DEEPFISH Project

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DEEPFISH Project:

Applying an ecosystem approach to the sustainable management of deep-water fisheries.

Part 2:

A new approach to managing deep-water fisheries.

Marine Institute
UNIVERSITY OF PLYMOUTH

SAMS report no. 259b

SCOTTISH ASSOCIATION for MARINE SCIENCE

Contents

Executive summary

Deep-water fisheries are relatively new having only developed in the last 40 years. However, in their short history they have already had a significant impact on deep-water fish populations with most commercial species being harvested 'outside safe biological limits' and some species regarded as critically endangered. The long term future of these fisheries, and thus the communities that depend on them for economic and social stability, looks bleak.

Traditional fisheries management techniques in the form of total allowable catches were only recently (2003) applied to the deep-water fisheries of the NE Atlantic. This type of approach to fisheries management has arguably failed to prevent the collapse of shelf fisheries and is considered unlikely to be successful as a means of managing deep-water fisheries. A new 'ecosystem approach' to fisheries management has been called for globally, most recently by the European Parliament. One facet of the ecosystem approach involves consideration of the interactions between fish, fisheries and their environment. One of the most basic ways in which species interact is through predator-prey relationships - who is eating who. These type of interactions can be particularly important in the food-limited deep sea. Fishing can be regarded as the ultimate predator, selectively removing certain species at a faster rate than others. If we can construct a model of the food web, with fisheries as a member, we can begin to examine the impact of fisheries on ecosystems. In addition, we can identify the ecosystem impacts (and the impacts on other commercial species) of changes in fishing effort or catch.

Ecosystem modelling is one way in which we can begin to take an ecosystem approach to fisheries management. The Ecopath with Ecosim (EwE) food web modelling approach has been described as 'excellent' in its ability to conduct assessment and policy exploration. It is conceptually simple and has minimal data requirements and thus is highly suited to application to deep-water fisheries for which data are generally limited.

The deep-water fisheries of the Rockall Trough (ICES Division VIa) are some of the oldest deep-water fisheries in the world. This region is also one of the most well studied deep-sea regions in the world. As a result there is a relatively rich dataset from this region with which we can describe the pre and post fishery ecosystem. We have used best available data to construct an EwE model of the deep-water fisheries (400-2000m) of ICES Division VIa. This represents the first attempt to build an ecosystem model of a large scale multinational deep-water fishery. Details of the model construction are provided in a separate report (DEEPFISH Project: Part 1). The developed model performs well for those species for which we have good biomass data, however we are less confident over results produced for species where the baseline data covering estimated biomass is poor.

The model illustrates the well reported declining trend in biomass for most fish species since the onset of fishing. We have used the model to make predictions on the future of the fishery if fishing is sustained at current levels to 2020. The model suggests the newly lowered TACs should lead to recovery of some species, while for others the TAC would need to be lowered further still. In order to demonstrate the benefits of taking an ecosystem view of the fishery, we have used to model to investigate interactions between fish and fisheries in the model area. Hypothetical removal of the blue whiting fishery from 2007 to 2020 revealed the importance of this species in the diet of many demersal fish species and the importance of interactions between the blue whiting and demersal fisheries.

Improved data quality and availability will produce a model which can be used for more detailed management and policy analysis. This project has demonstrated that it is possible to develop ecosystem models of deep-water fisheries, and that a more holistic approach can reveal more about the complex fisheries interactions that would not be apparent through more traditional approaches to fisheries management. Ecosystem modelling, while not the single answer to deep-water fisheries management, certainly needs to be included in the tool kit available to fisheries managers.

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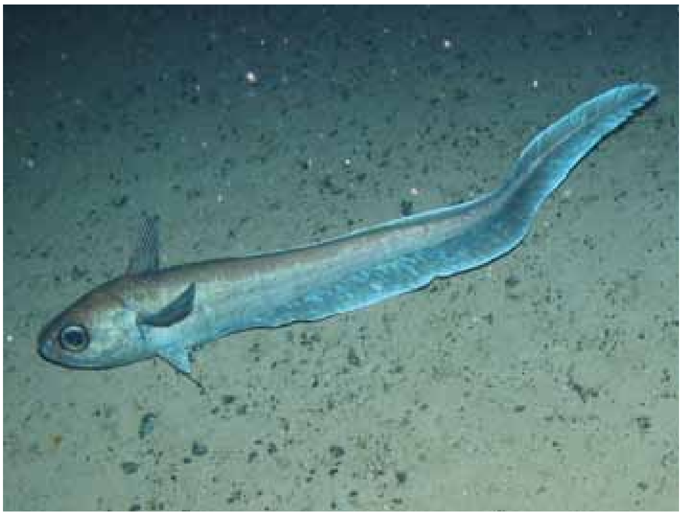
Introduction

The continental shelves have supported the major fisheries of the world for more than 1000 years. They have contributed significantly to global food supply, national wealth and the development of individual communities. However, since the industrial revolution, the development of more advanced preservation techniques (canning and freezing), and an ever growing human population, the collapse of these great fisheries have become commonplace. The Food and Agriculture Organisation of the United Nations (FAO) have estimated that eleven of the world's fifteen major fishing areas and 69% of the world's major fish species are in decline and in need of urgent management action. With fishery collapse comes economic and social problems, and thus sustainable management of the world's fisheries is in everyone's interest.

The collapse of shelf stocks has inevitably led to fishers and governments seeking new resources to exploit. The global reach of modern fishing fleets and fishing technology have left few areas unexplored, leaving only the deep-sea as a possible alternative. Attention has initially focused on the continental slopes which comprise less than 10% of the ocean floor, but has in recent years moved on to seamounts, ridges and other raised submarine features. Deep-water fisheries are defined as those carried out below 400m. Most are relatively new, having only developed since the 1970s. It is a sad fact, and a reflection of both the lack of management and a result of the biology of the species involved, that in the short 40 year history of these fisheries we are already at a stage where, in the NE Atlantic, most exploited deep-water species are considered to be harvested 'outside safe biological limits' and nine out of the fifteen most common deep-sea fish species (including commercial and non commercial species) have shown dramatic declines in abundance (Bailey et al., 2009). In the NW Atlantic the situation is no different, with five species of deep-sea fish (including roundnose grenadier) qualifying as critically endangered according to the World Conservation Union (IUCN) criteria (Devine et al., 2006).

Roundnose grenadier



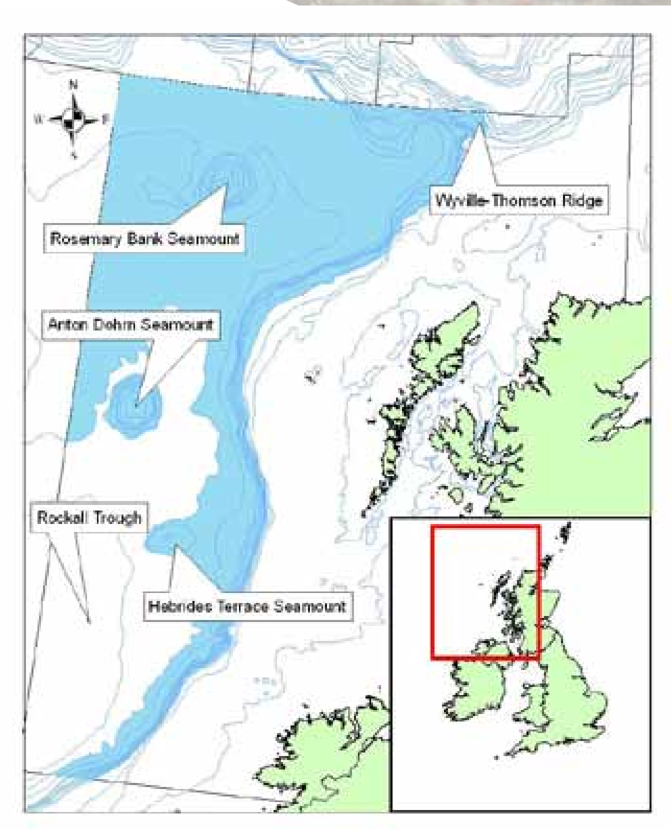
Deep-water fish species differ from their shallow water relatives in that they possess one or more of the following characteristics, which makes them vulnerable to over-exploitation: long-lived, slow growing, high age at first maturity and low fecundity (Gordon, 2001). In addition their often unusual body shape means that bottom trawls with mesh sizes appropriate to shallow water fishing are likely to retain a higher proportion of juvenile fish or species of small adult size, resulting high rates of discarding. Deep-water fish species are in general poorly armoured compared to their shallow water relatives and as a result experience extensive damage to the flesh within nets and passing through the nets (in the case of escapees). This damage coupled with the extreme change in pressure and temperature experienced by captured fish on hauling results in almost total mortality of deep-water discards (and suspected high mortality of escapees) (Gordon, 2001). The high mortality of young fish as a result of discarding (and passing through nets) coupled with the high age at first maturity of most species means that many individuals die before ever reproducing. Thus under fishing pressure the biomass of deep-water species will decline more rapidly than might be the case for a shelf stock.

The impact of massive reductions in the populations of long-lived fishes on the deep-sea ecosystem has yet to be evaluated. Bailey et al. (2009) recently observed the effects of deep-water fishing, in terms

of reductions in abundance of many fish species, to now reach the lower slope (approx. 2500 m), leaving only the abyssal and hadal zones unaffected. This is because many fish species found within fished depths (<1500m) have ranges that extend into deeper water. The deep-sea is considered a food-limited environment as ultimately all deep-water production must depend upon phytoplankton production at the surface. The impact of reductions in what are often predatory species is unknown. Mauchline and Gordon (1991) illustrated how important a trophic connection through pelagic animals is for deep demersal fishes. It follows that fisheries for deep-water pelagic species must impact upon deep demersal species, but the importance of this interaction is also currently unknown. In addition to the impacts upon fish species (both target and non target species) deep-water fisheries also impact upon the benthic component of the ecosystem. This is particularly the case for demersal trawl fisheries but applies to all gear that has contact with the seabed.

Global failure to adequately manage shelf fishery resources has resulted in fishing extending, often unregulated, into deeper and deeper waters. There is an urgent need to reassess how fisheries are managed and call a halt to the expansion of fishing into new areas prior to assessment of the impacts of that fishery and its long term sustainability in line with the precautionary approach. For deep-water fisheries such assessments are difficult as often few data are available on which to make a judgment. However, the Rockall Trough (ICES Division VIa) may be one of the few exceptions to this rule (Fig. 1). The deep-water fisheries of the Rockall Trough represent one of the oldest large scale deep-water fisheries in the world. This area, also known as the cradle of deep-sea biology, is one of the longest and most studied regions of the deep-sea in the world. This project focuses on ICES Division VIa and the ecosystem impacts and management of the deep-water fisheries therein.

Figure 1: The Rockall Trough, ICES Division VIa. Area covered by the DEEPFISH Project is shaded blue. Notable submarine features are named.



Monkfish, *Lophius piscatorius*, sits waiting to ambush prey.

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The history of scientific research in the Rockall Trough (ICES Division VIa)

While deep-water fishing in the Rockall Trough (ICES Division VIa) is relatively new, the scientific study of this region is not. 1868 saw the birth of the study of deep-sea biology in this region (and the world) with the voyage of the vessel HMS Lightning and in 1869 HMS Porcupine. These voyages finally disproved the then widely held theory that there was no life in the sea below 550m. Since those early days of the scientific investigation of the deep-sea, the Rockall Trough has remained an important area of study. As a result the deep sea off the West coast of Scotland has more information on the biology of the fish and invertebrate species of the system than any other deep sea system in the world (Gordon, 1999, Gage, 2001, Gordon, 2003, Gordon et al., 2003).

Studies of the fish populations of this region began when a series of deep-water research vessel fishery surveys (Tiefenfischerei = TIFI) were carried out during the 1970s and 1980s in the north-eastern Atlantic by the Federal Research Centre for Fisheries of Germany (hereafter referred to as the German trawl surveys). The investigations focused initially on the technology of fishing in the deep water of the continental slope and seamounts.

In 1973 the Scottish Marine Biological Association (now Scottish Association for Marine Science - SAMS) began a multidisciplinary study of the biology and oceanography of the Rockall Trough. The demersal fish studies began in 1975 and were centred on an area of the slope known as the Hebridean Terrace (approximately 56 – 57° N and 9 -11 °W). Unlike the German fisheries surveys these were aimed at providing biological information with an emphasis on seasonality. Different trawls were used to sample the total depth range which also provided information on catchability (Gordon and Duncan, 1985, Gordon and Bergstad, 1992). Detailed dietary studies were made of over 70 fish species. The surveys (hereafter referred to as SAMS surveys) ran until 1990.

Since 1998, Fisheries Research Services, Aberdeen (now Marine Scotland - Science) have conducted biannual and now annual deep-water surveys (hereafter referred to as FRS surveys) in the Rockall Trough. These three sources collectively provide a unique data set, spanning over 30 years, to study long term trends in the fish populations of the Rockall Trough and the impact of fishing from an ecosystem perspective.

The history of fishing in the Rockall Trough (ICES Division VIa)

The deep-water fisheries of the Rockall Trough are relatively new and several distinct deep-water fisheries can be defined based on gear type and target species

Bottom trawl fisheries

Trawl fishing of deep-water species in the Rockall Trough began in the early 1970s with German trawlers targeting spawning aggregations of blue ling (*Molva dypterygia*) in the northern part of the region. By the mid to late 1970s, French trawlers, who traditionally fished along the shelf edge for species such as saithe (*Pollachius virens*), began to move into deeper water to exploit blue ling, and gradually replaced the German fleet. There is little doubt that in the early years of this fishery, the by-catch of species such as roundnose grenadier (*Coryphanoides rupestris*), black scabbardfish (*Aphanopus carbo*), deep-water sharks and many other less abundant species were discarded. However, in 1989, following a marketing initiative by the French industry, these species began to be landed, and a multi-species all-year-round bottom trawl fishery along the continental slope developed. Although blue ling remains a target species, especially in spring and early summer, roundnose grenadier is a target species in its own right, with black scabbardfish and deep-water sharks landed as the main by-catch. The main bottom trawl fishery is undertaken by France, with over 90% of the landings from the deep-water trawl fishery by French vessels (excluding blue ling). Some UK vessels do land deep-water species as a by-catch of the monkfish trawl fishery, which developed in the early 1990s and is undertaken in the slightly shallower waters of the upper slope.

Orange roughy bottom trawl fishery

This fishery first developed in 1992 when the larger French trawlers, participating in the mixed demersal trawl fishery, began targeting orange roughy (*Hoplostethus atlanticus*) in deeper water (down to ~1700m) in areas of steep slopes and on the seamounts. This fishery developed rapidly, however, landings declined dramatically after a couple of years. This fishery has now all but ceased in Division VIa and effort has shifted to sub-area VII where the species has been targeted by Irish trawlers.

Image Copyright © JNCC, 2009
Orange roughy

Longline fishery

In addition to the deep-water bottom trawl fisheries there are also two important long line fisheries on the Atlantic slope. Norwegian long-liners fish along the shelf edge and upper slope between 150-450 m primarily for ling (*Molva molva*) and tusk (*Brosme brosme*), although blue ling are also targeted to a lesser degree. There is also a Spanish and Anglo-Spanish (UK registered Spanish vessels) long-line fishery for hake (*Merluccius merluccius*) with a by-catch of other deep-water species, such as blue ling and sharks. Depending on market prices, sharks (*Centroscymnus coelolepis* and *Centrophorus squamosus*) can sometimes be the target species.

Image Copyright © JNCC, 2009
Deep-water shark and orange roughy

Pelagic trawl fisheries

There are well established semi-pelagic trawl fisheries for blue whiting (*Micromesistius poutassou*) and argentine (*Argentina silus*). The blue whiting fishery is the larger of the two and is a directed fishery on spawning aggregations that occur between approximately 200-400 m depth (although fishing may be undertaken to a depth of 800 m). Fishing for blue whiting is principally undertaken by Norway, with the Netherlands and the UK also participating; landings data are available from 1973. The argentine fishery also targets spawning aggregations and is seasonal. It is mainly carried out by the Netherlands but with Ireland, Germany and the UK participating.

Gill net fisheries

The deep-water gillnet fisheries undertaken in Division VIa developed in the mid-1990s. The fishery operates between depths of 200 and 1200 m; the main target species are monkfish (*Lophius piscatorius*) and deep-water sharks, with a bycatch of red crab (*Chaceon affinis*). This fishery is believed to focus on Rockall and Rosemary Banks and on the continental slope near the Wyville-Thomson Ridge. The vessels involved, though mostly based in Spain, are registered in the UK and Germany. These fisheries are not well documented or understood and, until recently, appeared to be largely unregulated (Hareide et al., 2005).

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The ecology of some key commercially fished deep-water species

Roundnose grenadier (*Coryphanoides rupestris*)

Depth distribution: 180-2200m, maximum abundance between 500-1500m

Max age: >50 years, oldest individual recorded as 72 years

Age at first maturity: 14 years

Spawning period: May to November

Reproduction: The eggs, postlarvae and juveniles are pelagic, with the pelagic phase lasting almost 1 year, before the species takes up a principally demersal existence.

Diet: feeds predominantly on copepods, decapods, and fish supplemented by mysids, euphausiids, amphipods and cephalopods. The smallest fish feed predominantly on calanoid and cyclopoid copepods supplemented by a variety of other small organisms. Mysids, euphausiids, amphipods and decapods all become increasingly prominent in the diets of larger fish.

Fishery and stocks: Primarily fished as part of the mixed demersal trawl fishery. Fished for human consumption. The areas used as stock units for stock assessment purposes are based on hydrological hypothesis as to date there is little scientific data available on stock discrimination.

Roundnose grenadier

Black scabbardfish (*Aphanopus carbo)*

Depth distribution: 200-1600m, peak abundance and biomass at 750-1000m

Max age: 8-32 years, evidence conflicting but older estimates thought to be more reliable.

Age at first maturity: 3 based on lower maximum estimates, but age estimates uncertain.

Spawning period: November to December

Reproduction: It is currently believed that this species' life cycle is not completed in just one geographical area and that either small or large scale seasonal migrations occur. It has been postulated that this species spawns in the seas around Madeira from November to December. Egg and larval stages of this species are unknown, however juveniles are mesopelagic becoming benthic at some point. Fish caught to the west of the British Isles are pre-adults that are thought to migrate down to Madeira as they reach maturity.

Diet: Feeds mainly on pelagic and semi-pelagic species such as mackerel and blue whiting. However, new data from this project suggest squid may also be an important dietary component.

Fishery and stocks: Fished as part of the mixed demersal trawl fishery. Fished for human consumption. Due to the uncertainty of stock structure a single stock in NE Atlantic is considered. However, because of the different nature of fisheries in the northern and southern areas and lack of information on migration, the stock has traditionally been divided into northern and southern components for management purposes.

Monkfish (*Lophius piscatorius*)

Depth distribution: 245-1032m

Max age: 24 years

Age at first maturity: 14 years for females, 6 years for males

Spawning period: November to May

Reproduction: This species is thought to move offshore in late autumn and winter, and spawn in winter and spring. Eggs are pelagic, and juveniles have been observed in surface waters in May - July.

Female monkfish do not reach sexual maturity until they have attained a considerable size (>70cm).

Diet: This species is an ambush predator feeding primarily on fish. Monkfish can consume a wide range of prey types and their opportunistic diet generally reflects the species that are most available in a particular place at a particular time.

Fishery and stocks: This species is primarily fished by mixed demersal trawlers but also by a deep-water gill net fleet. Little is known about when and where monkfish spawn in northern European waters and consequently stock structure is unclear. Available evidence suggests populations from Divisions IVa, Division VIa, Rockall and possibly further south to sub-area VII are all one stock.

Large Demersals (Tusk and Hake) (*Brosme brosme*, *Merluccius merluccius*)

Depth distribution: Tusk 18-400m; Hake are found mostly between 70 and 370m but can be found deeper and shallower.

Max age: Tusk 20 years, Hake 12 years

Age at first maturity: Tusk 8-10 years; Hake 3-4 years

Spawning period: Tusk: April to July; Hake: February to July

Reproduction: Tusk spawns in shallow waters between 40-400 m, usually 100 to 200 m. The most important spawning grounds are located on the banks to the west and north of Scotland, around the Faroes and off Iceland, as well as the shelf edge along mid and north Norway at depth of 200 to 500 m. Hake spawn along the shelf edge, the main areas extending from north of the Bay of Biscay to the south and west of Ireland. After a pelagic larval stage, 0-group descend to the seabed at depths of more than 200 m, then move to shallower water (75–120 m) with a muddy seabed by September. There are two major nursery areas: the Bay of Biscay and off southern Ireland. As hake approach maturity (39cm, around 3 years for males, and 47cm, around 4 years for females), they disperse to offshore regions of the Bay of Biscay and Celtic Sea.

Diet: Both species are primarily piscivorous with blue whiting forming an important seasonal component to the diet.

Fishery and stocks: Tusk is a bycatch species in trawl, gillnet and long line fisheries in Division VIa. Norway has traditionally landed a dominant portion of the total, and around 90% of the Norwegian landings are taken by long liners. Based on genetic investigation ICES currently recognises the following stock units for tusk: Va and XIV; the Mid Atlantic Ridge; Rockall (Vb); I,II; and all other areas. Hake is landed as targeted or incidental catch by a wide variety of gears (bottom trawls, nets, and longlines). ICES assumes two stock units of hake, namely the northern stock in Sub-areas II, IV, VI and VII, and Divisions IIIa and VIIIa,b,d, and the southern stock in Divisions VIIIc and IXa.

Blue whiting (*Micromesistius poutassou*)

Depth distribution: 300-600m, mean depth of occurrence at 420m in the Rockall Trough

Max age: 7 years

Age at first maturity: 2-3 years

Spawning period: February to April

Reproduction: Blue whiting is a pelagic gadoid that occurs in the Rockall Trough primarily as a migrant passing through the region, with peak abundance in March to April when it forms large spawning aggregations. The major spawning takes place along the shelf edge and banks west of the British Isles. Juveniles are abundant in many areas, with the main nursery area believed to be the Norwegian Sea. Juveniles remain on the nursery grounds for 2 to 4 years before returning to spawn.

Diet: Primarily feeds on large zooplankton including euphausiids (krill) and other pelagic crustaceans.

Fishery and stocks: Morphological, physiological, and genetic research has suggested that there may be several components of the stock which mix in the spawning area west of the British Isles. However stock composition and dynamics are poorly understood and accurate estimates of the stock size are difficult due to the large population size, the species' considerable migratory capabilities and its wide spatial distribution. The population of the NE Atlantic is therefore treated as a single stock.

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Blue ling (*Molva dypterygia*)

Depth distribution: 300-1470m, most abundant between 750-1000m.

Max age: 30 years

Age at first maturity: 7 years

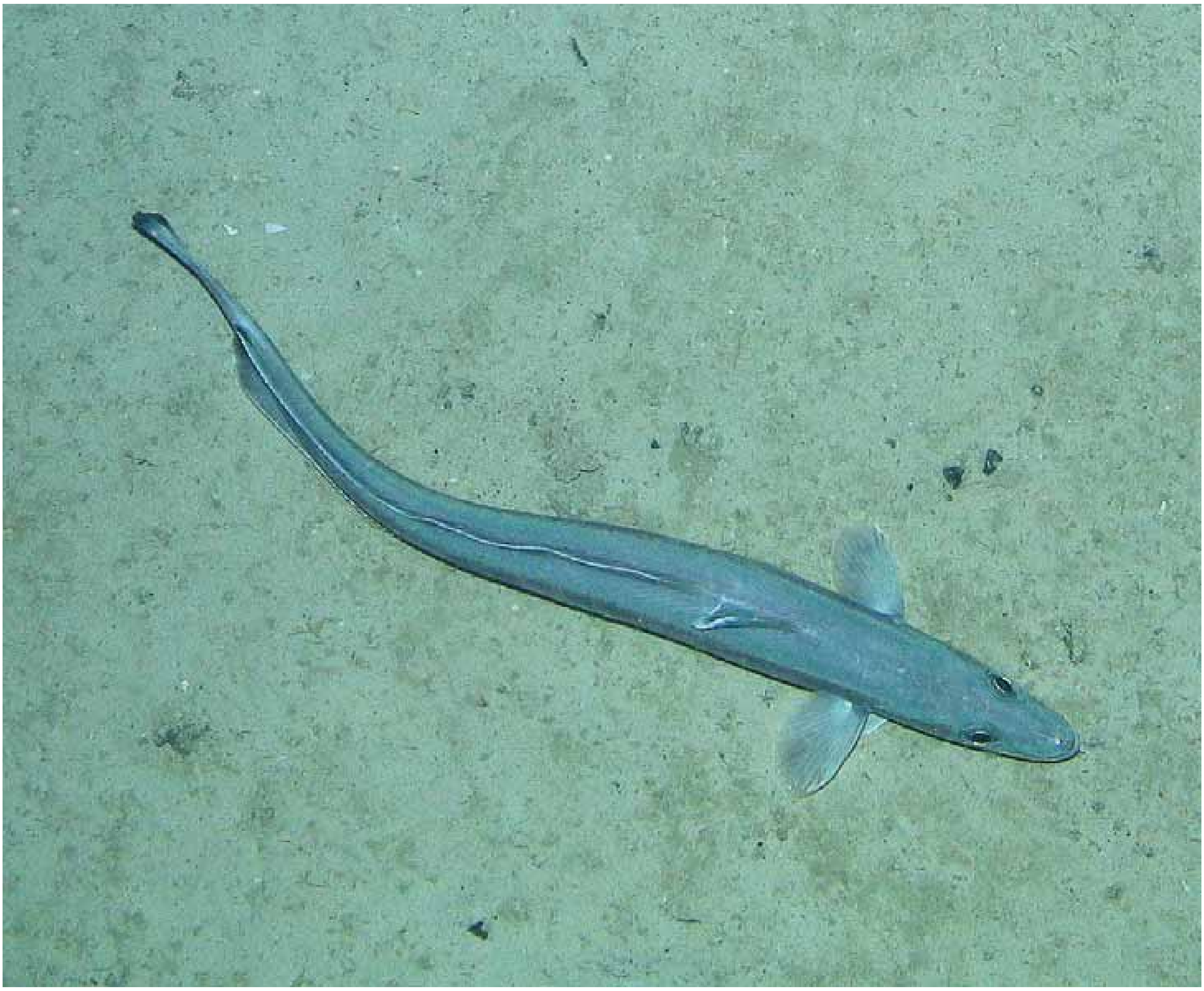
Spawning period: February to June

Reproduction: Egg and larval data suggest the existence of many discrete spawning grounds with spawning thought to occur from February to June. The eggs and larval stages have not been described but post larvae have been found in May off the Scottish coast at a depth of 1000m. The juveniles are pelagic until they reach a length of about 8cm when they become benthic.

Diet: Blue ling is primarily a piscivore but it also predates upon some epibenthic invertebrates, especially when young.

Fishery and stocks: Caught by both trawling and longlining in Division VIa. Stock structure is uncertain, however, it is known that there are at least two adult stock components, a northern stock in Sub-area XIV and Division Va with a small component in Vb, and a southern stock in Sub-area VI and adjacent waters in Division Vb, with further stock separation likely.

Blue ling



Deep-water fisheries management and the 'ecosystem approach'

The deep-water fisheries of the NE Atlantic were largely unregulated from their commencement in the 1970s to the early 2000s. Following repeated advice from the International Council for the Exploration of the Sea (ICES) that most stocks were "outside safe biological limits" the EC finally introduced biennial Total Allowable Catches (TACs) for 11 deep-water species: alfonsino, black scabbardfish, blue ling, forkbeard, greater silver smelt, ling, orange roughy, red seabream, tusk, and deep-sea sharks - these came into effect in January 2003. In addition further management measures were also put in place including the following requirements: vessels exploiting deep-water resources to have deep-water fishing permits; deep-water permitted vessels to have a fully operational satellite tracking device to ensure the enforcement of management measures; nations to designate specific ports where permitted vessels must land their catch; deep-water fishers to report fishing gear characteristics and fishing operations in logbooks; scientific observers to be deployed on deep-water permitted vessels to collect representative data that are adequate for the assessment and management of deep water fish stocks; a capping of effort (aggregate power and capacity) of deep-water fishing vessels to levels observed in the years 1998-2000. Closed areas were also introduced for the protection of orange roughy, and in December 2008 the EC introduced protection areas for spawning aggregations of blue ling in ICES Division VIa from March to May.

The principle method of management employed in deep-water fisheries remains through the use of TACs. However, managing deep-water fisheries in the NE Atlantic by TACs is unlikely to be successful for the following reasons. Many deep-water fisheries, are mixed fisheries with catches consisting of a range of species. Mismatch in the TACs assigned for species taken in mixed fisheries will inevitably lead to more discarding of over-quota species by vessels fishing undersubscribed species. This will lead to an increased fishing mortality on deep-water species because all discarded fish die as a result of changes in temperature and pressure on being brought to the surface from great depth, as well as (in the case of trawls) sustaining damage to their poorly armoured flesh in the net. In addition the TACs that were initially put in place were too high. Declared catches have been consistently lower than the TACs, which shows that the latter were not sufficiently restrictive and did not bring about the desired effect of a reduction in fishing mortality rates. misreporting of landings is also known to have occurred (Lorance et al., 2008) and this undermines the efficacy of catch controls.

Trawled black scabbardfish, the characteristic black flesh is almost completely abraded off in the net.

ICES Advisory Committee on Fisheries Management (ACFM) have always maintained the view, that TACs alone would not be an effective management measure for deep-water species. Effort control in the form of fleet or gear specific measures was highlighted as a more appropriate means of achieving sustainable deep-water fisheries management due to the nature of the fisheries being predominantly mixed. Reduction in fishing effort was viewed as the most promising way forward. Technical measures such as mesh-size regulation and selectivity grids were considered unlikely to be effective for deep-water fisheries because of the unusual shape and size of some species and the poorly armoured flesh, which is easily damaged when passing through the net, most likely resulting in total mortality of escapees. Closed areas, also considered as a possible management

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tool, were felt only likely to be of value as a long term measure. Lorance et al. (2008) suggested that the best way to manage deep-water fisheries may be a combination of effort and catch controls, with more emphasis placed on effort control compared with continental shelf fisheries given the difficulties of obtaining reliable stock assessments and managing mixed fisheries with TACs.

The use of TACs as the primary fisheries management tool within the EU has been widely criticized, most recently by the European Parliament who in January 2009 urged the Commission to reconsider the present system of TACs and quotas as the principal instrument for managing marine resources and its "usefulness" given the present fishing restrictions. The introduction of the new Common Fisheries Policy (CFP) in January 2003 focused on 'the ecosystem approach' as a way forward to a sustainable fishing industry.

The ecosystem approach

In the context of fisheries, a variety of interpretations of the ecosystem-based approach have been developed. For example, the FAO Fisheries Atlas, in its section on 'Basic Principles of Ecosystem Management', states:

'The overarching principles of ecosystem-based management of fisheries, aim to ensure that, despite variability, uncertainty and likely natural changes in the ecosystem, the capacity of the aquatic ecosystems to produce food, revenues, employment and, more generally, other essential services and livelihood, is maintained indefinitely for the benefit of the present and future generations, to cater both for human as well as ecosystem well-being. This implies conservation of ecosystem structures, processes and interactions through sustainable use. This implies consideration of a range of frequently conflicting objectives and the needed consensus may not be achievable without equitable distribution of benefits.'

This definition is useful in demonstrating that ecosystem-based management is not about managing or manipulating ecosystem processes - something that is clearly beyond our abilities. Rather, ecosystem-based management is concerned with ensuring that fishery management decisions do not adversely affect the ecosystem function and productivity, so that harvesting of target stocks (and resultant economic benefits) is sustainable in the long-term. Traditional systems of management, which have tended to focus on individual stocks or species, have not achieved this objective and consequently the economic activity that the ecosystem supports has become compromised.

Fisheries are dependent on the productivity of the whole ecosystem, and fisheries have an effect on, and are affected by, the supporting ecosystem of the target species. It therefore follows that prudent and responsible fisheries management should take account of the profound interactions between fisheries and their supporting ecosystem. No fish is an island, each interacts with other species in the form of predator-prey relationships and competition for resources and these interactions can have important implications for fisheries management.

One of the most basic ways in which species interact with each other and their surroundings is through feeding (or 'trophic') relationships (who is eating who). Gaining an understanding of the multitude of links between predators and their prey (the food web) provides a base for the development of a broader knowledge of an ecosystem. In the context of fisheries management, fishing can be regarded as the ultimate predator, selectively removing certain species from the ecosystem while leaving others untouched. If we can construct a model of the food web, with fisheries as a member, we can begin to examine the impact of fisheries on ecosystems. Perhaps of more value to fisheries management, we can identify the ecosystem impacts (and the impacts on other commercial species) of changes in fishing effort or catch. One fishery's discards may represent the juvenile stage of another fishery's target species; while the target of yet another fishery may represent the food source of another commercial species. Understanding the interactions between fisheries and fish species is therefore vital to the sustainable management of fish stocks.

The Ecopath with Ecosim model (EwE model)

One method of taking an 'ecosystem approach' to fisheries management is to use an ecosystem model. Although various models are available (Plagányi, 2007), many have high data demands are therefore are not suitable for use in a system such as the deep-sea for which data are sparse. The EwE modelling approach has been described as 'excellent' by FAO in its ability to conduct assessment and policy exploration (Plagányi, 2007). Ecopath is conceptually simple and ecological sensible. Essentially it is a food web model that allows the user to define the trophic interactions between species. In the model the fisheries are treated as just another predator in the system. Changes in the levels of predation over time (fisheries catches) can then be simulated and 'what if?' type questions asked about the outcome. For example, an EwE model would be able to predict the effect of current fishing pressure on the target fish species and all other species within the food web over time (20 years, 50 years, 100 years etc), or could predict the effect of banning certain fishing gear on a target fish species and all other species in the food web over time. The EwE model makes similar assumptions to most other ecosystem or even single species models, and can handle less than perfect data (Christensen and Walters, 2005, Christensen, et al., 2009). It is therefore a highly suitable ecosystem modelling tool to apply to deep-water fisheries for which there is limited data.

The data requirements for EwE are minimal, with the model requiring three of the following four data points for each group entered into the model:

- Biomass (B, tkm^{-2}) for the year under consideration
- Production/Biomass ratio (P/B, year^{-1});
- Consumption/Biomass ratio (Q/B, year^{-1});
- Ecotrophic Efficiency (proportion). This parameter indicates the unexplained mortality for each group and is often set to 95% when estimating the biomass.

In addition, for each group the diet composition is required as a contribution of the prey items by mass, and for each fishery the group specific landings (tkm^{-2}year^{-1}) and discards (tkm^{-2}year^{-1}) are required. To run the dynamic simulations in Ecosim yearly estimates of biomass, fishing mortality, and catch by species and/or gear is required to drive the model.

The blackmouth catshark, (*Galeus melastomus*) and the rabbit fish, *(Chimera monstrosa)*

The DEEPFISH project aims

Given the minimal data requirements of the EwE model, and the richness of the data available for the Rockall Trough, the DEEPFISH project aim was to construct an EwE model of the deep-water fisheries of Division VIa and use this model to:

1. Identify the impacts of the deep-water fisheries of Division VIa on the deep-sea ecosystem.
2. Predict the impact of continued fishing on the ecosystem (the 'business as usual' 2020 scenario)
3. Identify potential interactions between fisheries operating in Division VIa through examining hypothetical scenarios (the 'zero blue whiting catch' 2020 scenario)

Deepfish Project Part 2

Development of the model

The development of the model, data inputs and underlying assumptions made in the construction of the model are detailed in the report that accompanies this report (DEEPFISH Project: Part 1). The Ecopath model constructed is of the deep-sea ecosystem in 1974, before the development of significant fisheries in this region, and includes the area between 400m and 2000m depth. The Ecosim time dynamic simulations are run from 1974 to 2007 using available data on fishing mortality and fitting the model to landings and biomass.

Here we outline the model findings in relation to the project aims.

How has the tonnage of fish in Division VIa changed since the development of the deep-water fishery, and what does the future hold for this region if fishing continues at the 2010 TACS?

The 'business as usual' scenario

We have used the EwE model to investigate how the tonnage of key commercial, discard, and non commercial fish species has changed over time, from before the fishery developed (1974) to present (2007) (project aim 1). We have then run the model forward to 2020 (13 years) holding the TACs at the 2010 agreed levels to investigate what the future holds for these key species if fishing continues at current levels (project aim 2) [1].
(See table 1 for a summary of changes in biomass)

[1] It must be understood that the input data that allows the model to predict changes in biomass of all modelled species is catch data (TAC and associated discard biomass) not just TAC. The model assumes that there is no change in the level of discarding. Therefore any changes to the rate of discarding as a result of high grading or mismatched TACs between species taken together in the demersal trawl fishery will invalidate the predictions of the model.

It must also be understood that the predictions of the model are subject to the problems of data quality outlined in the technical report and we have attempted to highlight this for those species where data quality is particularly poor. It is strongly recommended that before citing the predictions of this model, stakeholders are made fully aware of the models limitations, in terms of the available data used in its construction.

Commercial species

Roundnose grenadier

The decline in the biomass of this species started when the commercial fishery began in 1988. The magnitude of the decline identified here (58%) is in line with the findings of other authors using different datasets and or different methods of assessment. Bailey et al. (2009) reported a 41% decline in abundance of this species pre and post fishery (1977-89 and 1997-2002) in the Porcupine Seabight. Basson et al. (2002) concluded that by end of 1998 exploitable biomass in sub areas VI, VII and Division Vb were close to 20% of virgin stock biomass. Lorance and Dupouy (2001) observed a decline in catch per unit effort (CPUE) for this species from 1989 to 1996 calculated from French deep-water trawl fishery data. The latest ICES assessments (ICES, 2008) show the declines in biomass continuing to 2007 (last year assessed) and are in contrast to the observation of a partial recovery modelled here from 2003 to 2007. The 2020 prediction of a recovery to 75% of 1974 (virgin stock) biomass may therefore be overly optimistic; however we would expect to see a recovery of stock biomass following the reduction in TAC.

Black scabbardfish

The decline in biomass of this species started before the development of the commercial trawl fishery in 1988, but has no doubt been exacerbated by it. The decline observed here is complementary to that observed by other studies (Lorance and Dupouy, 2001). Basson et al (2002) estimated that in 1998, the biomass of this species for sub areas VI, VII, XII, and Division Vb was at 19 to 24% of virgin stock biomass, lower than the 28% modelled here for 2007. The latest ICES assessments indicate a fairly strong overall declining trend in abundance from 1991 to present. The catch of this species in VIa is supported by sub-adult individuals of a stock which may migrate to southern areas to spawn. The likely migration of this stock to other areas that were exploited before 1988 may explain the decline observed prior to the development of the fishery in VIa. The 2020 prediction of a further decline in the biomass of this species to 15% of the pre-fishery biomass suggests the TAC for this group should be lowered further.

Monkfish

The apparent decline in biomass of this species started when the commercial fishery began in 1988. The findings of this study are in contrast to the findings of both the Scottish Tally book project (Dobby et al., 2008) and the fisheries independent Scottish monkfish surveys (Fernandes, 2008), both of which show a show a buoyant monkfish stock, with the latter suggesting a biomass increase of ~30% between 2006 and 2007 (16,021t to 18,344t). This species is not well represented in the model which deals with fish populations and fishing below 400m water depth. As most of the monkfish population and fishing effort is found shallower than this, the model inputs (and thus outputs) are unreliable. For these reasons the 2020 prediction for this species is unreliable.

Image credit: © Crown Copyright, all rights reserved, Monkfish, *Lophius piscatorius*

Large Demersals (Tusk and Hake)

The apparent decline in biomass for this group started before the development of the commercial trawl fishery in 1988, but has clearly been exacerbated by it. Although the general findings of an overall decline in biomass for tusk are consistent with the findings of other studies (ICES, 2008), new time series data from Norwegian longliners operating in VIa and targeting tusk show a relatively stable trend for the years 2000 to 2005 with an increase in the CPUE for 2006 and especially 2007. For hake our findings are in contrast to current thinking as ICES classify the northern hake stock as being at full reproductive capacity and being harvested sustainably. The model data suggest a sustained serious decline in biomass for tusk and hake combined. As with monkfish these species are not well represented in the model. Most of the population of both tusk and hake are found shallower than 400m (upper depth limit of the model) and thus the model inputs (and outputs) are unreliable. For these reasons the 2020 prediction for this group is unreliable.

Blue whiting

The findings of our model of a decline in biomass of this species are broadly in line with those of other studies. The ICES Working Group on Northern Pelagic and Blue Whiting Fisheries (ICES, 2007) state that the current estimate of the size of the blue whiting stock is uncertain because commercial catch data and data from scientific surveys give conflicting results. However, they also state that all models estimate a considerable decline in spawning stock biomass since 2003 and a fishing mortality that currently is above the precautionary level. Blue whiting is a highly migratory, pelagic species that is primarily found above 400m depth (the upper depth limit of the model). It is therefore difficult to obtain reliable estimates of biomass (hence the conflicting results from different studies) and is not well represented in the model. However, the general agreement of a decline in biomass of this species suggests the model trend is reliable, even if absolute biomass estimates are not. The 2020 prediction should therefore be viewed as an indication of the general direction of a trend in biomass and would suggest a reduction in TAC is required.

Table 1: Summary of the changes in weight (biomass) of key species from 1974 – 2007, and 2020

Category	Name	Species	Trend	Current status	2020 prediction	Comments on prediction
Commercial species	Roundnose grenadier	*Coryphanoides rupestris*	58% decline between 1974 and 2002 (98201t to 41546t); recovery 2003-2007 (56654t)	Recovering, currently at 58% of 1974 biomass	Recovery to 75% of 1974 biomass (73273t)	Accepted
	Black scabbardfish	*Aphanopus carbo*	72% decline between 1974 and 2007 (45323t to 12842t)	Declining, currently at 28% of 1974 biomass	Declining to 15% of 1974 biomass (6799t)	Accepted
	Monkfish	*Lophius piscatorius*	70% decline bewteen 1974 and 2007 (15108t to 4532t)	Declining, currently at 30% of 1974 biomass	Declining to 0.00006% of 1974 biomass (0.9t)	Unreliable
	Large demersals (Tusk and Hake)	*Brosme brosme, Merluccius merluccius*	80% decline between 1974 and 2007 (11331t to 2266t)	Declining, currently at 20% of 1974 biomass	Declining to 0.000011% of 1974 biomass (0.13t)	Unreliable
	Blue whiting	*Micromesistius poutassou*	70% decline between 1974 and 2007 (528773t to 156366t)	Declining, currently at 30% of 1974 biomass	Declining to 25% of 1974 biomass (133704t)	General trend accepted but absolute values questionable
	Blue ling	*Molva dypterigia*	5 fold increase between 1974 and 2007 (90647t to 453234t)	Increasing, currently at 5 times the 1974 biomass	Increasing to 6.64 times 1974 biomass (602046t)	Unreliable
Key discard species	Intermediate sharks: Portuguese dogfish, birdbeak dogfish, the leafscale gulper shark, the longnose velvet dogfish, Iceland catshark, and other Apristurus species.	*Centroscymnus coelolepis, Deania calceus, Centrophorus squamosus, Centroscymnus crepidater, Apristurus laurussonii*	80% decline between 1975 and 2005 (52877t to 10475t); recovery 2006-2007 (13597t)	Recovering, currently at 26% of 1974 biomass	Recovery to 84% of 1974 biomass (44568t)	General trend accepted but predicted recovery likey to be overly optimistic
	Baird's smoothead	*Alopecephalus bairdii*	73% decline between 1974 and 2005 (90647t to 24172t); recovery 2006-2007 (27194t)	Recovering, currently at 30% of 1974 biom ass	Recovery to 43% of 1974 biomass (38525t)	Accepted
	Rabbitfish (Chimaeras)	*Chimaera monstrosa, Hydrolagus mirabilis*	64% increase between 1974 and 2007 (8309t to 13597t)	Increasing, currently at 1.64 times 1974 biomass	Increasing to 3 times the 1974 biomass (24172t)	Treat with caution
Other deep-sea species	Benthopelagic fish: Blue-mouth redfish, Mediterranean grenadier, hollowsnout grenadier, Günther's grenadier, slender codling, North Atlantic codling, common mora, common Atlantic grenadier, roughnose grenadier, and all Sebastes spp.	*Helicolenus dactylopterus, Chalinura mediterranea, Coelorhynchus coelorhynchus, Coelorhynchus labiatus (previously C occa), Coryphaenoides guentheri, Halargyreus johnsonii, Lepidion eques, Mora moro, Nezumia aequalis, Trachyrhynchus murrayi, and all Sebastes spp.*	42% increase between 1974 and 2007 (114064t to 162409t)	Increasing, currently at 1.42 times 1974 biomass	Increasing to 1.68 times 1974 biomass (191869t)	Unreliable
	Benthic fish: Bonapart's spiny eel, smallmouth spiny eel, and blue antimora	*Notacanthus bonapartei, Polyacanthonotus rissoanus, Antimora rostrata.*	27% decrease between 1974 and 1990 (8309t to 6043t); recovery 1991-2007 (12086t)	Recovering, currently at 1.45 times 1974 biomass	Recovery to 3 times 1974 biomass (24172t)	Unreliable

Blue whiting are an important prey species for many of both the commercial and non-commercial fish species. The decline in biomass of blue whiting has implications on food availability for other commercial species (this issue is investigated further on P18).

Blue ling

The findings for this species of a progressive increase in biomass from 1974 to 2007 are in stark contrast to those of other authors. Lorance and Dupouy (2001) observed a strong decline in CPUE for this species from 1989-1996. Basson et al. (2002) estimated that in 1998, the biomass of this species for areas VI, VII, and Division Vb was below 20% of the virgin stock biomass. The latest ICES assessment of this species demonstrates a strong decline in abundance since 1989 (first year data available) (ICES, 2008). Blue ling is an aggregating species and in the early years of the fishery, the principal focus of the fleet was on spawning aggregations. In recent years blue ling has been taken mainly as a byÐcatch in French trawl fisheries for roundnose grenadier, black scabbardfish and deep-water sharks (ICES, 2008). The large catches of this species in 70s and 80s coupled with the subsequent decline in catches through the 90s and 00s has led the EwE model to estimate an increase in biomass over time as the model assumes mass balance. The conflict between the trend predicted by the model and findings of other authors suggests this species is not well represented in the model and as such the 2020 prediction should be considered unreliable.

Key discard species

Intermediate sharks: Portuguese dogfish (*Centroscymnus coelolepis*), birdbeak dogfish (*Deania calceus*), leafscale gulper shark (*Centrophorus squamosus*), longnose velvet dogfish (*Centroscymnus crepidater*), Iceland catshark (*Apristurus laurussonii*) and other Apristurus species.

This group contains the commercially fished siki sharks (Portuguese dogfish and leafscale gulper shark) the TAC for these has been reduced to zero in Division VIa, therefore we list them here under key discards. The decline in biomass of the siki sharks group observed from the model started when the commercial fishery began in 1988. This finding is in agreement with other studies: Lorance and Dupouy (2001) found a significant decline in CPUE from 1989-96 for the siki sharks; Basson et al. (2002) estimated that in 1998 the biomass of deep-water sharks in sub-areas VI, VII, and Division Vb was below 50% of the virgin stock biomass; Jones et al. (2005) recorded declining trends in CPUE for a number of squaliform sharks between 1998 and 2004 and overall catch rates of sharks as dramatically lower than those recorded from pre-exploitation surveys in the 1970s. The latest ICES assessments also noted substantial declines in CPUE series for both the Portuguese dogfish and the leafscale gulper shark in sub-areas VI, VII and XII, suggesting that the stocks of both species were depleted. The model prediction of a recovery in this group from 2005-2007 is interesting and is clearly related to the introduction of TACs for various deep-water species as well as deep-water sharks. The 2020 prediction of a recovery to 84% of virgin stock biomass is likely to be over optimistic for the following reasons: the deep-water gill net fishery (and shark bycatch from this fishery) have not been included in the model due to lack of available data; the model at present takes no account of the impact of fishing pupping / nursery areas. Incidental evidence suggests that Rosemary Bank Seamount (within Division VIa) may provide an important birthing and nursery ground for the leafscale gulper shark (Defra 2007). Continued shark bycatch from this area would no doubt hinder the recovery of the leafscale gulper shark and the ‘intermediate shark’ group.

Baird’s smooth-head

The decline in biomass of this species observed from the model started when the commercial fishery began in 1988. Baird’s smooth-head can represent a major proportion of the discards from the demersal trawl fishery. The decline in smooth-head biomass, as a result of heavy discarding, may have also contributed to the decline in the biomass of the intermediate sharks as smooth-heads represent an important prey species for the intermediate sharks. The 2020 prediction of a recovery in biomass of this species is a direct result of the reduction in TAC for various deep-water species.

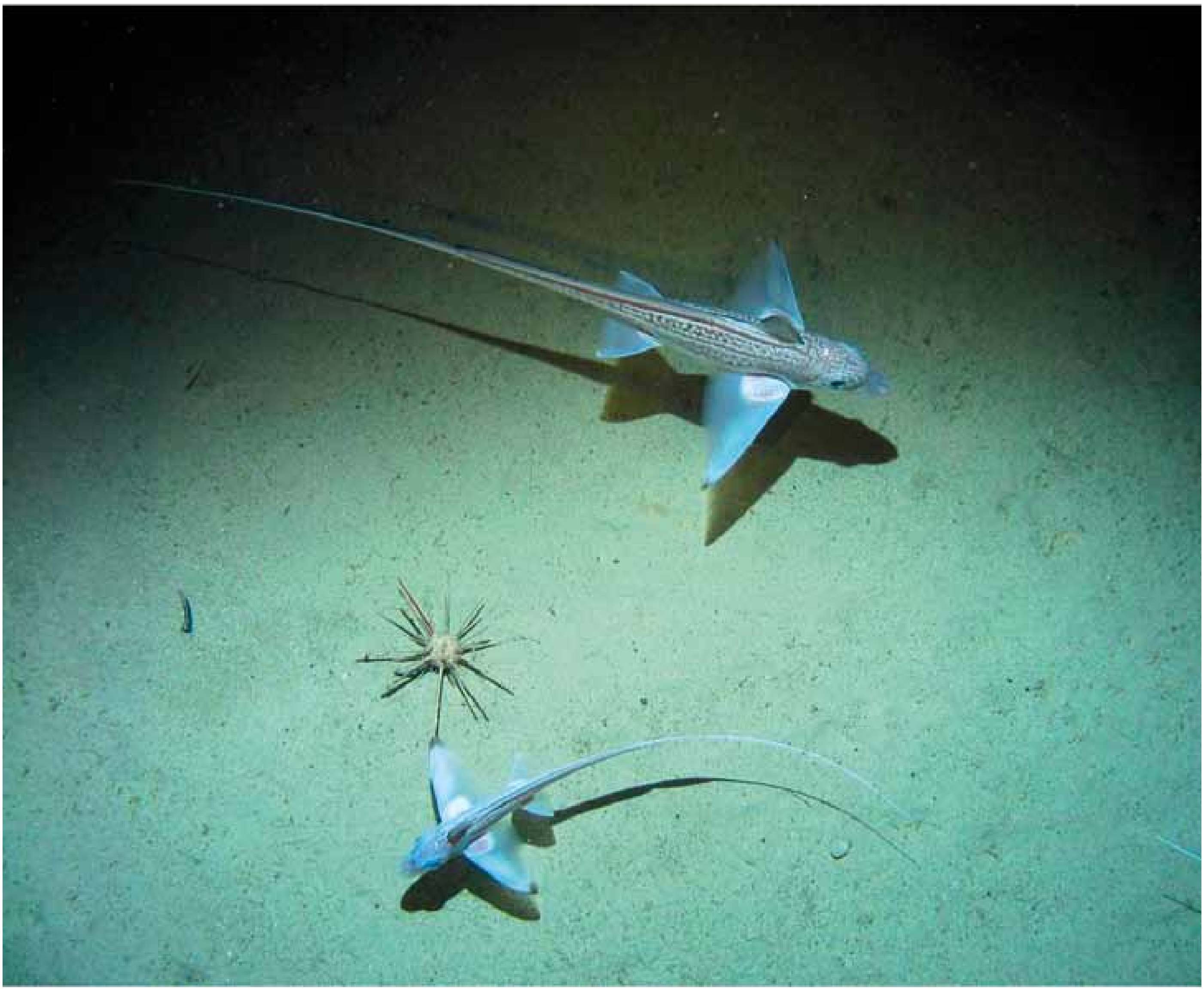
Deepfish Project Part 2

Chimaera

(Chimaera monstrosa, Hydrolagus mirabilis)

The increase in biomass of chimaeras observed in the model is unexpected since their low fecundity would suggest they are highly vulnerable to fishing pressure. The apparent increase in biomass started when the commercial fishery began in 1988 and suggests fishing may have had a positive impact on the chimaera, despite this group representing a significant proportion of the discarded biomass. The increase in biomass of chimaeras is most likely due to the decrease in abundance of their predators as a result of fishing as well as an increase in their principle prey. This group differ from most other groups in that they primarily feed on the benthos. We have very little understanding of the changes in benthic biomass from this area over time but it is possible their apparent increase in biomass is a result of changes to the benthic community. This group is primarily preyed upon by intermediate sharks and monkfish, both of which are seen to decline in biomass in the model. These trophic links were however assumed rather than observed links and thus the apparent increase in biomass for chimaeras should be treated with caution. Similarly the 2020 predicted further increase in biomass should also be treated with caution.

Image credit: © UK Department of Trade and Industry
Rabbitfish, *Chimaera monstrosa*



Other deep-sea species

Benthopelagic fish

The increase in biomass observed for this group appears to have started before the development of the demersal trawl fishery in 1988, but has clearly been affected by it. The apparent increase in overall biomass for this group is in contrast to the findings of Bailey et al. (2009), who, in their studies of changes in the abundance of deep-water fish populations from the Porcupine Seabight, found strong significant declines in the abundance of the common Atlantic grenadier (*Nezumia aequalis*), the spearsnouted grenadier (*Caelorinchus labiatus)* and the roughnose grenadier (*Trachyrhynchus murrayi*). They also found weakly significant declines in the abundance of Günther's grenadier (*Coryphaenoides guentheri*), but no significant declines in the abundance of the North Atlantic codling (*Lepidion eques*) when comparing pre and post fishery time periods (1977-89 and 1997-2002). The data on which the Bailey et al. (2009) study is based is more reliable than the data used in this model, thus the increase in biomass and the 2020 prediction of a further increase in biomass for this group should be regarded as unreliable.

Benthic fish

The apparent increase in overall biomass for this group is in contrast to the findings of Bailey et al. (2009) in their studies of changes in the abundance of deep-water fish populations from the Porcupine Seabight, pre and post fishery (1977-89 and 1997-2002). These authors found the smallmouth spiny eel, (*Polyacanthonotus rissoanus*) had declined in abundance by 77% and the blue antimora (*Antimora rostrata*) had also declined significantly. The apparent increase in their biomass observed in the model is most likely due to a decrease in predation pressure on this group, as a result of removal of their predators by fishing activity, coupled with their ability to switch prey preference to octopus and squid (itself experiencing lower predation pressure as a result of fishing). The data on which the Bailey et al. (2009) study is based is more reliable than the data used in this model, thus the increase in biomass and the 2020 prediction of a further increase in biomass for this group should be regarded as unreliable.

Summary

In general, the EwE model reflects currently held theory on the state of deep-water stocks. Here we have provided example model outputs for key commercial, discard and other deep-sea species / groups. We have deliberately selected some for which the model appears to work well, e.g. roundnose grenadier, black scabbardfish, and deep-water sharks; and others for which the model produces questionable results e.g. blue ling, monkfish, hake (as part of the large demersals group) [For the full list of species modelled see the DEEPFISH Project: Part 1 report]. For the those species for which the model produces results that conflict with current scientific opinion, we must question the validity of the input and as a result output data. For species such as blue ling (and orange roughy, not mentioned here but present in the full model) that form large spawning aggregations, it is difficult to obtain reliable estimates of biomass. The biomass estimates for blue ling from the three different datasets used to produce the EwE model would indicate a general trend of rise in biomass over time, thus the model has followed this trend in its prediction. For both monkfish and hake (as part of the large demersals group) the model also produced questionable results. Both these species are principally fished above 400m depth (the shallow limit of the model) and thus are not well represented in the model. In order to investigate changes in these species over time, the model would need to include shallow shelf areas. The predictions made by the model of the effects of continued fishing on species biomass by 2020 suggest that while the reduced TACs in place for roundnose grenadier and sharks should result in some recovery of the stock, the TAC for black scabbardfish is too high. As roundnose grenadier and black scabbardfish are taken together in the mixed demersal trawl fishery, it would suggest that the TAC for roundnose grenadier would also need to be lowered to prevent over capture of black scabbardfish.

Deepfish Project Part 2

How does the blue whiting fishery in VIa affect the biomass of predatory species that feed on blue whiting and thus their predicted recovery or decline over the next 13 years?

The ‘zero blue whiting catch’ scenario.

In order to demonstrate the value of ecosystem modelling and how it differs to traditional forms of fisheries modelling we decided to investigate some of the potential interactions between fisheries operating in VIa. Given the importance of blue whiting to the diet of many deep-water fish species (Fig. 2) we decided to investigate the effects of this fishery on the biomass of some of the key demersal species / groups. Following on from the ‘business and usual’ scenario, where we looked at the predicted changes in fish biomass over the next 13 years (to 2020) based on current TACs, here we have simulated the total cessation of the blue whiting fishery from 2007 to 2020 to identify how that fishery effects the predicted changes in biomass of the key demersal species*.

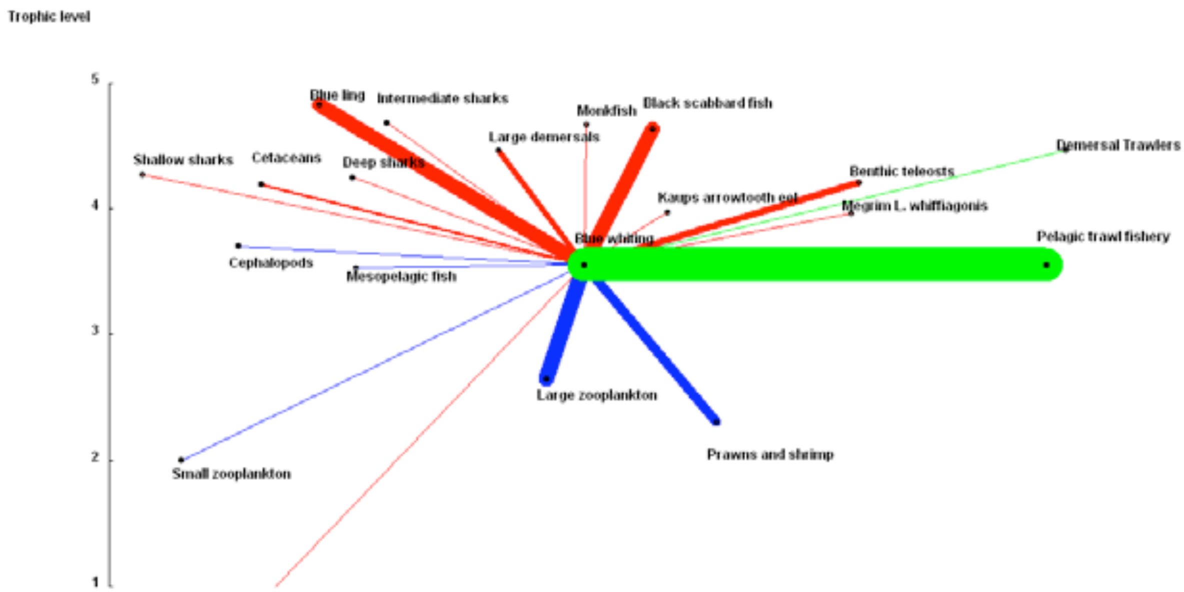
Figure 2: Predators and prey of blue whiting in 1974. Red = predator, blue = prey, green = fishery, size of line indicate size of predation pressure in 1974.

Below: Modelled decline in blue whiting biomass from 1974 to 2020. Biomass estimates from the three different datasets used in the model are shown for the years where data exist. Here we examine the effect of stopping all blue whiting fishing in 2007

Commercial species

Roundnose grenadier

Although blue whiting do not make up an important part of the diet of roundnose grenadier, these species’ share a common prey group, prawns and shrimp. Prawns and shrimp are the principle prey of roundnose grenadier and the second most important prey group for blue whiting (Fig. 2). It is possible that increased competition for food, experienced by roundnose grenadier as a result of the increasing biomass of blue whiting, may lead to the slower rate



* Table 2 summarises the changes in the model predictions from the ‘business as usual’ scenario to the ‘zero blue whiting catch’ scenario

of recovery observed. The blue whiting fishery has therefore had a positive impact on the biomass of this species, and the demersal trawl fishery targeting it.

Black scabbardfish

The decline in blue whiting biomass in VIa since 1974 has led to octopus and squid taking on a more important role in the diet of black scabbardfish, going from a 55% contribution to 90% contribution, while blue whiting have been reduced from a 45% contribution to the diet to a 25% contribution. Under a scenario of zero blue whiting catch, the model predicts that the decline in black scabbardfish biomass would continue, but would not be as severe (Table 2). The observations of a decline in the biomass of black scabbardfish prior to the development of the demersal trawl and long line fisheries in VIa, together with the slowed rate of decline in this species with increasing biomass of blue whiting, suggests that the decline in available prey for black scabbardfish has impacted the population and needs to be considered when addressing the management of this species. In contrast to roundnose grenadier, the blue whiting fishery has had a negative impact on this species and the demersal trawl fishery targeting it.

Monkfish

In 1974 this species fed primarily on blue whiting, octopus and squid, benthic fish and chimaera. Over the time period of the model the decline in blue whiting biomass as a result of the blue whiting fishery and the observed increase in biomass of both benthic fish and chimaera has resulted in these groups featuring more heavily in the monkfish diet. Under a scenario of zero blue whiting catch, the model predicts that monkfish biomass would still crash, but the rate of decline would be slowed. This suggests that the blue whiting fishery has a negative impact upon this group and the fishery targeting it. However that impact is not as important as observed for some other groups (e.g. black scabbard fish).

Large Demersals (Tusk and Hake)

As with monkfish and black scabbardfish, blue whiting forms an important part of the diet of this group making up 76% of the diet in 1974. Although blue whiting still make up an important part of the diet of this group, benthic fish are now the principle prey item, possibly as a result of their apparent increase in biomass. Under a scenario of zero blue whiting catch, the model predicts that the decline in large demersal biomass would still occur but at a reduced rate. This, together with the observations of a decline in the biomass of this species prior to the development of the demersal trawl and long line fisheries in VIa, suggests that the decline in available prey for large demersals has impacted the population, and this needs to be considered when addressing the management of this group. The blue whiting fishery has therefore had a negative impact on tusk and hake biomass and the fisheries targeting them.

Blue ling

Under a scenario of zero blue whiting catch, the model predicts that the biomass of this group would still increase but this increase would be greater. Blue ling are an important predator of blue whiting (Fig. 2). The principle prey of blue ling in the model are argentine (55% of diet) and blue whiting (30% of diet). With the cessation of the blue whiting fishery, blue whiting becomes a more important prey item than argentine, each contributing 45% and 40% of the diet respectively. It is likely that the increasing biomass of blue whiting, as a result of the removal of the blue whiting fishery, means that more food is available for blue ling and thus the rate of increase in population biomass is raised. The blue whiting fishery therefore has had a negative impact on this species and the fisheries targeting it.

Key discard species

Intermediate sharks: Portuguese dogfish, *Centroscymnus coelolepis;* birdbeak dogfish, *Deania calceus*; the leafscale gulper shark, *Centrophorus squamosus*; the longnose velvet dogfish, *Centroscymnus crepidater*; Iceland catshark, *Apristurus laurussonii*, and other *Apristurus* species.

Under a scenario of zero blue whiting catch, the model predicts that recovery of this group would still occur, but at a reduced rate, suggesting the blue whiting fishery has a positive impact on this group. The principle predator of intermediate sharks is blue ling. The predicted increase in biomass of blue ling under the 'zero blue whiting catch' scenario leads to an increase in the predation pressure exerted by blue ling on intermediate sharks. This increase in predation pressure on intermediate sharks has in turn led to a reduced recovery rate for this group. In addition, the principle prey of the intermediate sharks are octopus and squid, and mesopelagic fish. However, Baird's smooth-head also features in the diet of this group, although only to a minor degree. The recovery of Baird's smooth-head biomass was also impaired under the 'zero blue whiting catch' scenario and this could have contributed to the lower predicted rate of recovery of intermediate sharks.

Baird's smooth-head

Under a scenario of zero blue whiting catch, the model predicts that the biomass recovery would still occur but at a reduced rate. The principle predator of this species is intermediate sharks, which are predicted to recover less well under this scenario suggesting that the predation pressure exerted by them on Baird's smooth-head would be less. One might then expect the recovery of this species to be increased not decreased. The impaired recovery of Baird's smooth-head under this scenario is therefore likely to be a result of increased competition exerted on this species by the recovering blue whiting population for their mutual prey - prawns and shrimp. Prawns and shrimp only make up a small percentage of the smooth-heads diet (10%) as this species feeds predominantly on gelatinous zooplankton, however, it would appear to be significant. The blue whiting fishery therefore has a positive impact on this species.

Chimaera

(Chimaeras monstrosa, Hydrolagus mirabilis)

The blue whiting fishery appears to have very little impact on this group. This is most likely because the diet of Chimaeras is principally composed of benthic invertebrates, and there is very little trophic connection between this group and many of the other modelled fish species.

Other deep-sea species

Benthopelagic fish

Under a scenario of zero blue whiting catch, the model predicts that an increase in biomass would still occur but at a slower rate. This suggests the blue whiting fishery may have a positive influence on the biomass of this group. The principle prey of benthopelagic fish are prawns and shrimp, other benthic invertebrates and Kaup's arrowtooth eel. The principle predator of prawns and shrimp are blue whiting. The increase in biomass of blue whiting as a result of the simulated zero catch mean there is less food available for the benthopelagic fish group, resulting in a reduction in the predicted rate of biomass increase in this group over time.

Benthic fish

The blue whiting fishery appears to have very little impact on this group despite blue whiting forming a major component of their diet (55%). One might expect the increase in blue whiting biomass, as a result of the simulated zero catch, to have a positive influence on the biomass of this group. The principle predators of benthic fish are large demersals and monkfish, both of which decline less rapidly under the 'zero blue whiting catch' scenario and thus exert a greater predation pressure, and therefore an overall negative impact on the benthic fish biomass. It is likely that the positive effects of increased prey availability are balanced by the negative effects of higher predation pressure leading to no identifiable change in the biomass of this group under this scenario.

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A deep-water shark contemplates a potential meal.

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Redfish (Sebastes) in a cold water coral reef.

Summary

For most species examined the hypothetical removal of the blue whiting fishery (and all associated effort) led to changes in the 2020 biomass predictions. Some of these changes were positive (roundnose grenadier) while others were negative (black scabbardfish). However, all serve to highlight the influence of the blue whiting fishery on demersal species biomass through the food web, and thus the influence of this fishery on other fisheries in the region.

Pelagic species such as blue whiting and perhaps, more importantly, mesopelagic species form a vital energetic link between food production at the sea surface (phytoplankton) and demersal species at the seabed. The deep-sea is a food limited environment and the biomass of fish species found on the continental slopes is entirely supported by the effective transfer of energy from surface waters to the deep-sea by pelagic species. These types of trophic links and resulting fishery interactions are not considered by more traditional fisheries modelling but clearly influence the populations under study.

The example provided by the blue whiting fishery is not intended to 'demonise' this fishery nor to suggest any immediate changes to management. Instead the purpose is to illustrate the value of taking an ecosystem view of a region and the additional information that models such as EwE can provide, which can then be taken into consideration when management options are being considered. Ecosystem modelling is not intended to replace more traditional methods of stock assessment, but work along side them to add an important new perspective to fisheries management.

Category	Name	Species	2020 prediction under 'business as usual' scenario	2020 prediction under 'zero blue whiting catch' scenario	Change in prediction
Commercial species	Roundnose grenadier	Coryphanoides rupestris	Recovery to 75% of 1974 biomass (73273t)	Recovery to 61% of 1974 biomass (59676t)	Rate of recovery reduced
	Black scabbardfish	Aphanopus carbo	Declining to 15% of 1974 biomass (6799t)	Declining to 22% of 1974 biomass (9820t)	Rate of decline reduced
	Monkfish	Lophius piscatorius	Declining to 0.00006% of 1974 biomass (0.9t)	Declining to 0.0001% of 1974 biomass (2t)	Rate of decline reduced
	Large demersals (Tusk and Hake)	Brosme brosme, Merluccius merluccius	Declining to 0.000011% of 1974 biomass (0.13t)	Declining to 0.07% of 1974 biomass (755t)	Rate of decline reduced
	Blue whiting	Micromesistius poutassou	Declining to 25% of 1974 biomass (133704t)	Recovery to 56% of 1974 biomass (296113t)	From decline to recovery
	Blue ling	Molva dypterigia	Increasing to 6.64 times 1974 biomass (602046t)	Increaseing to 7 times the 1974 biomass (645103t)	Rate of rise increased
Key discard species	Intermediate sharks: Portuguese dogfish, birdbeak dogfish, the leafscale gulper shark, the longnose velvet dogfish, Iceland catshark, and other Apristurus species.	Centroscymnus coelolepis, Deania calceus, Centrophorus squamosus, Centroscymnus crepidater, Apristurus laurussonii	Recovery to 84% of 1974 biomass (44568t)	Recovery to 80% of 1974 biomass (42302t)	Rate of recovery reduced
	Baird's smoothead	Alopecephalus bairdii	Recovery to 43% of 1974 biomass (38525t)	Recovery to 41% of 1974 biomass (37014t)	Rate of recovery reduced
	Rabbitfish (Chimaeras)	Chimaera monstrosa, Hydrolagus mirabilis	Increasing to 3 times the 1974 biomass (24172t)	Increaseing to 3 times the 1974 biomass (24928t)	No change
Other deep-sea species	Benthopelagic fish: Blue-mouth redfish, Mediterranean grenadier, hollowsnout grenadier, Günther's grenadier, slender codling, North Atlantic codling, common mora, common Atlantic grenadier, roughnose grenadier, and all Sebastes spp.	Helicolenus dactylopterus, Chalinura mediterranea, Coelorhynchus coelorhynchus, Coelorhynchus labiatus (previously C occa), Coryphaenoides guentheri, Halargyreus johnsonii, Lepidion eques, Mora moro, Nezumia aequalis, Trachyrhynchus murrayi, and all Sebastes spp.	Increasing to 1.68 times 1974 biomass (191869t)	Increasing to 1.53 times the 1974 biomass (174495t)	Rate of rise reduced
	Benthic fish: Bonapart's spiny eel, smallmouth spiny eel, and blue antimora	Notacanthus bonapartei, Polyacanthonotus rissoanus, Antimora rostrata.	Recovery to 3 times 1974 biomass (24172t)	recovery to 3 times 1974 biomass (24928t)	No change

Table 2: Summary of the how the 2020 predictions of changes in weight (biomass) of key species are altered by the hypothetical removal of the blue whiting fishery.

Conclusions

Ecopath takes a trophic perspective and treats fisheries as the ultimate predator. It can cope with less than perfect data (Christensen and Walters, 2005, Christensen, et al., 2009) and is therefore a highly suitable tool to apply to deep-water fisheries. The DEEPFISH project has demonstrated that it is possible to construct an ecosystem model of deep-water fisheries and thus apply the ecosystem approach to their management. While the challenges of obtaining reliable datasets for these fisheries means the model outputs are questionable for some species, this is the case for all approaches to deep-water fisheries management. However, the benefits of applying this type of approach to examine the potential impact of fisheries management strategies are significant. We have demonstrated, using the blue whiting fishery as an example, how the EwE model can be used to look at interactions between fisheries, and how management decisions made on single species / single fishery basis can have far reaching effects on other species / fisheries. This type of interaction, not accounted for in more traditional stock assessments and management decisions, highlights one of the key reasons for looking at fisheries from an ecosystem perspective. As more reliable and better datasets become available through projects such as the EU funded DEEPFISHMAN, and long term monitoring programs such as that carried out by the Marine Scotland, the pilot model constructed here under the DEEPFISH project can be refined and used as an additional tool to aid in the sustainable management of these evolving fisheries.

Image © Crown Copyright, all rights reserved,
the North Atlantic codling (*Lepidion eques*) shelters beside a cobble.

Deepfish Project Part 2

Further work

The EwE model constructed by the DEEPFISH project should be considered a pilot study in applying the ecosystem approach to deep-water fisheries management. The current model clearly has limitations due to the quality of the data that it is based on. However, these problems are not unique to the model – indeed they are the same limitations experienced by other studies and fisheries management tools that require accurate species biomass and discard estimates as their starting point. All models can be improved, but that does not mean that we should not begin to incorporate ecosystem based management approaches into fisheries management plans. Importantly we need to ensure that the data required by such models is collected for future use.

For the species for which we have reasonable data e.g. roundnose grenadier, black scabbardfish, we can be more confident of the model's predictions of change in biomass and the observations of fisheries interactions. However, for those species where data are less reliable e.g aggregating species such as blue ling, the biomass predictions are less reliable. We do not recommend that too much weight be put on the model's outputs concerning these species until better estimates of biomass become available. However, even with the current limitations the model outputs do still provide an important insight into species and fishery interactions and the role of commercial species in the wider food-web.

False boarfish (*Neocyttus helgae* within a coral garden.

In order to improve the model to the point where reasonable predictions could be made, more reliable estimates of biomass pre and post fishery are required. Such a dataset does exist for the Porcupine Seabight region (sub-area VII) and may become available in the future. Information on species composition and estimates of discard biomass also needs to be improved. It is hoped that projects such as the EU funded DEEPFISHMAN will provide not only more reliable discard estimates but also biomass estimates. Given the scale of management of many of the species modelled and the likely spatial area occupied by stocks, the model should be expanded to cover the relevant range of the species of interest. For example the black scabbardfish population in Division VIa is composed of sub-adults and is thought to be part of the same stock that is fished off Portugal and Madeira. By only considering fishing pressure in Division VIa the model is missing an important part of the fisheries impacts on this species. In addition, working at the scale of Division VIa meant that many assumptions had to made as to the proportion of the population of a species or group within VIa and the proportion of the landings and TAC taken in VIa (where this was not already separated). This inevitably will lead to more inaccuracies in biomass estimates.

Despite the limitations of this model we have demonstrated that developing whole-ecosystem models for the deep sea is possible and does generate useful information that can inform future sustainable management plans for this fishery. The EwE modelling approach allows more than just the incorporation of fisheries and food-web interactions into management planning. It can also incorporate economic information so that the financial implications of management decisions can be tested. In addition the Ecospace extension to the program allows the effect of spatial closures (both ecological and economic) to be investigated. With the increasing emphasis on the use of marine protected areas as a management tool, this type of model could prove invaluable in the future. In this pilot study we have not attempted any of these more advanced uses of EwE. However we hope that in future this initial study can be built upon to allow such uses.

Key references

The DEEPFISH Project: Part 1 report, which contains much of the background information presented here, is fully referenced. In this short report we have only cited key references for ease of reading. Those cited in the text are detailed below.

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French and Spanish versions of both DEEPFISH reports are also available as pdf documents.

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A report detailing the development of the model is available (DEEPFISH Project: Part 1 report), for a hard copy please contact Dr Kerry Howell at the

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