

# A review of the spatial extent of fishery effects and species vulnerability of the deep-sea demersal fish assemblage of the Porcupine Seabight, Northeast Atlantic Ocean (ICES Subarea VII)

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We review information from scientific trawl surveys carried out between 1977 and 2002 in the Porcupine Seabight and Abyssal Plain area of the Northeast Atlantic (240–4865 m water depth). Since the late 1980s, commercial bottom-trawl fisheries targeting mainly roundnose grenadier (*Coryphaenoides rupestris*), black scabbardfish (*Aphanopus carbo*), and orange roughy (*Hoplostethus atlanticus*) have been operating at depths of 500–1500 m, intersecting the depth ranges of 77 demersal fish species that would therefore be vulnerable to fishery effects. Comparisons of trawls pre-1989 and post-1997 indicate a significant decrease in total abundance of demersal fish down to 2500 m. Detailed analyses of the 15 most-abundant species showed that nine species with depth ranges within the commercial fishing depth have decreased in abundance. Other species were either not affected (*Bathypterois dubius*) or only affected at the shallow end of their range (*Coryphaenoides guentheri*). Species with a minimum depth of occurrence >1500 m (*Coryphaenoides armatus* and *Coryphaenoides leptolepis*) increased in abundance over part of their depth range. Decreases in abundance are probably caused by commercial fishing activities, an effect that is transmitted downslope by removal of fish at the shallow end of their depth range, resulting in declines at the deeper end of the depth range. The estimated fishery area is ca. 52 000 km<sup>2</sup>, but the potential impact probably extends to ca. 142 000 km<sup>2</sup> and to many non-target species.

**Keywords:** abundance, continental slope, fisheries, impacts.

## Introduction

A general problem in fisheries management is that scientific investigation usually begins some years after a commercial fishery has been established (Haedrich *et al.*, 2001) and estimates of pre-fishery conditions must be done by extrapolation or other indirect means. For shelf-sea fisheries, exploitation has often persisted for centuries before scientific management methods have been adopted (Rosenberg, 2003). Deep-water fisheries have developed comparatively recently, mainly since the 1970s, and new resources have been opened up by vessels searching the high seas, exploiting patches, then moving on (Merrett and Haedrich, 1997). Scientific assessment has generally followed after the opening up of fishing areas. In contrast, the deep waters of the North Atlantic Ocean southwest of Ireland were first explored by scientists during the voyage of the HMS “Porcupine” in 1869 searching for evidence of life at great depths (Anon., 1869; Thomson, 1873). The voyage attracted widespread public attention, and the name of

the vessel was subsequently ascribed to topographical features of the seabed in this area—the Porcupine Bank, Porcupine Seabight, and the Porcupine Abyssal Plain. The deep-sea fauna of this area has become rather well known; Merrett *et al.* (1991a, b) completed a comprehensive survey of the demersal ichthyofauna of the area based on trawl surveys undertaken from 1977 to 1989 by the UK Institute of Oceanographic Sciences together with the Scottish Marine Biological Association. In contrast to the early dredging equipment, these trawls were equipped with electronic acoustic telemetry devices, enabling bottom contact time to be measured, so swept-area and the number of fish per unit area (abundance) could be estimated. These data provide a unique baseline before development of a deep-water fishery in the area from ~1990 on (Lorance, 1998; Lorance *et al.*, 2008). Indeed, Gordon and Duncan (1987) published information on the orange roughy before the fishery developed. During 1997–2002, the University of Aberdeen repeated these trawl stations as

an adjunct to behavioural, morphological, and physiological studies on deep-sea fish (Priede *et al.*, 1999; Trudeau *et al.*, 2000; Collins *et al.*, 2005; Bailey *et al.*, 2005).

Bailey *et al.* (2009) analysed the data from these two trawl series and showed that between pre-1990 and post-1990 trawl samples, there had been a significant decline in the abundance of demersal fish over a larger fraction of the upper slope of the Porcupine Seabight and attributed this to the activity of the deep-water fishing fleets. In this paper, we present this analysis in more detail, relate it to a recent re-evaluation of the species richness in this area (Priede *et al.*, 2010), and apply Geographic Information System (GIS) techniques to estimate the area of the fishery impact.

## Material and methods

### Fishery data and scientific sampling

Landings data were taken from ICES WGDEEP (2008) for three species in which separate listings were available for Subarea VII: roundnose grenadier (*Coryphaenoides rupestris*), orange roughy (*Hoplostethus atlanticus*), and black scabbardfish (*Aphanopus carbo*). These may differ from officially reported landings because they include additional information from Working Group members and are considered more accurate for assessment purposes. Total landings by all countries were taken to indicate general trends in the fishery.

Trawl sampling was carried out in the Porcupine Seabight and the Abyssal Plain area of the Northeast Atlantic Ocean within ICES Subarea VII, Divisions b, c, j, and k. In all, 187 demersal trawls at depths from 240 to 4865 m were taken between 1977 and 2002 using a 45-foot (13.7-m) semi-balloon otter trawl (OTSB, Marinovich Trawl Co., Biloxi, USA) fished on a single warp (Merrett *et al.*, 1991a). Nominal spread of the mouth of the trawl (width of seabed sampled) was 8.6 m, and haul duration was varied between a bottom contact time of 30 min at the shallowest stations and 3 h on the abyssal plain, with a tow speed of

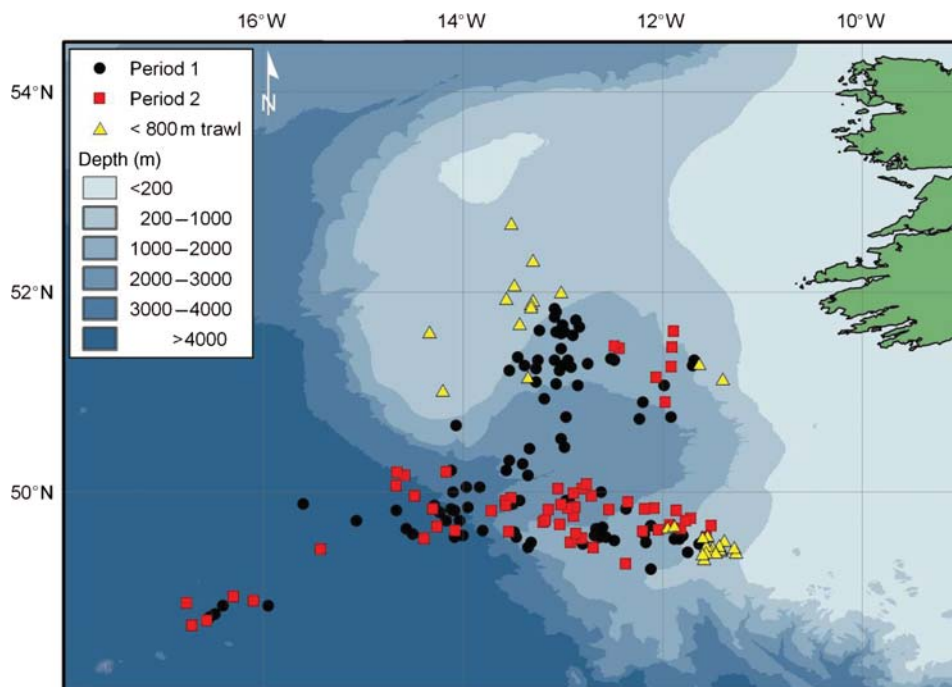
2–2.5 knots. This approximately equalized the sizes of catches across the depth range. The mean area of seabed swept by the trawl was  $59\,978 \pm 32\,923 \text{ m}^2$  (s.d.,  $n = 187$ ). Substantial overlaps in the personnel present over the period of the study ensured consistency of techniques and fish identification. Cruises were in different seasons to avoid biasing of sampling in relation to any fish migrations that might occur. This small trawl was effective at catching a wide range of species, but because of the limited herding action and low towing speed, large and highly mobile species such as sharks and black scabbardfish were poorly represented in the catch (Merrett *et al.*, 1991a; Gordon *et al.*, 1996).

For analysis, the trawls were divided into three categories (Figure 1). Period 1 trawls were taken during the years 1977–1989 at depths >800 m (95 trawls). Period 2 trawls were taken during the years 1997–2002 at depths >800 m (59 trawls). Trawls shallower than 800 m, mainly from Period 1, were used for analysis of the minimum depth of occurrence of slope-dwelling fish (33 trawls).

### Data analysis

Species presence at different depths was analysed using the entire dataset of 187 trawls, minimum and maximum depths of occurrence were determined. Comparison of abundance of fish during Periods 1 and 2 was done using the two datasets for trawls deeper than 800 m. Trawls from 1997 ( $n = 8$ ) were omitted from the analysis because the bottom contact detector had failed and there were no data for duration on the seabed. Abundances were calculated from trawl swept-area (calculated from time on the bottom, vessel speed, and door spread) giving numbers of fish per square kilometre of seabed.

Generalized additive mixed models (GAMs; Zuur *et al.*, 2007; Wood, 2008) were used to describe the change in abundance of fish with respect to depth and to compare between Periods 1 and 2 as described by Bailey *et al.* (2009). These data were



**Figure 1.** ICES Subarea VII (Divisions b, c, j, and k) in the Northeast Atlantic Ocean, showing the locations of the trawls.

square-root transformed to reduce the effect of outliers (mostly occasional trawls with very high catches). Visual assessments of variograms and bubble plots found no evidence of temporal or spatial autocorrelation, respectively (for details, see Bailey *et al.*, 2009). There were differences in the spatial distribution of trawls at the shallow end of the depth range <2000 m between the two periods, but Bailey *et al.* (2009) showed that this has weak effect on the analysis.

Data were explored for changes in the presence or the absence of the 15 most-abundant species. For *H. atlanticus*, which occurs over a relatively narrow depth range (960–1677 m), an additional analysis was done to compare the probability of capture between Periods 1 and 2. As a result of the large number of zeros for this species, the data were transformed to presence–absence, and a GAM with binomial distribution and logistic link function was used.

### GIS methods

Charts of Subarea VII were prepared from the General Bathymetric Chart of the Oceans (GEBCO). The GEBCO Grid Demonstrator version 2.12 was used to select the extent of the study area and export the bathymetric grid to the ASCII file. The ASCII file was converted to a raster dataset using the ArcView 9.3 by ESRI. In addition to the bathymetry raster, a slope layer was used in this study. To properly calculate slopes, we transformed the raster from the geographic coordinate system to the projected coordinate system, namely to Universal Transverse Mercator (UTM) based on the World Geodetic System (WGS) 1984 ellipsoid for a specific zone, 28N. As a result, both location and height data were stored in metres, which allowed us to estimate a slope raster accurately.

The area directly impacted by fishing was assumed to be between 500 and 1500 m deep, but avoiding slopes more than 20%. This then reflects the available information on the disposition of the fishery during the 1990s, more recent VMS and logbook data (Fisheries Science Services, 2009), and excludes steep slopes that are inaccessible to conventional demersal trawling. Commercial hauls for *H. atlanticus*, however, may target peaks and steep slopes but in very restricted areas, so overall fishery area estimates would not be greatly affected. To retrieve the fishing area, the reclassification procedure was used. First, the raster bathymetry was reclassified to obtain a 0–1 integer-value raster map, indicating by ones the areas with depths between 500 and 1500 m. Second, the slope raster was reclassified to get ones for relatively flat sites (slopes  $\leq 20\%$ ) and zeros for steep sites (slopes  $> 20\%$ ). The two reclassified raster maps were subsequently multiplied to obtain a raster map of fishery area. To estimate the area of fishery, this map was converted to a vector layer that was subsequently projected onto the European Albers equal-area conic projection. These two steps allowed us to calculate the feature area with acceptable accuracy. A similar approach was applied to determine areas corresponding to 10% decrements in abundance of fish. We, therefore, reclassified the bathymetry raster, converted the resulting layers to vectors, and again projected the resulting spatial data to the European Albers equal-area conic projection. Therefore, the map of decrease in fish abundance comprised a series of zones around the fishing area that corresponded to different depth ranges. For presentation, calculated areas were rounded to the nearest 1000 km<sup>2</sup>. Note that the slope criterion was not utilized for the latter exercise because it is assumed that fish distribute themselves regardless of slope and indeed in some cases may prefer steep slopes and the associated rocky terrain.

All resulting maps were displayed in conventional latitude and longitude coordinates in the geographic coordinate system WGS 1984 with a prime meridian at Greenwich.

## Results

### Fishery trends

For the three species *C. rupestris*, *H. atlanticus*, and *A. carbo*, there were no recorded landings before 1989 (Figure 2). Reported landings of *C. rupestris* grew from 222 t in 1989 to a peak of 1922 t in 1994. *Hoplostethus atlanticus* reported landings were just 3 t in 1989 and peaked at 3101 t in 1992, followed by a higher second peak in 2002 of 5465 t. *Aphanopus carbo* records begin with 10 t in 1990 and peaked at 662 t in 1994. For all three species, the reported landings strongly decreased after 2002.

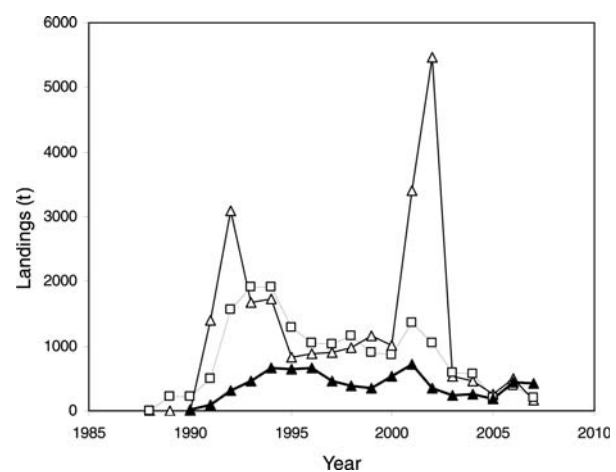
### Species depth distribution

In all, 108 demersal fish species from 39 families were identified from trawls (from 240 to 4865 m) in the study area (Figure 3). Of these, 77 species intersect the presumed 500–1500 m depth range of gears used by commercial fishing vessels operating in this area.

### Changes in total abundance and the area impacted by the fishery

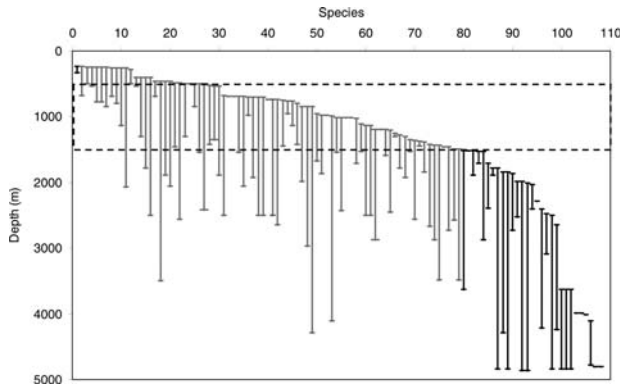
Between Periods 1 and 2, there was a significant decrease in the abundance of demersal fish (all species pooled) at depths <2525 m (Figure 4). At 1000-m depth, the abundance decreased from 10 102 (s.e. +2372, –2123) to 4795 (s.e. +2515, –1986) ind. km<sup>-2</sup>. Reduction of more than 50% was detectable down to 1863 m. The fitted lines for Periods 1 and 2 cross at 3086 m. At greater depths, there is evidence of increase in fish abundance with a peak at 3985 m of +43% but at maximum depth of the survey (4860 m), there is a decrease (–40%), but all differences at depths >2525 m are not statistically significant.

Projecting these data onto a chart of the area, it is evident that there is a reduction in fish abundance of over 50% in a large part of Subarea VII. The total area within ICES Subarea VII susceptible to the deep-water fishery between 500 and 1500 m was estimated as 52 000 km<sup>2</sup>. The total area with a reduction in abundance of

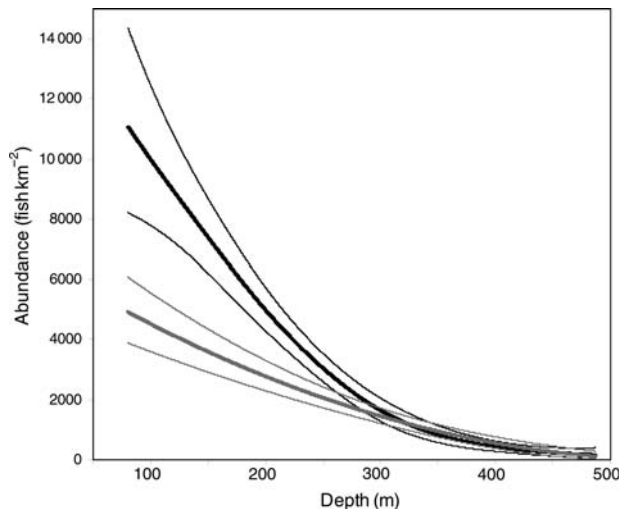


**Figure 2.** Landings of deep-sea demersal fish from Subarea VII as reported in ICES (2008). Total landings by all countries: squares, roundnose grenadier (*C. rupestris*); open triangles, orange roughy (*H. atlanticus*); closed triangles, black scabbardfish (*A. carbo*).





**Figure 3.** Maximum and minimum depths of 108 species of fish identified in trawl surveys. Dashed lines indicate the assumed deep range of commercial fishing activity 500–1500 m deep. Seventy-seven species with depth ranges intersecting the fishery zone are marked in grey. Other species in black. Key to species analysed in this paper: *S. kaupii* 16, *C. labiatus* 19, *N. aequalis* 20, *L. eques* 27, *C. rupestris* 37, *P. rissoanus* 41, *C. mediterraneus* 42, *A. rostrata* 48, *H. atlanticus* 50, *B. dubius* 55, *C. guentheri* 62, *T. murrayi* 64, *H. macrochir* 75, *C. leptolepis* 92, *C. armatus* 93. For identification of other species, see Priede et al. (2010).



**Figure 4.** Abundance of fish—all species pooled (numbers  $\text{km}^{-2}$ ) in trawl surveys. Black line: Period 1, 1977–1989 (127 trawls); grey line: Period 2, 1997–2002 (60 trawls). After Bailey et al. (2009). Thick lines: fitted GAMs; thin lines: 95% confidence intervals.

>50% (500–1863 m) was 67 000  $\text{km}^2$  and the area of significant impact (500–2525 m) occupied 106 000  $\text{km}^2$ . Potentially, the impact of the fishery (500–3086 m) extends over 142 000  $\text{km}^2$ , which is 2.74 times the area directly affected by deep-water fishing gears (Figure 5).

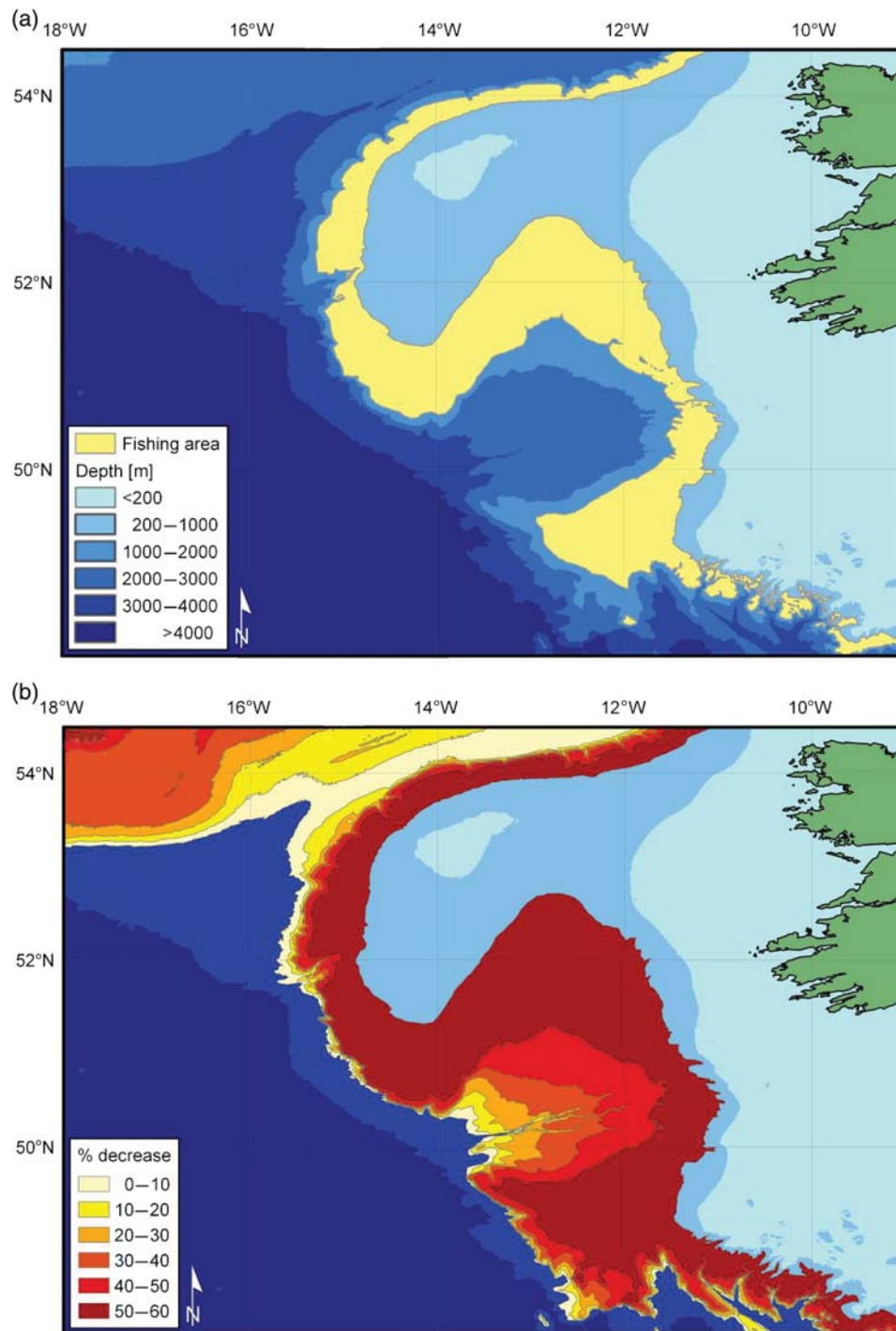
### Individual species

GAMs were fitted to the 15 most common species to investigate species-specific changes in abundance with depth and to determine changes in abundance between Periods 1 and 2 (Figure 6). The individual fish species are investigated in taxonomic order.

*Halosaurus macrochir* (Günther, 1878), Elopiformes, Halosauridae, abyssal halosaur, with a depth range

1440–3485 m, significantly ( $p < 0.0001$ ) reduced in abundance over its entire depth range between the two periods from 219 to 131  $\text{km}^{-2}$  (overall mean density). Its distribution showed a generally increasing abundance with depth down to its maximum depth. *Polyacanthonotus rissoanus* (De Filippi and Verany, 1857), Elopiformes, Notacanthidae, smallmouth spiny eel, depth range 740–2500 m, peaked in abundance at 1500 m and significantly ( $p < 0.001$ ) decreased in abundance between the two periods. The overall mean abundance decreased from 211 to 56  $\text{km}^{-2}$  with a most pronounced change at the shallow end of its depth range. *Synphobranchius kaupii* (Johnson, 1862), Anguilliformes, Synphobranchidae, Kaup's arrowtooth eel, depth range 407–2500 m, was the most-abundant species in the surveys (overall mean 4099  $\text{km}^{-2}$  in Period 1) and strongly decreased ( $p < 0.0001$ ) in abundance to an overall mean of 2110  $\text{km}^{-2}$  in Period 2. The decrease was most pronounced at the shallow end of its depth range. In addition, the point of peak abundance for this species shifted slightly deeper. *Bathypterois dubius* (Vaillant, 1888), Aulopiformes, Ipnopidae, spiderfish, depth range 1016–2434 m, peaked in abundance close to 1500 m and showed no significant change in abundance between the two periods, with overall mean abundances of 128 and 141  $\text{km}^{-2}$ .

Eight species of Macrouridae (Gadiformes) were important in samples at various depths. *Caelorinchus labiatus* (Koehler, 1896), spearsnouted grenadier, depth range 472–1900 m, is a relatively shallow-living macrourid that peaked in abundance at 1300 m and significantly decreased ( $p < 0.001$ ) in abundance between the two periods, with the greatest change at the shallow end of its depth range. *Coryphaenoides armatus* (Hector, 1875), abyssal grenadier, depth range 2016–4865 m, is a deep-living cosmopolitan species that showed no significant change in abundance between the two periods (overall values of 318 and 292  $\text{km}^{-2}$ ), but there was some evidence of increases in abundance over the range 3000–4000 m. *Coryphaenoides guentheri* (Vaillant, 1888), Günther's grenadier, depth range 1200–2875 m, showed a weak but significant change in abundance ( $p < 0.01$ ). A detailed examination of the curves (Figure 6) reveals a decrease in abundance in Period 2 at <2000 m and no change in abundance at greater depths, the overall mean changing from 680 to 602  $\text{km}^{-2}$ . *Coryphaenoides leptolepis* (Günther, 1877), ghostly grenadier, depth range 1993–4865 m, showed a non-significant ( $p > 0.05$ ) increase in abundance above its depth of maximum occurrence, 4000 m but with overall mean abundances of 110 and 83  $\text{km}^{-2}$  in the two periods, respectively. *Coryphaenoides mediterraneus* (Giglioli, 1893), Mediterranean grenadier, depth range 743–2645 m, significantly decreased in numbers ( $p < 0.001$ ) with a peak in abundance at 2000 m, and the overall mean decreased from 196 to 39  $\text{km}^{-2}$ . *Coryphaenoides rupestris* (Gunnerus, 1765), roundnose grenadier, depth range 706–1932 m, is one of the target species of the deep-water fishery. The abundance of this species was highest at 1500 m, and the results show a significant decrease in abundance by 41% ( $p < 0.001$ ) between the two periods from 578 to 341  $\text{km}^{-2}$ , with the most pronounced effect at depths <1500 m. *Nezumia aequalis* (Günther, 1878), common Atlantic grenadier, depth range 472–2058 m, also significantly decreased in abundance ( $p < 0.001$ ) across its depth range from 1072 to 252  $\text{km}^{-2}$ . *Trachyrincus murrayi* (Günther, 1887), roughnose grenadier, occupies a narrow depth range of 1205–1600 m, almost entirely within the commercial fishing zone. The results show that *T. murrayi* strongly declined in abundance ( $p < 0.001$ ) between the two periods, from 437 to 105  $\text{km}^{-2}$ .

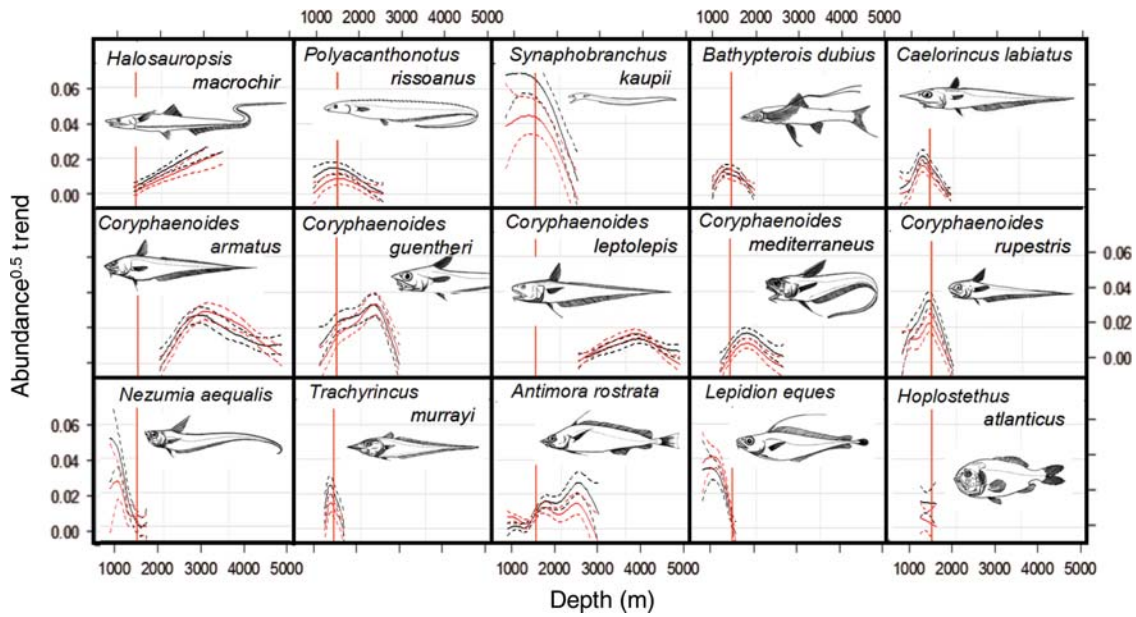


**Figure 5.** (a) The deep-water fishing area in ICES Subarea VII. It is assumed that vessels fish between 500 and 1500 m deep on slopes of less than 20%. (b) Estimated area of the fishery impact, percentage reduction in total demersal fish abundance based on depths trends in Figure 4.

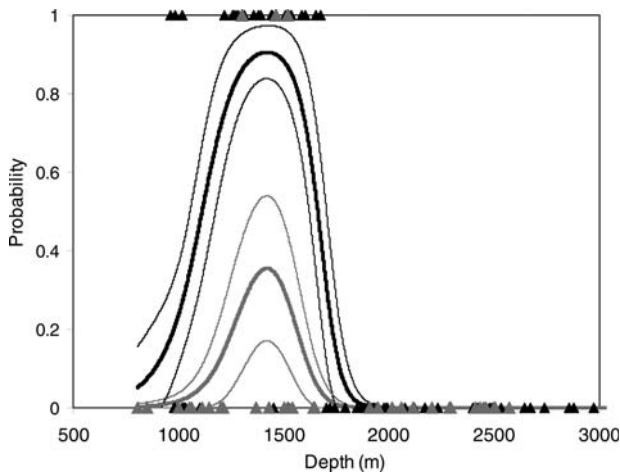
There were two Moridae (Gadiformes) species in the analysis: *Antimora rostrata* (Günther, 1878), blue antimora, depth range 853–2970 m, significantly decreased in abundance ( $p < 0.01$ ). At the shallow end of its depth range (<1500 m), however, the results indicate an increase in abundance, whereas at the deepest part of the depth range >2000 m, where the species is more abundant, a strong decrease in abundance between the two periods was detected. Averaged over the entire depth range, the change was

from 250 to 127 km<sup>-2</sup>. *Lepidion eques* (Günther, 1887), North Atlantic codling, depth range 506–2420 m, increased slightly in abundance in the shallower part of its depth range, although this change was not significant ( $p > 0.05$ ). The overall mean was 778 km<sup>-2</sup> in Period 1 and 1023 km<sup>-2</sup> in Period 2.

*Hoplostethus atlanticus* (Collett, 1889), Beryciformes, Trachichthyidae, orange roughy, depth range 960–1677 m, was caught in very small numbers ( $n = 3$  trawls) in Period 2 with



**Figure 6.** Abundance trends (square root of number of fish  $\text{km}^{-2}$ ) for the 15 most numerous species in the survey area. GAM plots are fitted to the data. Black lines, Period 1; grey lines, Period 2; dashed lines: 95% CIs.



**Figure 7.** GAM plot of probability of capture of orange roughy (*H. atlanticus*) during Period 1 (thick black line) and Period 2 (thick grey line). Thin lines indicate the 95% CIs. The depth axis extends to 4865 m, the maximum depth sampled, but has been truncated at 3000 m for clarity. All probability values at depths >3000 m were <0.001.

a highly significant decline ( $p < 0.001$ ) in abundance of this species between the two periods from 204 to  $13 \text{ km}^{-2}$ . Comparison of the probability of capture in Periods 1 and 2 is shown in Figure 7. Results showed that the probability of the capture of *H. atlanticus* is significantly reduced in Period 2. The deviance explained by the GAM is 62.9% (Table 1). The depth distribution of *H. atlanticus* has not changed, but probability of capture in any given OTSB haul at the depth of most frequent occurrence (1440 m) decreased from 90% in Period 1 to 36% in Period 2. None of the other most common species showed such a trend, and in general, there was no discernible change in the probability of capture. This is in accord with the observation by

Bailey *et al.* (2009) that there is no change in species richness between Periods 1 and 2. We hypothesize that since *H. atlanticus* tend to form aggregations, as abundance was depleted, the probability of encounter decreased, whereas other species, which are more dispersed, continued to be found in most trawl hauls, though in reduced numbers.

In summary, of the 15 species analysed, both fishery target species *C. rupestris* and *H. atlanticus* declined in abundance. A further seven species showed significant declines in abundance between the two periods, and these were all species with depth ranges intersecting the commercial fishing depths. Two species living at commercial fishing depths—*L. eques* and *B. dubius*—were not affected, however, and *L. eques* even increased in abundance. The deeper-living species *C. armatus* and *C. leptolepis* were also not negatively affected, but rather increased in abundance across parts of their depth range.

## Discussion

The deep-sea trawl dataset ( $n = 161$  trawls) for the Porcupine Seabight and abyssal plain at depths from 800 to 4865 m for the years 1977–2002 was first assembled by Bailey *et al.* (2009), who described a decline in fish abundance extending down to 2500 m. They rejected possible long-term environmental changes and inferred an impact from a commercial fishery. Priede *et al.* (2010), making no reference to temporal change or commercial fishing activity, analysed data from 187 trawls at depths from 240 to 4865 m, defined the depth ranges of 108 species found in the area, and described the resultant patterns of species richness. In the present paper, we combine information from these two papers with information from the commercial fishery to examine how vessels operating over a relatively limited depth range can affect the fish assemblage over wide areas of the continental slope.

The first appearance of deep-sea fish species in official catch statistics from Subarea VII in 1989 coincides with a period of decline in shelf-seas fisheries in northern Europe. In the North



**Table 1.** Change in probability of capture of orange roughy (*H. atlanticus*): summary of results of the GAM shown in Figure 7.

	Probability of capture				s(Depth)	Depth distribution		
	Estimate	s.e.	z-value	p-value		Edf	$\chi^2$	p-value
Intercept	-21.54	16.22	-1.33	0.184	2.69	2.824	0.364	
Factor (Period 2)	-2.86	0.51	-5.59	<0.001				

s.e., standard error; s(depth), the smoother fitted for mean depth for both periods; Edf, estimated degrees of freedom obtained by cross-validation.

Sea, for example, cod (*Gadus morhua*) stocks had declined below recognized safe limits, fishing mortality exceeded  $F = 1 \text{ year}^{-1}$  and ICES advised a decrease in TACs to avoid further decline in spawning-stock biomass (ICES ACOM, 2009). Nevertheless, a TAC of 124 000 t was recommended in 1989, so the landings of deep-sea fish shown in Figure 2 do not represent a major shift of effort by the fleets. Rather this was a specialist development initially by vessels from France, mainly targeting *C. rupestris*, which probably began a few years earlier with catches recorded among miscellaneous species (Lorance *et al.*, 2001). Grenadiers may have previously been discarded, but it is from 1990 that significant targeted fisheries developed for *C. rupestris*, *H. atlanticus*, and *A. carbo*. Imports of *H. atlanticus* from Australia and New Zealand, where the Chatham Rise fishery peaked at 90 000 t in 1990 (Koslow *et al.*, 2000), stimulated the market, and any additional landings from Northeast Atlantic waters were much sought. From 1992 to 2002, Northeast Atlantic landings were sustained by increases in effort involving vessels from Spain, UK, the Faroes, and Ireland, as well as the French fleet. The secondary peak in catches on *H. atlanticus* in 2002 (Figure 2) is represented by large catches by Ireland before the implementation of a quota management system in 2003 that first limited landings to lower levels (ICES WGDEEP, 2008) and has subsequently been reduced to zero landings. Our sampling in Period 1 (1977–1989) can therefore be considered largely pre-fishery, and by Period 2 (1997–2002), the fishery had become well-developed and it was evident by the end of this period that management measures would be necessary.

At the maximum depth of the commercial fishery of 1500 m, the survey data indicate a species richness of 47, with species richness per research trawl of 12–20 species (Priede *et al.*, 2010). Figure 3 shows that 77 species intersect the depth range of the fishery and hence are likely to be vulnerable. Furthermore, examining Figure 3, the depth ranges of 39 species extend below 1500 m, suggesting that if fish are mobile and move across the 1500-m depth boundary, fishery effects may be transmitted down the slope. From trawl surveys, Lorance (1998) showed that there was no shift in species composition in this area following the onset of the fishery, and Bailey *et al.* (2009) also detected no change in overall species composition between Periods 1 and 2. In the orange roughy fisheries of the Chatham Rise and Challenger Plateau of New Zealand, no changes were observed in fish community structure (Clark and Tracey, 1994; Clark, 1995, 1999), although more than half of the species monitored showed a decline in abundance of the order of 50%.

Overall in the fishing area, total abundance of fish decreased by >50%, similar to that observed in the New Zealand orange roughy grounds. The present study, however, is possibly unique in that the trawl survey extended to 4800 m, over three times the depth of the commercial fishery. It is evident that the impact of the fishery extends over an area much larger than the 52 000 km<sup>2</sup> directly influenced by the fishery. It could be argued that the area of

impact of 142 000 km<sup>2</sup> shown in Figure 5b is an overestimate owing to inclusion of the non-contiguous areas in the northwest corner of the study area, but there is further intense fishing activity on the slopes of the Rockall Bank and Rockall Trough in Subarea VI (ICES WGDEEP, 2008), so no doubt these regions are similarly affected. It is well-established that trawl fisheries have a direct mechanical effect on the seabed through the destruction of the seabed, removal of corals, and benthic invertebrates (Jennings and Kaiser, 1998; Koslow *et al.*, 2000; Clark and Rowden, 2009). Here, we show that because of the mobility of fish species, the impact on targeted and non-targeted fish populations may be much more widespread.

The trawling technique we used was not targeted at fish aggregations, so whereas for *H. atlanticus* we detected a decrease in the probability of capture from 90 to 36%, Irish commercial vessels were able to achieve landings of 5114 t in 2002 (ICES WGDEEP, 2008) presumably by targeting aggregations on the tops of seamounts and similar topographic features. The fishery has since fragmented into two components: the targeted fishery on adult aggregations and predominantly smaller individuals caught on gentle slopes as part of the mixed catch from deep-water trawling (ICES WGDEEP, 2008). Following scientific advice from ICES, the European Union has implemented area closures and a zero TAC with effect from 2010 (EC, 2008).

For *C. rupestris*, the depth of maximum abundance, 1500 m, coincides with the maximum depth of commercial fishing, and the abundance at this depth decreased from 1024 to 484 km<sup>-2</sup>. There is uncertainty regarding the status of this stock, but it is characterized by the fact that a wide size range of fish are mixed on the commercial fishing grounds (Lorance *et al.*, 2001, 2008), and it is estimated that 50% of the catch by number is discarded as being below marketable size. It takes 15 years for *C. rupestris* to reach marketable size, and it is unlikely that any juveniles either passing through the nets while on the seabed or caught and discarded survive. Our data show clear evidence of depletion by around year 2000, and there is evidence of continued decline in spawning-stock biomass since that time (ICES WGDEEP, 2008). The fishery is clearly exploiting a stock approximately half of which lies deeper than 1500 m. As fish of a wide size range are caught by commercial vessels, though with discarding of small size classes (Lorance *et al.*, 2001), it is evident that there is sufficient movement up and down the slope for the fishery impact to extend down to the maximum depth of occurrence of this species at 1932 m.

Two species—*N. aequalis* and *L. eques*—had most of their abundance within the fishery zone <1500 m deep (Figure 6). The former showed a significant decrease in abundance but the latter appears to have been unaffected by the fishery, indeed possibly increasing in numbers. This may reflect some kind of ecosystem effect in that the population may have benefitted from the removal of predators. Evidence of such effects in deep-water fisheries has been weak, but Lorance (1998) noted that the decline in sharks in Subarea VII was quite marked.

Nine species occurring within the fishing zone extend in significant abundance into deeper waters and can be regarded as potential transmitters of fishing impacts down the slope; these are *H. macrochir*, *P. rissoanus*, *S. kaupii*, *B. dubius*, *C. labiatus*, *C. guentheri*, *C. mediterraneus*, *T. murrayi*, and *A. rostrata*. *Halosaurus macrochir* shows a significant decline over its entire depth range, but this is curious because only a very small part of the range is at <1500 m. Most species recruit at the shallow end of their depth range and perhaps the fishery is disrupting key early stages of the life history. The eels *P. rissoanus* and *S. kaupii* both show a clear decline, and *S. kaupii*, which is numerically dominant, greatly influences the fish total abundance curves in Figure 4. *Synphobranchus kaupii* are a very conspicuous active component of the upper slope fish fauna of the Northeast Atlantic Ocean (Uiblein et al., 2002; Bailey et al., 2006) and appear at food falls, often represented by large numbers of small individuals <20 cm long (Priede et al., 1994) and with a body diameter <10 mm, i.e. likely to pass easily through trawlnets. It is probable that few of these fish are retained by commercial trawls to appear as discards and that most fishing-induced mortality is while passing through the meshes of the net (Davis, 2002).

*Bathypterois dubius* appears to be unaffected by the fishery; it is unlikely that solitary lifestyle and hermaphrodite reproduction (Froese and Pauly, 2009) confer such resilience. The macrourids *C. labiatus*, *C. mediterraneus*, and *T. murrayi* all show a simple decline in abundance throughout their depth range, so extend the fishery impact into deeper waters. *Coryphaenoides guentheri* shows a significant decrease in abundance at depths <1500 m but the deeper living component of the stock appears to be unaffected. This therefore cannot be regarded as a transmitter species in the present context. *Antimora rostrata* shows a highly significant decrease in abundance between 2000 and 3000 m and clearly contributes to the decrease in total fish abundance at these depths; however, paradoxically, there is an increase in numbers at <1500 m. This may be related to recruitment events with younger fish appearing at the shallow end of the depth range or may be further evidence of an ecosystem effect of the fishery.

Two species of deep-living macrourids, *C. armatus* and *C. leptolepis*, are beyond the reach of the fishery and showed no significant change in abundance. Both species showed a non-significant increase which is reflected in the cross-over in the total abundance curves in Figure 4. Bailey et al. (2006) observed a significant increase in abyssal fish abundance on the Northeast Pacific which they related to changes in surface productivity. These deeper-living fish in the Porcupine Seabight and the abyssal plain area may be responding in a similar way and can be regarded as control species, indicating that decrease in fish abundance at the shallower depths is unlikely to have been caused by natural effects.

Although the extension of species ranges into deeper waters beyond the fishing zone propagates the fishery impact over a much larger area, there is a converse effect that the zone deeper than 1500 m can be regarded as a natural Marine Protected Area (MPA), possibly ameliorating the effect of the fishery on the target species. This could certainly be significant for *C. rupestris*; however, studies have shown that to be effective, MPAs must be accompanied by a reduction in fishery effort (Steele and Beet, 2003; Kaiser, 2005; Jones, 2007). The existence of a deep-water reserve does not absolve the need for management measures.

This study shows that in addition to widely enumerated concerns regarding the impacts of deep-water fishing (Roberts,

2002), a slope fishery can have adverse effects on many non-target species, and the effect extends outside the area of operation of fishing vessels. These factors must be taken into account in moves to ecosystem-based management schemes.

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