries (i.e. the Antarctic, New Zealand, Australia: Gilman *et al*., 2007).

Some of these fisheries also have variable, and often unknown, amounts of bycatch of other species which are likely discarded. No discards captured from these depths are likely to survive due to decompression from capture at great depths and the physical trauma of trawl capture, especially those species with gas-filled swimbladders. Most of the grenadiers evaluated in this report are now bycatch and not targeted by specific fisheries, with the exception of the Roundnose Grenadier in the northeast Atlantic. Still, that is a mixed-species fishery. Current management plans, fisheries data, and any existing stock assessments for grenadiers are available from the appropriate management agencies (i.e., NAFO, CCAMLR, ICES, US NMFS, the New Zealand Ministry of Fisheries).

RECOMMENDED SUSTAINABLE MANAGEMENT ACTIONS FOR GRENADIER FISHERIES

The history of overexploitation of grenadiers, their unproductive life history characteristics, the issue of bycatch, and the potential deleterious impacts of bottom fishing gears on VMEs make fisheries that include grenadiers extremely difficult to manage sustainably. However, we believe such fisheries could be sustainable given certain regulations and management actions, as listed below.

However, we believe such fisheries could be sustainable given certain regulations and management actions

1) Fishing effort and fishing mortality must remain very low (with F being much lower than M).
2) Bycatch and discard amounts and composition must be monitored by observers and reporting must be mandatory. Such actions are especially important, considering that in these deep-sea fisheries virtually all of the catch dies during capture (Koslow *et al*. 2000; Bailey *et al*. 2009). Knowledge of bycatch and discarding is essential for understanding the nature of the fishery impacts on grenadiers, which are typically bycatch. This will require the implementation of an observer program such as has been successfully implemented by certain RFMOs (i.e. the observer program mandatory for several of the NAFO Regulatory Areas). Such an approach is also necessary to understand the full ecosystem effects of deep-sea bottom fishing, which are usually deleterious for many reasons (Durán Muñoz *et al*., 2009; Murillo *et al*., 2010).
3) The development of comprehensive systems of spatial planning is important to the integrated governance of the deep sea (UNEP 2007). Marine spatial planning should thus be considered an important element of a comprehensive strategy for achieving sustainability of deep sea fisheries. Spatial and temporal management tools such as Marine Protected Areas (MPAs) could be particularly useful in data-poor situations such as encountered in the deep seas (FAO 2007). However, there is very little known about the spawning grounds and seasons of grenadiers, and also the distribution, abundance, and dispersal of their larval and juvenile offspring. Therefore, it would be difficult to decide upon spawning and seasonal closures. Still, if relatively large areas of the seafloor could be protected from bottom fishing, this might benefit multiple species, including fishes and invertebrates, not just grenadier populations. Protected areas should be distributed over the range of the

grenadier species to cover potentially distinct stocks, of which only a few have been identified (Katsarou and Naevdal 2001; White *et al*. 2009). It is important to protect areas in which aggregated bycatch/discards are highest. The protected areas should be situated as to maximize the number and area coverage of VMEs (i.e. corals), thus reducing conflicts with fisheries. Such an approach will protect VMEs and the entire species assemblage of which grenadiers are a part. Furthermore, these protected areas will provide a benchmark to fished areas. Time series monitoring of both closed and fished areas is required and may provide empirical measures of r (intrinsic rate of population increase) as populations in closures rebound.

4) The spatial footprint of deep-sea bottom fishing (all gears) should be frozen and a such measure has been implemented by NAFO and suggested by ICES, but has not really been implemented in the Pacific or Southern Ocean. This action, in conjunction with the development of MPAs, would prevent fishers from moving to areas that are unstudied, that may contain newly fished species, that may contain more important habitats for these fishes, or potentially contain VMEs. Such action would halt the widely recognized problem that fisheries managers are unable to keep pace with new developments in deep-sea fisheries in places heretofore unfished (Haedrich *et al*. 2001).
5) Utilize a vessel monitoring system (VMS) to enforce marine spatial planning units and to truly understand the spatial distribution of fishing activity. Such a VMS is a potentially valuable source of information on spatial and temporal patterns of fishing activity at multiple scales (Mills *et al*., 2007). A VMS system has been successfully implemented by some nations and is mandatory for EU fishing vessels > 15m length; however, the vessels are not required to report when they are fishing, so indirect evidence such as vessel speed has to be used as a proxy (Benn *et al*., 2010) .It is important that this system record position frequently (i.e. every 20-30 minutes) so that it can be used effectively to record the positions of fishing activities. The resulting data would be essential for reviewing and improving the design and management of marine spatial units.

ADDITIONAL TYPES OF INFORMATION REQUIRED FOR SUSTAINABLE MANAGEMENT OF GRENADIER FISHERIES

While the amount of information regarding the biology and productivity of grenadiers is growing, our knowledge lags far behind that of shallow water stocks. Indeed these fishes should be considered data-poor species (Gonzalez-Costas 2010; ICES 2010). The working group evaluated those data that would be required to successfully manage a sustainable grenadier fishery based on the above requirements. The data types are divided into three categories: Indispensable, Useful, and Not Critical.

INDISPENSABLE – these data are absolutely required for sustainable management of the species

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Biomass/stock size – Both fishery-dependent and fishery-independent estimates of catches, effort and stock size are required. Fishery-dependent data could be reliable if observer and VMS systems are employed. Regular fishery-independent surveys will provide random stratified data for biomass estimation and are required to estimate yearly TAC. Recent scientific advice from ICES and NAFO both state that much of the data collected for grenadiers are incomplete and of no, to limited use for stock assessments for these species (ICES 2010; NAFO 2010b). Hence, better reporting measures are needed.
Fishing effort and its spatial distribution – Due to the current data-poor status of these fisheries, marine spatial planning efforts could be much more effectively planned and implemented with improved data on fishing effort and its spatial distribution for both target and bycatch species. Current NEAFC regulations stipulate that fisheries occurring in new areas in the NEAFC Regulatory Area must be accompanied by an impact assessment and biological sampling program, but these data are not widely available at the moment (ICES 2010). Within the NAFO regulatory area, data collection requirements are in place for vessels fishing in new areas and areas closed to bottom trawling are in effect (NAFO 2010a).
Age/size/sex structure – Fishery-independent surveys will allow for the determination of these variables in order to understand life history, development of age-structured population models, and measure changes in length frequency and size and age at maturation (i.e., fisheries-induced evolution, Heino *et al*. 2002), which often arise during heavy fishing exploitation. Otolith growth zones, which are the principal means of ageing bony fishes, are more difficult to apply to deep-sea fishes because their periodicity cannot be assumed. Thus, we would encourage all such data collection to employ age validation techniques such as radiometric (Radium-226 to Lead-210 ratios) and bomb radiocarbon markers in more deep-sea grenadier species (Andrews *et al*. 1999; Burton *et al*. 2000, Cailliet *et al*. 2001; Kerr *et al*. 2004 & 2005).
Spatial distribution of biomass and structure – The marine environment is very patchy and knowledge of this patchiness must be understood for robust estimates of population biomass and for aiding in stock delineation.
Time series monitoring – This is required to monitor the effect of fishing mortality on the population as well as the potentially dynamic effects on stocks, both fished and unfished, of climate cycles such as El Ninos and decadal climate oscillations (i.e. North Atlantic Oscillation).
Mandatory reporting of catch, bycatch, and discards including composition – This should be required in addition to the Vessel monitoring System stated above.
Reproductive output estimates and recruitment – Currently reproductive output estimates are based solely on female fecundity, but models suggest that some of these species may only spawn every few years (Drazen 2008). Additionally, the distribution and abundance of larvae and juveniles of grenadiers are virtually unknown or very poorly known. Empirical data is lacking and a better understanding of reproductive output is needed. This requires data on fecundity, spawning timing, recruitment, recruitment variability, and the distribution and abundance of larvae and juveniles.

USEFUL – these data are desirable for management but not absolutely required.

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Habitat mapping – Multibeam bathymetric sampling of the habitat areas of fished species would enable informed placement of MPAs and would likely identify at least some VMEs such as coral mounds (Durán Muñoz *et al*., 2009).
Movement patterns – A variety of methods including active tracking, or behavioral studies, would enable an understanding of adult movements. This type of data would allow for a greater understanding of stock structure and the presence of any aggregation behavior among other things. No such data exist currently for any deep-sea species, however, advances in technology are proceeding at a rapid pace and tagging technologies are now available for operation to depths of at least 1,000 m (Sigurdsson *et al*. 2006).
Stock delineation/genetics – Many bathyal fishes have wide geographic ranges (Merrett and Haedrich 1997). However, we know that the North Atlantic is divided into at least three distinct stocks for Roundnose Grenadier (White *et al*. 2009) and Roughhead Grenadier (Katsarou and Naevdal 2001). Nothing is known of the stock structure of other species.
Early life history – Grenadier larvae are extremely rare even after considerable sampling efforts in many parts of the oceans and the often large biomass of the species (Bergstad and Gordon 1994). It is thought that the larvae may not occur in surface waters or may develop very quickly, descending to greater depths than regularly sampled (Merrett and Barnes 1996). What is clear is that knowledge of the early life history of these fishes is an impediment to our understanding of dispersal and stock structure and also to the processes affecting recruitment. Efforts should be made to identify grenadier larvae and understand their spatial and temporal occurrence in the oceans.
Trophic ecology – The diets of grenadiers are diverse (Anderson 2005; Drazen *et al*. 2001; Laptikhovsky 2005; Madurell and Cartes 2006) but often few data are available because the gas in their swim bladders causes stomach eversion upon capture. Biochemical approaches can be useful (Drazen *et al*. 2009; Drazen *et al*. 2008; Stowasser *et al*. 2009) and have shown that some species consume large

quantities of epipelagically-derived carrion. A better understanding of grenadier diets and of their most important predators would allow the use of ecosystem models in their management. This would also be the first information required to evaluate the importance of removal of these animals to deep-sea food webs (Heithaus *et al*. 2008; Pace *et al*. 1999).

CONCLUDING COMMENTS

As a result of our analysis of the literature on these species of grenadier, we feel that the following life history features dictate how their fisheries most likely will act over time. Grenadiers, in general, are: 1) K-selected species; 2) have boom & bust fisheries; 3) often exhibit strong population declines; 4) most likely will have long recovery times; 5) have unpredictable reproductive output and recruitment patterns; and 6) generally do not appear to have clear habitat utilization patterns. If there are to be any sustainable fisheries for these fishes, these traits need to be understood better and then considered in management plans.

Species	Max longevity (yrs)	Age 50% maturity	Natural mortality (m)	Fecundity	Biomass	Fishery type	Spawning season	Depths of max abundance	Current fishing effort (F)	Current management regime
Giant	56	23	0.052-0.079, 0.12	231,000	high	T, LL, BGL	all year	400-1500	Low	TAC (Russia), unregulated (USA)
Pacific	73	20-30	0.057, 0.16	150,000	high-med	T	all year	700-1500	Was high, low now	Unregulated
Popeye	15	3-6	0.295, 0.22	17,000	med	T	all year	400-1400	Low	TAC (Russia), unregulated (USA)
Roundnose	72	10-14	0.1-0.2	70,000	med	T	all year	400-1500	NWA low, NEA high	Regulated (BT closed areas, moratorium (NWA), TAC (NEA)
Roughhead	25	13-16	0.2	80,000	low	T, LL	all year	800-1500	Low	NWA prohibited (BT closed areas), TAC (NEA)
Ridge-scaled	37-42	11-13	Z=0.15	57,000	med	T, LL	Unknown	200-1000	Low	Unregulated (NZ), regulated (CCAMLR)

Table 10. Summary of life history characteristics and current fishing information for large and abundant grenadiers. Fecundity estimates were taken from the literature and may not reflect true estimates if grenadiers do not spawn annually. Fishery type refers to trawl (T), longline (LL) or bottom gill net (BGL). Under Current Management Regime, the letters in parentheses refer to the country or organization of jurisdiction. USA is the United States of America, BT is bottom trawl, NWA is northwest Atlantic, NEA is northeast Atlantic, NZ is New Zealand, and CCAMLR is the Commission for the Conservation of Antarctic Marine Living Resources.

Productivity Attributes	Giant	Pacific	Popeye	Roundnose	Roughhead	Ridge-scaled
r (intrinsic rate of population increase)	1	1	1	1	1	1
Maximum age	1	1	3	1	2	1
Maximum size	1	1	2	1	1	1
von Bertalanffy growth coefficient (K)	1	1	1	1	1	1
Estimated natural mortality	1	1	2	2	2	1
Measured fecundity	2	3	2	2	3	2
Breeding strategy	–	–	–	–	–	–
Recruitment pattern	–	–	–	–	–	–
Age at maturity	1	1	1	1	1	1
Mean trophic level	1	1	2	1	1	2
Ranking	1.13	1.25	1.75	1.25	1.50	1.25
Susceptibility Attributes						
Management strategy	3	3	3	2	3	2
Area overlap	2	2	2	1	1	1
Geographic concentration	2	2	2	2	2	1
Vertical overlap	1	2	1	1.5	1.5	1
Spawning stock biomass level	1	1	1	3	3	1
Seasonal migrations	1	NA	1	2	2	–
School/aggregations	3	2	3	3	2	–
Morphology affecting capture – longline	2	2	NA	NA	2	–
Morphology affecting capture – bottom trawl	3	3	3	3	3	3
Survival after capture and release	3	3	3	3	3	3
Desirability / value of fishery	1	1	1	2	2	1
Fishery impact to EFH or habitat	3	3	3	2	2	3
Ranking	2.08	2.17	2.08	2.38	2.27	1.90
Vulnerability	2.16	2.10	1.65	2.23	1.96	1.97

Table 11. Productivity and Susceptibility scores applied to six grenadier species, resulting in the final assessment of their vulnerability below (see Patrick *et al*. 2010 for further details about attributes and scaling used). Breeding strategy and fecundity were unknown (see text for fecundity). All grenadier productivity estimates assessed the productivity of grenadiers on a global scale (not fisheries specific). An NA meant that attribute was not applicable to grenadiers using the scale of Patrick *et al*. (2010), while a – meant that not enough information was known.

Productivity Attributes – mixed-trawl scale	Giant	Pacific	Popeye	Roundnose	Roughhead	Ridge-scaled
Maximum age	1	1	2	1	2	1
Maximum size	2	3	3	3	3	3
Estimated natural mortality	1	1	3	2	2	1
Measured fecundity	3	3	2	3	3	2
Breeding strategy	3	3	3	3	3	3
Age at maturity	1	1	3	2	2	2
Mean trophic level	1	1	3	2	2.5	1.5
Ranking	1.71	1.86	2.71	2.29	2.5	1.93
Productivity Attributes – grenadier only scale						
Maximum age	1	1	3	1	2	2
Maximum size	1	2	3	2	1	1
Estimated natural mortality	1.5	1.5	3	2.5	3	–
Measured fecundity	3	3	1	2	2	2
Breeding strategy	3	3	3	3	3	3
Age at maturity	1	1	3	2	1.5	2
Mean trophic level	1	1	3	2	2.5	1.5
Ranking	1.64	1.79	2.71	2.07	2.14	1.92
Susceptibility Attributes – grenadier only scale						
Area overlap	2	2	2	1	1	1
Geographic concentration	1.5	1.5	1.5	1	1	1
Vertical overlap	3	2	3	2.5	2.5	3
Spawning stock biomass level	1	1	1	3	3	1
Seasonal migrations	1	1	1	2	2	–
School/aggregations	2	2	2	2	2	–
Morphology affecting capture	2	2	2	2	2	2
Survival after capture and release	3	3	3	3	3	3
Desirability / value of fishery	1	1	1	1	1	1
Fishery impact to EFH or habitat	3	3	3	2	2	3
Management strategy	3	3	3	2	2	3
Ranking	2.05	1.95	2.05	1.95	1.95	2.00
Vulnerability	1.71	1.54	1.08	1.33	1.28	1.47

Table 12. Productivity and Susceptibility scores applied to six grenadier species. All grenadier productivity estimates assessed the productivity of grenadiers on a global scale (not fisheries specific). Productivity attributes were assessed two ways: scaled to the deep-water mixed trawl fishery under the current management (see the Deep-water Mixed Trawl Fishery Group Report for details) and to grenadiers-only, using data for the attributes as specified in Table 1. Susceptibility was the same scale as that used by Cope *et al.* (in press). A – indicated not enough was known about that particular attribute.

Figure 9.
Results of the PSA analysis using the attributes and scaling of Cope *et al.* (in press), see Table 2 for attributes. All grenadier species (globally) are illustrated with black symbols and red symbols are shelf and slope species of the North Pacific (off the California coast).

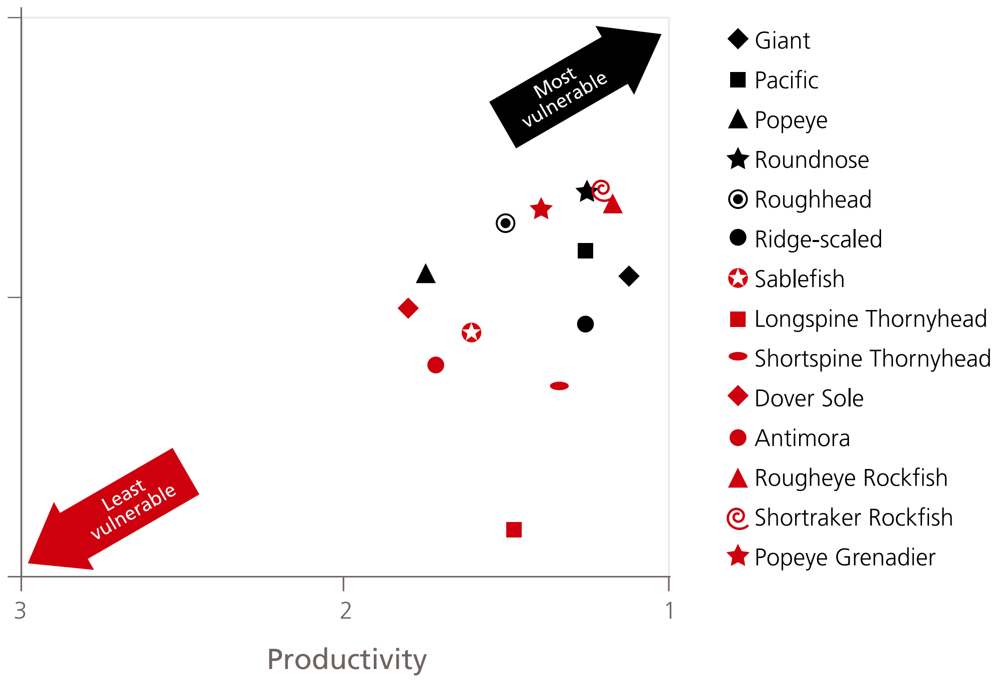
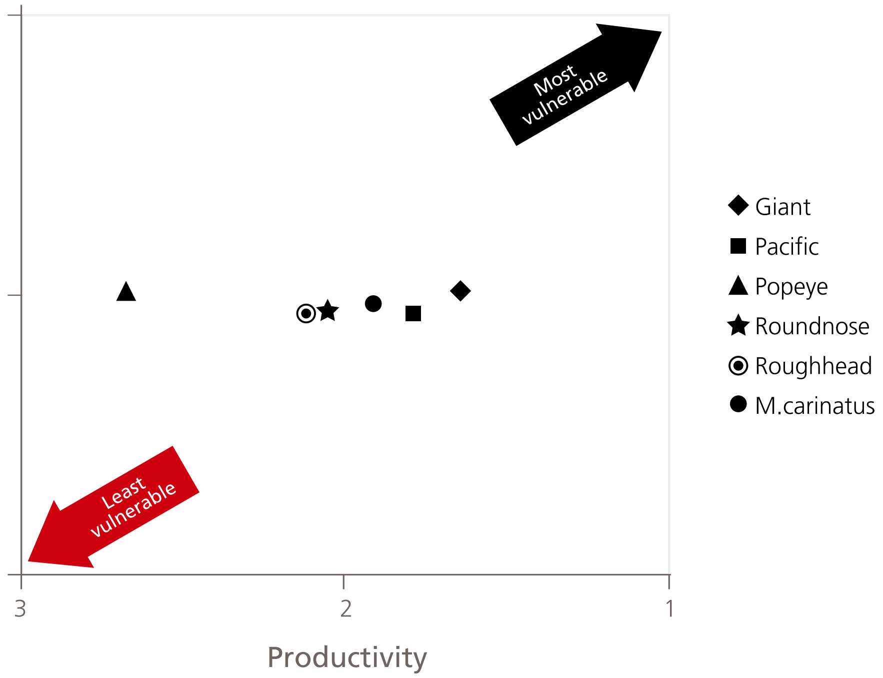


Figure 10.
Results of the PSA analysis using productivity scaled only to grenadier species (global scale, not fisheries specific, see Table 1 for data and Table 3 for attributes) and susceptibility attributes and scaling of Cope *et al.* (in press). An ad hoc Working Group Analysis of the PSA Method



Productivity – Susceptibility Analysis of Deep-Sea Fish Species in a Global Context

Participants:
L. Watling,
J. Drazen,
J. Devine,
M. Dunn,
K. Baker

In the previous analyses in this report, deep-sea fish species were investigated using the productivity – susceptibility analysis (PSA) promoted for United States nearshore and pelagic fisheries by Patrick *et al*. (2009, 2010). All deep-sea species were considered only either within the context of a Northeast Atlantic mixed bottom trawl fishery, or, in the case of the grenadiers, as a taxonomic unit of species caught largely as bycatch. The attributes of productivity and selectivity used were re-scaled from the values in Patrick *et al*. for the particular group of species being considered. For example, in the Northeast Atlantic mixed trawl fishery, values for maximum size, fecundity, age at maturity, etc., were scaled according to the maximum and minimum values known for the 16 species of bony and cartilaginous species either targeted or caught as bycatch in that fishery. On the other hand, the susceptibility attributes used were scaled exactly as in Patrick *et al*. The grenadier group used, for the most part, the attribute scales for both productivity and susceptibility as outlined in Patrick *et al*, with the exception of fecundity, in which case values were halved because it was thought that grenadiers do not spawn every year.

The result of these analyses was that most species in the Northeast Atlantic mixed trawl fishery had susceptibilities below 2, i.e., were not considered to be very susceptible to overfishing. On the other hand, several species in that group, notably the deep-water sharks, had very low productivities and were considered to be highly vulnerable to the effects of fishing. A similar result was produced for the grenadiers, except that in several cases the susceptibility rankings were greater than 2. Most of the grenadiers were also on the lower end of the productivity scale.

On the other hand, we also need to know how the productivity and susceptibility of these deep-sea species compares with various shallow-water and pelagic fisheries, and we decided to use as a basis the results from Patrick *et al*. (2010). Therefore, we re-scaled the data for our deep-sea species for the productivity and susceptibility attribute scales and weighting of variables as in Patrick *et al*., using the spreadsheet provided on the NOAA web page, nft.nefsc.noaa.gov/PSA_pgm.htm. Final scores were then plotted using a standard graphical plotting program (Fig. 11). Finally, means and 95% confidence intervals of productivity and susceptibility values for the nearshore California groundfish species, Northeast US groundfish species, and species in the Atlantic shark complex taken from Patrick *et al*. (2009), along with the values for the Northeast Atlantic mixed trawl fishery and grenadiers caught by trawls, were plotted (Fig. 12) so that the deep-sea fishery species could be compared with their shallow water counterparts.

Using the scales and weighting of attributes from Patrick *et al*. (2010) produced a slightly different picture of the deep-sea species. Only eight of the 21 species had susceptibility values below 2, and all but two species had productivity scores below 2 (Fig. 11). These values suggest that there are several deep-sea species, especially grenadiers and sharks, that are likely to be vulnerable to deep-sea fishing. Interestingly, however, black scabbardfish, greater forkbeard, roundnose grenadier, and two species of sharks had very low susceptibility scores, lower even than most of the shallow water or pelagic species considered by Patrick *et al*. (2010). The two shark species, however, had very low productivity ratings.

When comparing the species in these various groups, plotted with 95% confidence intervals around the means of productivity and susceptibility, some other trends become obvious (Fig. 12). Most noticeably, the productivity scores for the deep-sea groups are quite low, with means of 1.5 or lower. At the same time, however, with the singular exception of orange roughy, the susceptibility scores are also very low, the means being lower than for any of the shallow water species groups. While the confidence intervals for the grenadier group overlaps that of the shallow Atlantic shark complex, suggesting there is no significant difference between the two groups, the productivity and susceptibility attributes for the Northeast Atlantic mixed trawl fishery species are significantly different from the values for any of the shallow water

groups. Interestingly, while the mean productivity of the group is quite low, the mean susceptibility is also quite low, in fact, is lower than for the two shallow water groundfish species groups.

Does this result make sense, or do the susceptibility criteria not reflect the realities of deep-sea fish species life histories and resultant vulnerabilities?

In this analysis, the susceptibility criteria from Patrick *et al*. (2010) that were used included: 1, areal overlap; 2, vertical overlap; 3, seasonal migrations; 4, aggregations or other behavioral responses; 5, morphology affecting capture; 6, survival after capture; and 7, management strategy in place. Criteria not rated included: 1, geographic concentration; 2, fishing rate relative to M; 3, biomass of spawners; 4, desirability/value of the fishery; and 5, fishery impact to EFH or habitat in general for non-targets. From this list one can see that one weakness has to do with the lack of information for most deep-sea species. For example, it is not possible to know or estimate the fishing mortality rate relative to natural mortality rate, and the biomass of the spawning part of the population is unknown.

In addition, all susceptibility criteria rated were given equal weight. Increasing the weights of some criteria raises the susceptibility of the lowest rated species a bit, perhaps as high as 2.0, but the values still do not approach those of the NE United States groundfish species group, for example.

Some of the susceptibility criteria might truly reflect the potential of a species to be vulnerable to the effects of fishing. These would include aggregating or other behavioral responses that would make capture easier by trawls, and survival rate after capture, which for most deep-sea species will be low either due to expansion of the gas bladder or physiological stress due to changing water temperature. Knowing the proportion of spawning stock that is captured, and whether the fishery is occurring during or before the mature fish have been able to spawn, would be useful criteria. Also important would be information regarding the degree to which the take of non-target species affects the food supply of the target species.

Other susceptibility criteria listed by Patrick *et al*. and used here put deep-sea species at a disadvantage when compared with shallow water species. For example, areal and vertical overlap with the fishery can be relatively low if the species is known to range over a whole ocean basin. Such hyperdispersion might mean that not all members of the population are not so easily caught, resulting in a low susceptibility score, but it could also mean that the ability of individuals to find mates when mature will be reduced. In this scheme, such low overlap both vertically and areally is considered to be a positive condition when in fact it might be disadvantageous in the face of fishing pressure. Another example is the criterion of management strategy. If targeted stocks have catch limits and proactive accountability measures and non-target stocks are closely monitored, the attribute is given a low susceptibility score. But this does not account for how badly depleted the stock was at the time the management strategy was finally put in place. Thus, a stock that is currently at 10% of virgin biomass, but is now being managed, is given a lower susceptibility rating than one for which there has been little fishing and for which there is currently no management plan.

This analysis has shown that while the PSA technique might be a useful conceptual tool for looking at the relative vulnerabilities of fish species or species groups, the method has some shortcomings that need to be considered before the tool is used for deep-sea fisheries. The productivity side of the relationship seems to be well estimated, with deep-sea and low fecundity shallow water species being properly placed along the productivity axis, but the susceptibility criteria need to be re-evaluated.

Productivity – Susceptibility Analysis of Deep-Sea Fish Species in a Global Context cont.

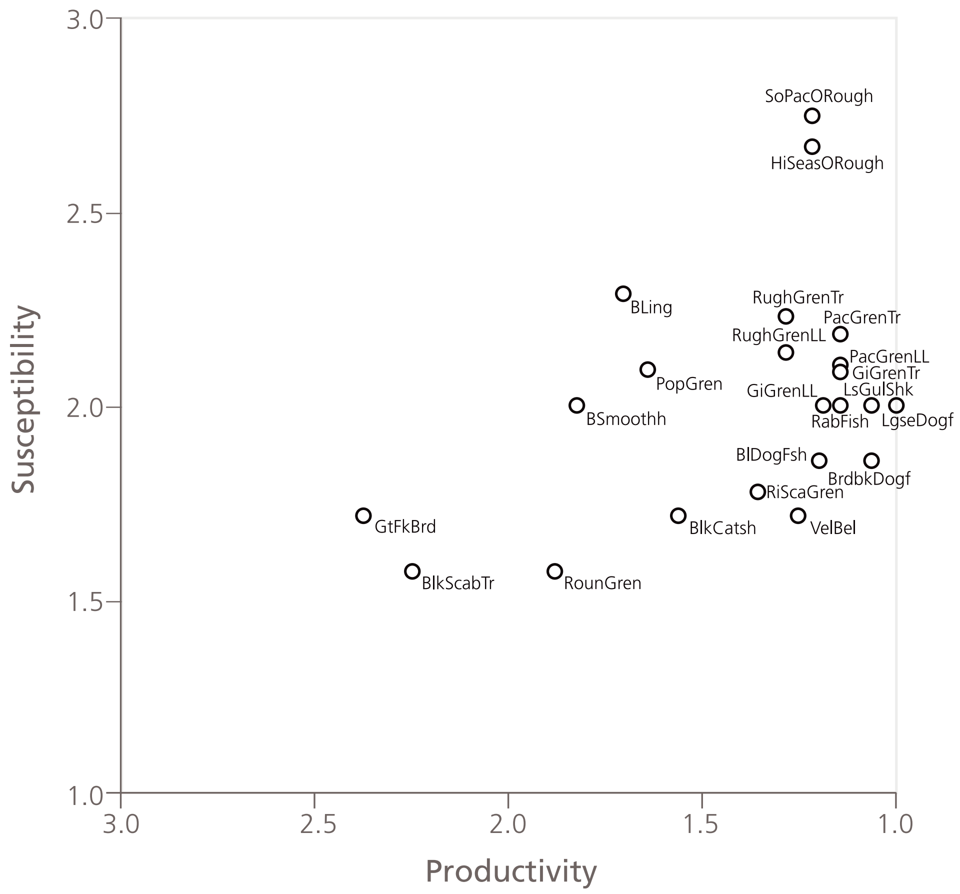


Figure 11. PSA results for deep-sea fish species considered in the mixed trawl fishery, orange roughy, and grenadier assemblage sections of this report.

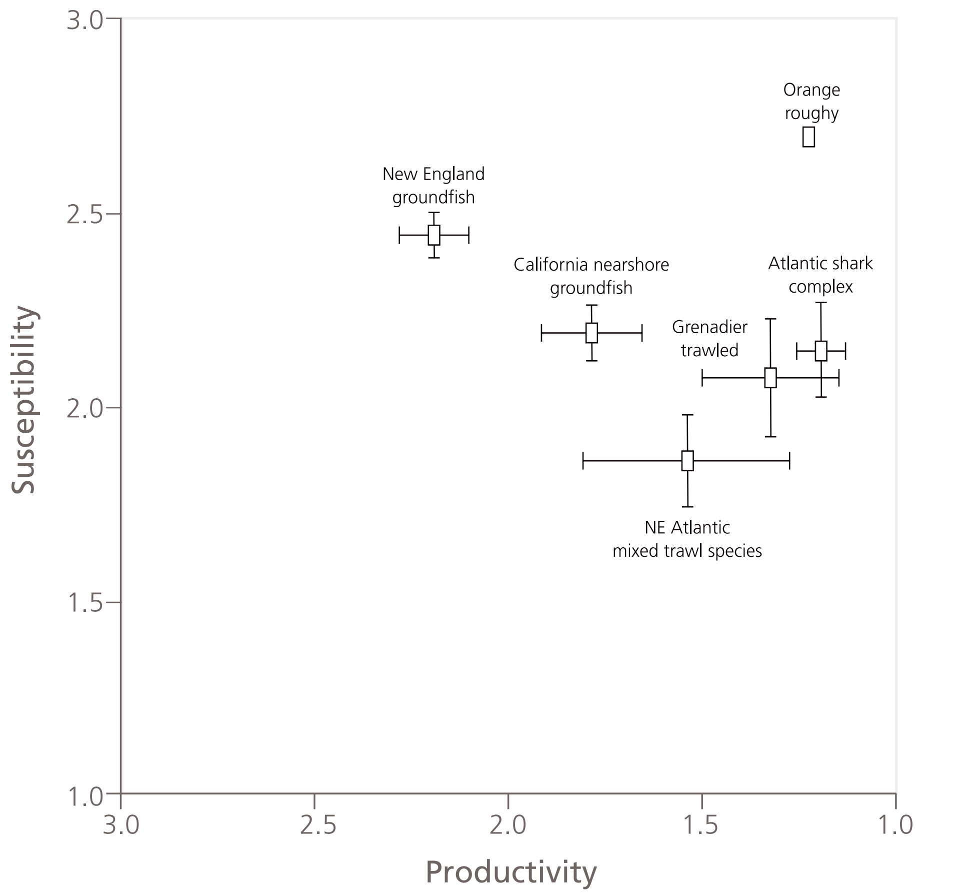


Figure 12. PSA results of deep-sea fish species groups plotted with three species groups from Patrick *et al.* (2010). Values plotted are means +/- 95% confidence limits for both productivity and susceptibility scores.

DEEP-WATER FISHING IN TROPICAL LATITUDES: THE BRAZILIAN EXPERIENCE

Jose Angel A. Perez

The Brazilian Economic Exclusive Zone (EEZ) encompasses an area of 3.5 million Km², mostly bathed by waters of the southwestern Atlantic Ocean. Roughly 25% (911,000 km²) of this area is occupied by the continental shelf that is particularly broad at the northern (north of 2-N), southeastern and southern sectors (south of 23-S). This extensive area is principally influenced by the south Atlantic subtropical gyre and particularly three eastward-flowing water masses that split into northern and southern branches as they encounter the Brazilian continental margin: the Tropical Water (TW, 0 – 150 m depth), the South Atlantic Central Water (SACW, 150 – 500 m depth) and the Antarctic Intermediate Water (AIW, 500 – 1200 m depth). Below 1200 m the North Atlantic Deepwater Water (NADW) flows southwards along the entire continental margin. Biological productivity at the surface is generally low except for the northern and southern extremes of the EEZ where pelagic habitats are moderately enriched by the influence of the Amazon River discharge (north), the north-south oscillation of the Subtropical Convergence and the summer localized upwelling events of the SACW (south) (Rossi-Wongtschowski *et al.*, 2006). The higher productivity and the broad soft sediment-covered continental shelf area contributed for the establishment of a demersal fishing industry in these sectors of Brazilian coast mostly sustained by penaeid shrimps and scienid fish stocks. During nearly 40 years, despite the activity of a continuously growing fishing fleet, annual catches (both pelagic and demersal) remained generally low, when compared with fishing areas in higher latitudes, hardly surpassing 700,000 t. Moreover, by the end of the 1990's, nearly 70% of the known stocks had been fully or overexploited (Haimovici *et al.*, 2006a).

Such economic scenario motivated the occupation of the slope areas both as a survival strategy of the trawl fleet and as an outcome of a governmental deepwater fishing development program. This program stimulated national companies to charter foreign deep-water fishing vessels, which were authorized to operate in the entire Brazilian EEZ, off the 200 m isobath, and fully monitored by VMS and observers (Perez *et al.*, 2003). In 2000 – 2001, in addition to a fraction of the national trawl fleet, foreign gillnetters and trawlers started to operate in Brazilian waters leading the occupation of the upper slope (250 – 500 m) and triggering the commercial exploitation of monkfish (Lophius gastrophysus), argentine hake (Merluccius hubbsi), Brazilian codling (Urophycis mistacea) and argentine short-fin squid (Illex argentinus). In 2002, a pot fishing fleet started to operate on the lower slope (500 – 1000 m) aiming at concentrations of the deep-water crabs (Chaceon notialis and Chaceon ramosae) joined, two years later, by chartered trawlers aiming at deep-water shrimps (family Aristeidae) chiefly the scarlet shrimp (Aristaeopsis edwardsiana). Chartered fishing activity gradually decreased between 2004 and 2007 as many foreign vessels moved away from Brazilian waters. During the 2000 – 2007 period, slope areas were shared by national and foreign vessels, the former predominating since 2004. By the end of 2007, 96% and 66% of all fishing hauls conducted by the chartered fleet were concentrated in the slope off southeastern and southern Brazil (south of 19-S) and on the lower slope (500 – 1000m) respectively (Perez *et al.*, 2009).

Total catches of the main demersal slope targets varied from 5,756 t in 2000 to a maximum of 19,923 t in 2002, decreasing to nearly 11,000 t in 2006. These annual figures have represented 2 to 8% of the total demersal catch landed annually in the same period. Brazilian codling, monkfish and argentine hake were the three most important resources, accumulating catches during the 2000 – 2006 period of 33,877 t, 24,099 t and 14,563 t respectively. Catches of deep-water crabs, monkfish and deep-water shrimps were fully exported to EU and Asian markets rendering approximately 12.4, 8.8 and 8.3 million dollars in the same period respectively (Perez *et al.*, 2009).

Such an explosive fishing development demanded for fast and precautionary management actions as early as 2001. Preliminary assessments of these stocks were restricted to estimates of total biomass available at the fishing grounds using abundant geo-referenced catch rate records produced either by observers on board of the chartered fleet or scientific surveys conducted in 2002. In addition MSY as a fraction of the total virginal biomass available for fishing (MSY/Bo) was estimated for each stock using life history parameters (L∞, K, M; Kirkwood *et al.*, 2004) and regarded as limit reference points. These estimates formed the basis for the management plans proposed for these fisheries whose adoption by Brazilian fisheries authorities was generally slow and incomplete.

All targeted stocks have shown important abundant reductions during the exploitation period. In the upper slope mixed trawl fisheries, for example, biomass reductions of the argentine hake, brazilian codling and monkfish were close to 50% in the first 2-3 years. Until 2008 reported catches were generally higher than the estimated sustainable levels even after the termination of chartered fleet operations in 2003. No signs of recovery were shown by annual abundance indices variation, a pattern particularly critical for the monkfish, which seems to live longer, grow more slowly and reproduce later than the other targeted fish (Table 13). Moreover the species was the sole target of a chartered gillnet fleet which highly contributed to the reduction of the stock abundance between 2001 and 2002 (Perez *et al.*, 2005).

Analysis of non-intentional catches have been conducted using samples collected by observers and used to incorporate ecosystem-focused management measures into the proposed management plans. That included, for example, two no-take areas on the slope off southeastern and southern Brazil designed to protect monkfish populations and also the main bycatch components (wreckfish, sharks, rays, birds and others) (Perez, 2007).

DEEP-WATER FISHING IN TROPICAL LATITUDES: THE BRAZILIAN EXPERIENCE

Jose Angel A. Perez

The lower slope trawl fishery directed at deep-water shrimps has been of particular concern in that matter, since it can produce significant catches of truly deep-water forms, such as rattails, alfonsinos, oreos, deep-water corals and others.

In summary the short-lived Brazilian deep-water fishing episode has produced some important lessons about exploitation of demersal resources beyond continental shelves:

- Opportunities for sustainable deepwater fishery in regions where productivity is relatively low at the surface (i.e. tropical latitudes) are even lower than in high-productivity ones.
- Fish stocks exploited in Brazilian slope areas were not typical deepwater resources, from a life-history perspective, but still decreased very rapidly to biological unsafe conditions, probably due to their originally small population abundance.
- Incentives for development of such fisheries, such as the chartering program, while important for data acquisition, may exceed the fishing capacity required for sustainability.
- Only a very small (few fishing units) highly controlled fisheries can be envisioned to be sustainable on slope areas off Brazil.
- Having VMS and Observers in 100% of fishing trips is critical not only as a source of the targeted stock data, but also as the only way to acquire information on the demersal and benthic community structure affected by the fishery.
- Assessment initiatives must be conducted promptly and use holistic (biomass) models to come up with precautionary recommendations in the early stages of the fishery.
- Management must act very fast to implement those measures. Brazilian management system was not fast or effective enough.

	Loo		K		Max Age	Female maturity		1st catch		M	F/Z	MSY/Bo
	Male	Female	Male	Female		Size	Age	Size	Age			
Monkfish [1,2]	55.1	94.6	0.30	0.12	>18 yrs	51.7	~8 yrs	26.7	~4 yrs	0.25	0.61	0.06
Argentine Hake [3]	47.5	65.7	0.35	0.26	~12 yrs	35.7	~6 yrs	20.6	~1 yrs	0.30	0.68	0.10
Brazilian Codling [4]	50.7	69.9	0.20	0.15	~14 yrs	43.9	~2 yrs	26.5	~2 yrs	0.30	0.66	0.09

Table 13. Life history and fishing parameters estimated for three fish targets of the mixed fishery conducted on the slope areas of southeastern and southern Brazil. Length measures are in cm.

1. Lopes, 2005
2. Perez et al, 2005
3. Vaz-dos-Santos & Rossi Wongstchowski, 2005
4. Haimovici et al, 2006b

Habitat Impact of Deep-Sea Fisheries

Participants:
L. Watling in consultation with the other break-out groups.

Introduction and Methods

Deep-sea fisheries are primarily conducted with the use of bottom trawl gear, which is both large and heavy. However, in some areas, bottom longlines are used. Both bottom gear fisheries can cause habitat damage when the fishing grounds overlap with the distribution of vulnerable marine ecosystems (Bavestrello *et al*., 1997; Roberts *et al*., 2000; Krieger, 2001; Fosså *et al*., 2002; Reed, 2002; Hall-Spencer *et al*., 2002; Davies *et al*, 2007). To place these fisheries in an ecosystem management framework, the habitat impacts of the fishing method needs to be considered. Watling and Norse (1998) and Norse and Watling (1999) developed criteria for assessing the habitat impact of bottom contact fishing gear, taking note of the severity, frequency, and return interval of the gear on bottom habitat.

Severity (S) is a measure of the degree to which the bottom is modified either by mixing of sediment or removal of erect, stationary, bottom dwelling species. Severity can also be considered in terms of the force applied to the sea floor by the fishing gear. Bottom trawls were determined to have high severity by Watling and Norse (1998) because most trawls are kept on the bottom by heavy doors, or the footrope of the trawl is armored with bobbins or disks; therefore a fish species caught by bottom trawls is scored, S=3. Bottom hook and gill net fishing methods apply little force to the bottom, but they often remove erect bottom fauna, so the severity rating of bottom long-line or gill net fisheries is moderate (S=2). Fishing with one hook per line likely results in only small numbers of bottom animals being removed; thus the severity of individual fishing lines is low (S=1).

Frequency (F) is the percentage of habitat area disturbed per year. Trawl gear covers large areas of the bottom, depending on the width of the trawl and duration of the tow. The number of tows conducted will add to the total area covered on an annual basis. If the fishery disturbs >5% of the habitat of a target species on an annual basis, then frequency is rated as high (F=3); less than 5% is moderate (F=2), and less than 1% is low (F=1). For deep water species these estimates are hard to derive. An alternative is to consider the proportion of ICES squares actually fished for the target species relative to all ICES squares at the appropriate depth in the area of interest of the fishing nations. If more than 50% of the squares have been fished, F=3, 10-50%, F=2, less than 10%, F=1.

Return interval (RI) is a measure of how often the area is disturbed. This measure is important relative to the longevity of the bottom-dwelling species disturbed or removed. If the return interval is less than the average life span of the species being removed, then return interval is high (RI=3). If several generations of recruits are allowed to re-establish themselves in the disturbed area before disturbance occurs again, then return interval is low (RI=1).

A habitat impact score can be derived in at least two ways: 1) habitat score, recorded as proportion of maximum possible, adding only those components that have been scored; a score of 1 indicates the fishery received the maximum score of 3 in each category; and 2) following Patrick *et al* (2010), a Euclidean distance habitat impact value was calculated using the values for the three categories. In the latter case the score is calculated as sqrt((S^2-1) +(F^2-1) + (I^2-1)) (Figure 13), with the maximum distance = 3.464. These scores were combined in a 3-dimensional Euclidean calculation with productivity and susceptibility scores to produce an overall Ecosystem Impact Value for each fishery species.

BLUE LING

Habitat impact score: 1.0 for ICES areas VI & Vb; 0.5 for ICES area Va;
Habitat impact distance: 2.828.
Severity: this species was caught mostly as bycatch in a mixed species bottom trawl fishery until a longline fishery started in ICES subarea Va. Since trawls are used in many ICES subareas, the severity for this species is rated as high (S=3), but could be rated as moderate in ICES subarea Va. (S=2)
Frequency: Trawl fisheries are extensive in ICES areas VI and Vb, so frequency is probably high (F=3), but should be quite low in the longline area, Va (F=1).
Return Interval: it is not known how many tows have been taken, or how often areas are fished, so RI is unknown (RI=?).

BLACK SCABBARDFISH

Habitat impact score: trawl area, 0.78; mixed trawl and longline area, 0.78; longline area, 0.33. **Habitat impact distance, trawl area:** 2.828.
Severity: in areas where there is a trawl fishery, severity is high (S=3), but in longline areas S=1, and perhaps 2.5 for areas where the fishery is both a trawl and longline fishery. The longline fishery generally uses a method where the hooks do not impact the bottom.
Frequency: this is difficult to estimate since we have cpue data but no clear delineation of effort distribution. Even so, from ICES WGDEEP 2010, it can be seen that effort aimed at this fishery is widespread over the preferred depth range of the fish. Therefore, F = 3 for trawl and perhaps F=1 for the longline fisheries, and F=2.5 for the mixed trawl and longline areas.
Return Interval: on the assumption that areas of the bottom are repeatedly trawled, and that most of the species in the area are shorter-lived infaunal dwellers (that is, there is no information on bycatch indicating that large, erect species were present in the trawl area) scores are assigned as RI=1 for trawl areas, RI=2 for mixed trawl and longline areas, and RI=1 for longline areas. The latter score is based on the fact that longlining occurs repeatedly in a relatively small areas of the bottom, so even though only a few erect species will be brought up each time, the species taken are long-lived and won't be replaced in a meaningful time frame.

GREATER FORKBEARD

Habitat impact score: 0.78.
Habitat impact distance: 2.828.
Severity: this species is taken primarily as bycatch in the Northeast Atlantic mixed trawl fishery, S=3.
Frequency: here it is assumed that trawl frequency will be the same as for black scabbardfish, the primary species in the mixed trawl fishery., F=3.
Return Interval: same as for black scabbardfish, RI=1.

ROUNDNOSE GRENADIER

Habitat impact score: 0.78.
Habitat impact distance: 2.828.
Severity: In ICES areas where bottom trawls are used (Faroe-Hatton, Skagerrak, and Celtic Sea), S=3. On the Mid-Atlantic Ridge (MAR), fish are currently caught primarily with pelagic trawls the impact of which cannot be determined at this time
Frequency: In the bottom trawl area, most of the effort covers more than 50% of the appropriate ICES squares, so F=3.
Return Interval: the fauna in the area where trawling is conducted for this species is primarily composed of sediment dwellers. Most of those species will have life spans of less than 5 years, and so recolonization of the areas disturbed by trawl gear is likely to occur successfully before that area of the bottom is trawled again. RI=1.

ORANGE ROUGHY

Habitat impact score: 1.0.
Habitat impact distance: 3.464.
Severity: this species is fished primarily with deep water bottom trawl gear designed to slide along the surface of the seamount or ridge area where the fish aggregate, resulting in near complete removal of all erect fauna, S=3.
Frequency: although somewhat harder to estimate, it should be noted that fishing of seamounts is for the most part a sequential depletion fishery. Thus the area to be fished is continually moving to unfished areas leaving previously fished areas behind. In addition, when a seamount is fished for this species it is usually fished heavily until the aggregation is removed. F=3.
Return Interval: since the seamount fishery is sequential, and moves from one seamount to another (for the most part), it is not likely that a previously fished seamount will be fished again. However, since most of the species removed from the seamount are very long-lived (hundreds to thousands of years) and have low recolonization potential, perhaps on the order of a century or more, then any repeat fishing on that seamount within 100 years would signify a high return interval. RI=3.

GIANT AND POPEYE GRENADIER

Habitat impact score, bottom trawl areas: 0.78.
Habitat impact distance: 2.828.
Severity: caught by bottom trawl in NW Pacific (S=3) and with longlines in Alaska, where there is erect fauna along the Aleutian Ridge and in the Gulf of Alaska, but erect fauna is sparse in the Bering Sea (S=2). Only giant grenadiers are caught on longlines.
Frequency: between 25 and 50% of the area is trawled, F=3, and very little area is impacted by longlines (F=1)
Return Interval: in the trawled area any spot might be trawled again rarely, due to especially to low level of effort (RI=1). Longline fishery is not likely to disturb the same spot more than once over the generation time of the species (R=1).

PACIFIC GRENADIER

Habitat impact score: 0.55.
Habitat impact distance: 2.000.
Severity: the fishery where this species is taken uses primarily bottom trawls, S=3.
Frequency: only a small area out of all possible habitat area is fished for this species, F=1.
Return Interval: there is little evidence of repeat fishing even though the area fished is small, RI=1

ROUGHHEAD GRENADIER

Habitat impact score: 1.0 for trawl fishery, 0.37 for longline fishery.
Habitat impact distance: 3.464 for trawl fishery, 0.500 for longline fishery.
Severity: Trawl gear, S=3, longlines S=1
Frequency: trawl F=3, longlines F=1.5
Return Interval: RI =3, longlines RI = 1

RIDGE-SCALED GRENADIER

Habitat impact score: 0.78.
Habitat impact distance: 2.449
Severity: this species is taken largely as bycatch in the bottom trawl fishery for orange roughy, S=3.
Frequency: around NZ and Falkland Islands, most of the appropriate area is trawled, due to patchiness of the fishing effort, F=2.
Return Interval: intensity of fishing is patchy over a wide area RI=2.

Deep-sea fisheries that depend on the use of bottom trawl gear do considerable damage to the bottom habitats in which the fishing occurs

Conclusions

Deep-sea fisheries that depend on the use of bottom trawl gear do considerable damage to the bottom habitats in which the fishing occurs. In some fisheries the damage is limited due to the small area that is being fished, but it is not known how much bottom habitat can be disturbed on a regular basis before the bycatch species begin to decline in abundance or face the possibility of local extinction. Shepard *et al* (2010) have shown, for example, that bottom trawling can diminish the overall productivity of the bottom community and Kaiser *et al* (2002), among others, have documented long term changes in the bottom communities in the North Sea region in areas where bottom trawling is frequent. It is now well-known that deep-sea corals and sponges often live for centuries and most likely have very low recovery potential. Smaller invertebrates have much shorter life-times, but if the frequency of trawling is high, even those species may have difficulty recovering their former abundance. In addition, little is known about the time required for the sediment to restore the properties that make it possible for sediment-dwelling animals to re-establish themselves.

To determine the potential ecosystem impact of fishing, the vulnerability measure of Patrick *et al*. (2010) was extended by combining the habitat distance score with the productivity and susceptibility scores into a Euclidean distance measure of ecosystem impact. These three variables are plotted in Figure 14 and the values used are summarized in Table 14. Two fisheries reviewed here, those for orange roughy and roughhead grenadier, have the highest possible habitat impact values while six of the remaining ten trawl fishery species have moderately high values. Fisheries using longlines generally have ecosystem impact values below 2.

Fish Species	Severity	Frequency	Return Interval	Habitat Impact Score	Habitat Distance Score	Productivity	Susceptibility	Ecosystem Impact Value
Orange Roughy	3	3	3	1	3.464	2.14	3	3.967
Roughhead Grenadier	3	3	3	1	3.464	1.5	2.27	3.855
Roundnose Grenadier	3	3	1	0.78	2.828	1.25	2.38	3.458
Giant Grenadier	3	3	1	0.78	2.828	1.13	2.08	3.414
Popeye Grenadier	3	3	1	0.78	2.828	1.75	2.08	3.118
Blue ling	3	3	0	1	2.828	2.29	2.29	3.027
Ridge-scaled Grenadier	3	2	2	0.78	2.449	1.25	1.9	2.978
Greater Forkbeard	3	3	1	0.78	2.828	2.71	2	2.842
Black scabbardfish	3	3	1	0.78	2.828	2.43	1.83	2.830
Pacific Grenadier	3	1	1	0.55	2.000	1.25	2.17	2.726
Black Scbbardfish Longline	1	1	1	0.33	0.000	2.43	1.83	0.117
Giant Grenadier Longline	2	1	1	0.44	1.000	1.13	2.08	2.159
Roughhead Grenadier Longline	1	1.5	1	0.37	0.500	1.5	2.27	1.764
Popeye Grenadier Longline	2	1	1	0.44	1.000	1.75	2.08	1.651

Table 14. Summary of habitat impact, productivity, and susceptibility values used to determine Ecosystem Impact Value for each fishery species.

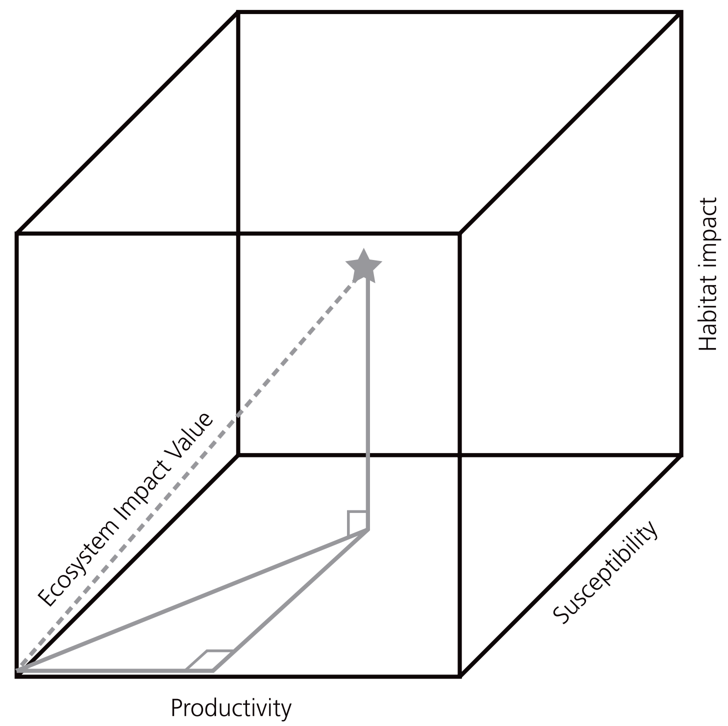
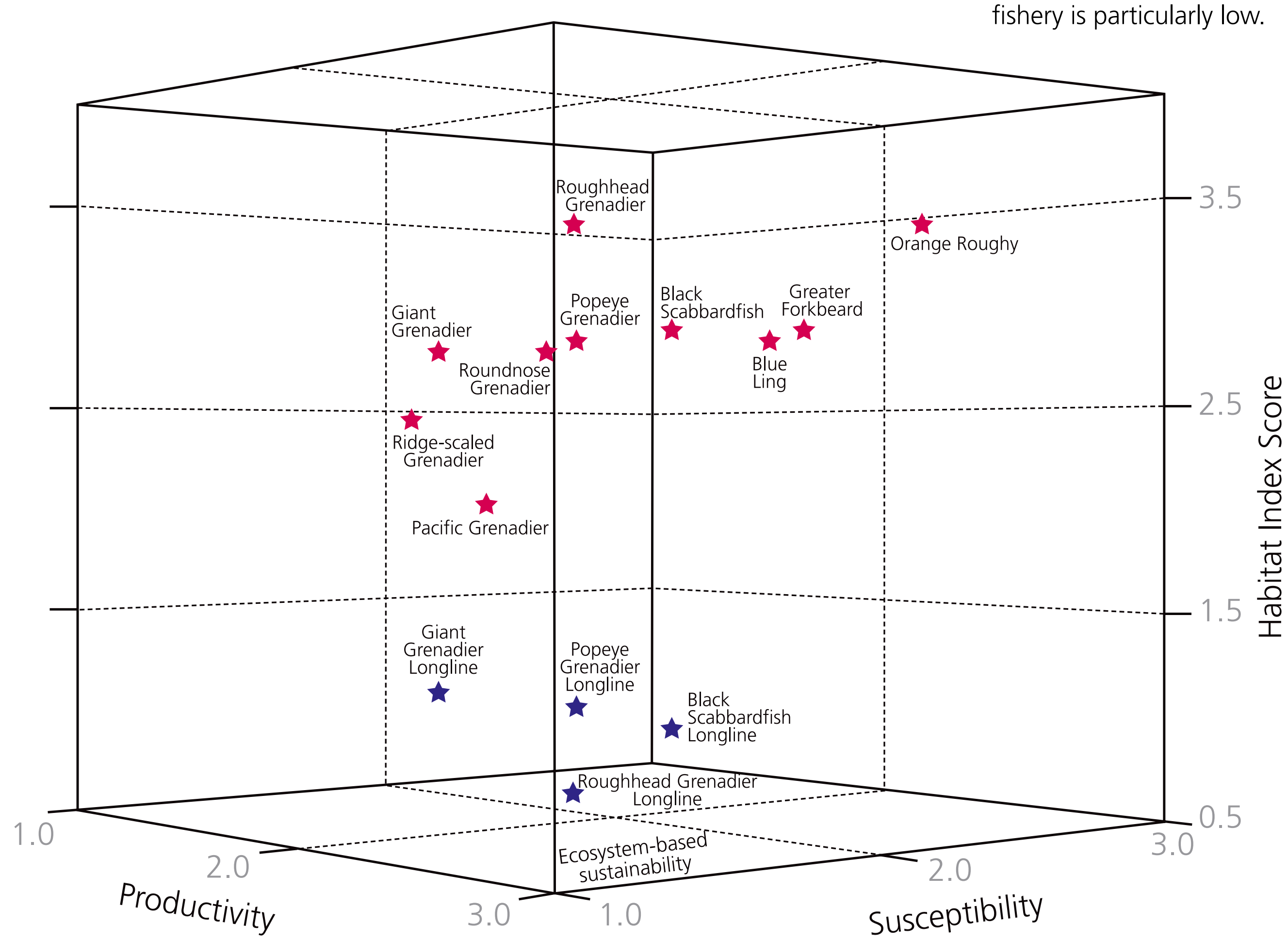


Figure 13. The three factors making up the Ecosystem Impact Value are productivity, susceptibility, and habitat impact distance. These factors are combined using a 3-dimensional Euclidean distance calculation.

Figure 14. Ecosystem Impact of Fishing is determined by plotting each species in 3-dimensional space according to the productivity and susceptibility scores, and the habitat impact distance factor. Orange Roughy and Roughhead Grenadier have the highest overall Ecosystem Impact Score, the teleosts of the Northeast Atlantic taken by long lines (purple) are lowest, and the mixed trawl fisheries and grenadier complex are intermediate. None of the scores for a trawl fishery is particularly low.



Summary and Conclusions

The UN General Assembly has recognized that deep-sea fisheries might not be sustainable and that the damage to vulnerable marine ecosystems might be too great.

Background legal and fisheries framework

1. The UN General Assembly has recognized that deep-sea fisheries might not be sustainable and that the damage to vulnerable marine ecosystems might be too great. In 2009 the UN General Assembly endorsed a set of guidelines proposed by FAO for management of deep-sea fisheries in high-seas areas. These guidelines require conducting impacts assessments to minimize ecological damage as well as to identify and to protect the vulnerable marine ecosystems .

2. Most fish stocks are routinely assessed with quantitative models, but for deep-sea species the data are often too incomplete for the model to accurately or precisely determine the level of the stock, the proportion of mortality due to the fishery, and the sustainable yield. Thus, at present it may be more appropriate to look at sustainability of deep-sea species by using qualitative or semi-quantitative models, such as the productivity – susceptibility model, which attempts to match life history features with management factors.

3. In some areas of the ocean, such as the North Atlantic, widespread species may consist of several genetically distinct populations that in the long run may need to be managed as independent stocks, due to their varied responses to environmental variables and to fishing pressure. Contrary to popular belief, homogeneous, panmictic populations are the exception, not the norm for deep-sea species.

4. Commercially exploited deep-sea fish may be evolutionarily related to continental shelf species, or may be evolved from species with a long history in the deep ocean. Species with shallow-water relatives will have population and metabolic characteristics more like shallow water species and they will be different from those whose ancestors have lived in the deep for millions of years.

Fishery Case Studies: Summaries of What is Known

5. Orange roughy is a relatively well studied and very long-lived (at least 100 years) globally distributed fish that forms spawning and feeding aggregations on flat grounds, but especially around seamounts, ridges, hills, and drop-offs, in water of more than 500 m depth. Little is known about some aspects of the life history of this species. Orange roughy are caught with large bottom trawls, and consequently environmental damage is severe. The fishery has frequently demonstrated serial depletion of fish aggregations. Most stocks of orange roughy are now believed to be depleted, and several fisheries are closed.

6. Blue ling also forms spawning aggregations around seamounts and banks in the North Atlantic and is susceptible to sequential depletion. Maximum age is about 17 years with maturity reached at about 6 years. In spite of the high fecundity, exploitable biomass has been steadily dropping.

7. Black scabbardfish appears to have an unusual life history, spawning in the southern part of its range with the juveniles developing in the northern area. The fishery in the north is promulgated with trawls but in the south bottom longlines are used. Catches in the north have been declining but have remained steady in the southern part of its range.

8. Deep-water sharks and their relatives are under severe threat. Most species that have been examined show very little population rebound potential, primarily due to their low reproductive rate. However in general, population biology information for most species is limited or non-existent.

9. Grenadiers in the North Atlantic grow slowly and mature around 10-14 years. Fecundity is moderately high, but stock biomass indices are declining precipitously. Population recovery time estimates for these species are thought to be on the order of several decades. Two species are now listed as threatened (CITES) in the western North Atlantic.

10. Grenadiers in the North Pacific are biologically similar to those in the North Atlantic with slow growth and moderate fecundity. They are taken by both Russian and American fishing industries. Landings have remained steady in both US and Russian EEZs and remain a small fraction of total biomass estimates. Along the western slope of the US grenadiers are taken mostly as bycatch and are discarded.

Sustainability of deep-sea fisheries

DEFINING A DEEP-SEA FISH BASED ON LIFE HISTORY AND PHYLOGENETIC CHARACTERISTICS

11. While the term deep-sea fishery applies to any species caught at depths below the continental shelf, a deep-sea fish may have certain life history characteristics depending on whether the species is derived from a shelf species or whether it has a long evolutionary history in the deep ocean. The latter have been termed "ancient" or "primary" deep-sea fishes and the former are labeled "secondary".

12. In the North Atlantic, the top five commercially important fish species are secondarily-derived deep-sea species. The next five most important species are all primary and are all recent additions to the deep water fishery.

In the North Atlantic, the top five commercially important fish species are secondarily-derived deep-sea species

13. An examination of the biological characteristics of 41 species of shelf-dwelling and deep-sea fish suggests they can be arranged into three groups: 1) a group consisting of only ancestral deep-sea species; 2) a group containing some ancestral species and some secondary species that are mostly slope dwelling species; and 3) a mixed group of shelf and slope-to-shelf species.

14. Depth of occurrence explains most of the variability in life history attributes, such as age at 50% maturity, growth rate, maximum fecundity, and the potential rate of population increase. These features are most likely a response to environmental gradients that occur with depth, such as increasing pressure, decreasing light level, temperature, food availability, and animal biomass.

ORANGE ROUGHY

15. Most orange roughy fisheries have historically been boom and bust, with stocks depleted in the North Atlantic, off southern Africa, and in the South Pacific. The fishery is often characterised by sequential depletion of fish aggregations, with only a few fisheries around New Zealand and Australia being prolonged, most likely due to the relatively large stocks, and effective fishery management systems.

16. Orange roughy stocks have been difficult to assess, and monitoring of stocks is difficult. Knowledge of stock size and trajectory is a key requirement for management, and therefore a sustainable orange roughy fishery must focus on stocks where credible monitoring and assessment can occur.

17. Fishing for orange roughy requires the use of large and heavy bottom trawls, that have a severe impact on vulnerable deep-sea fauna. A sustainable orange roughy fishery, therefore, must also be one that minimizes bottom contact.

18. A sustainable orange roughy fishery must have a credible monitoring, control, and surveillance system. Many orange roughy fisheries have not operated with effective monitoring, and have not been sustainable.

To be sustainable, an orange roughy fishery might focus on spawning aggregations on flat ground where biomass levels can be monitored using acoustic methods

19. To be sustainable, an orange roughy fishery might focus on spawning aggregations on flat ground where biomass levels can be monitored using acoustic methods, with catch limits set from these biomass estimates using a demonstrably robust harvest rule.

20. The experience of orange roughy is not unique. Other deep-sea commercial fishes, such as oreos and black cardinalfish, have proven equally difficult to study. The lesson from orange roughy is that deep-sea fisheries will be difficult and expensive to monitor and assess, should be controlled carefully to prevent overcapacity and ecosystem damage, and should follow a precautionary approach.

NORTHEAST ATLANTIC MIXED TRAWL FISHERY

21. The Northeast Atlantic mixed trawl fishery primarily targets blue ling, roundnose grenadier and black scabbardfish with deep water sharks often taken as bycatch. It is estimated that stocks of roundnose grenadier and black scabbardfish have declined by 50%, blue ling by 75%, and deep water sharks by over 90%.

22. A productivity – susceptibility analysis of 16 key species (5 targeted teleosts, 10 sharks, and one chimaera) was done to assess vulnerability of the species commonly caught as part of this fishery. The analysis followed the methodology of Patrick *et al* (2010), but fewer variables were used and the variables were not weighted. Three management scenarios were considered: 1) continue current practices; 2) ban all trawling below 1000 m depth; and 3) ban trawling during the blue ling spawning season.

23. Under the current management regime, the most vulnerable species was blue ling, followed by a group of sharks and the chimaera. The least vulnerable species were black scabbardfish and roundnose grenadier. Current take of large deep sharks is unsustainable. These species are at <10% of initial biomass and probably cannot recover at present bycatch rates. Blue ling is vulnerable to overfishing because of its aggregating spawning behavior. Black scabbardfish and greater forkbeard are intrinsically productive and the stock could be rebuilt by fishing stocks when they are not concentrated.

24. Changing the management regime to limit trawling to depths shallower than 1000 m reduces the vulnerability of three deep shark species, reduces slightly the vulnerability of most other species, but increases the vulnerability of greater forkbeard due to probable increased effort on the upper slope habitat favored by this species.

25. Changing the management regime to eliminate trawling during the blue ling spawning aggregation season reduced the vulnerability of blue ling considerably, but the susceptibility attributes of the other species remained unchanged.

26. It may be potentially feasible to sustainably fish non-spawning stocks of the bony fishes in this fishery, but it is currently impossible to avoid bycatch of the vulnerable deep water sharks and relatives, whether using trawls or hooks.

GRENADIER FISHERIES

27. While there are a few targeted grenadier fisheries, most grenadier species are taken as bycatch in other deep-sea fisheries. However, reliable catch statistics are available only for a few of the larger grenadier species.

28. Grenadiers typically are long-lived, have slow growth, mature late, have moderately low fecundities, and may not reproduce every year, all features that might put the species at risk under commercial exploitation.

29. A productivity – susceptibility analysis indicated that popeye, roundnose, and roughhead grenadiers were more productive than giant, Pacific, and ridge-scaled grenadiers. All species examined were determined to be approximately equally susceptible to fishing pressure.

30. A sustainable fishery for grenadiers must have very low fishing mortality, which also means that the degree to which grenadiers are caught and discarded as bycatch needs careful monitoring.

DEEP-SEA FISH PRODUCTIVITY – SUSCEPTIBILITY ANALYSIS IN A GLOBAL CONTEXT

31. A post-workshop analysis of the deep-sea fish species in the previous sections was conducted. The species were rated according the broad criteria used for shallow water species in Patrick *et al*. (2010). The grenadiers and deep water sharks were seen to have very low productivity ratings.

32. A few species, related to shallow water bony fishes, had moderate to high productivities and also had very low susceptibility ratings.

33. Several species, including some of the deep water sharks, also had low susceptibility ratings. An examination of the susceptibility criteria used by Patrick *et al*. (2010) and by our working groups suggested that the some of the criteria used might not be appropriate, whether for shallow water or deep species.

HABITAT IMPACTS OF DEEP-SEA FISHERIES

34. Deep-sea fisheries are conducted primarily with bottom trawl gear, with bottom longlines used in some areas. Both bottom gear fisheries can cause habitat damage when the fishing grounds overlap with the distribution of vulnerable marine ecosystems (VMEs). To fish at depths reaching 1500 m or more, bottom trawls need to be large and heavy, and when they impact the bottom, the damage to the bottom habitat is extensive and severe. Damage to the bottom from longlines is much more highly localized, but erect epifauna, such as corals and sponges, can still be removed.

To fish at depths reaching 1500 m or more, bottom trawls need to be large and heavy, and when they impact the bottom, the damage to the bottom habitat is extensive and severe

35. An analysis of habitat impacts of fishing was completed by rating the severity, frequency, and return interval of the method used to take each fish species. Orange roughy and roughhead grenadier fisheries had the highest possible habitat impact rating, while the longline fisheries were generally rated the lowest.

36. Species with low vulnerability ratings (e.g., the species of the Northeast Atlantic mixed trawl fishery) often had high ecosystem impact ratings because they were fished using bottom trawls. It is suggested that the habitat damage will eventually reduce the capability of the species to replenish itself in the bottom trawl areas, and may be one reason why most of these fisheries are at such low biomass levels compared to when trawling commenced.

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Background: Discarded trawl net, Nashville Seamount, 2500 m **Photos:** Claire Girard

Grenadier (*Nezumia* sp.)