Report

Current Biology

A Scientific Basis for Regulating Deep-Sea Fishing by Depth

Highlights

- First derivatives are calculated of non-linear trends in ecological indices with depth
- The ratio of discarded to commercially valuable fish biomass increases with depth
- The ratio of Elasmobranchii to commercially valuable fish biomass increases with depth
- Potentially negative impacts increase from 600 m, and catch value decreases

Authors

Jo Clarke, Rosanna J. Milligan, David M. Bailey, Francis C. Neat

Correspondence

j.clarke.1@research.gla.ac.uk

In Brief

Clarke et al. use a novel technique to show depths where ecological indices and the value of catch significantly change using long-term scientific deep-sea trawl data from the NE Atlantic. The results suggest that between 600 and 800 m the commercial benefits derived from fishing start to be outweighed by potentially negative ecological consequences.

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A Scientific Basis for Regulating Deep-Sea Fishing by Depth

Jo Clarke,[1,*] Rosanna J. Milligan,[1] David M. Bailey,[1,3] and Francis C. Neat[2,3]
[1]Institute of Biodiversity, Animal Health, and Comparative Medicine, University of Glasgow, Graham Kerr Building, Glasgow G12 8QQ, UK
[2]Marine Scotland Science, Marine Laboratory, 375 Victoria Road, Aberdeen AB11 9DB, UK
[3]Co-senior author
*Correspondence: j.clarke.1@research.gla.ac.uk
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SUMMARY

The deep sea is the world's largest ecosystem [1], with high levels of biodiversity [2, 3] and many species that exhibit life-history characteristics that make them vulnerable to high levels of exploitation [4]. Many fisheries in the deep sea have a track record of being unsustainable [5, 6]. In the northeast Atlantic, there has been a decline in the abundance of commercial fish species since deep-sea fishing commenced in the 1970s [7, 8]. Current management is by effort restrictions and total allowable catch (TAC), but there remain problems with compliance [9] and high levels of bycatch of vulnerable species such as sharks [10]. The European Union is currently considering new legislation to manage deep-sea fisheries, including the introduction of a depth limit to bottom trawling. However, there is little evidence to suggest an appropriate depth limit. Here we use survey data to show that biodiversity of the demersal fish community, the ratio of discarded to commercial biomass, and the ratio of Elasmobranchii (sharks and rays) to commercial biomass significantly increases between 600 and 800 m depth while commercial value decreases. These results suggest that limiting bottom trawling to a maximum depth of 600 m could be an effective management strategy that would fit the needs of European legislations such as the Common Fisheries Policy (EC no. 1380/2013) [11] and the Marine Strategy Framework Directive (2008/56/EC) [12].

RESULTS AND DISCUSSION

There has been a recent global debate as to whether there is a depth beyond which fisheries cannot be expected to operate in an economically and ecologically sustainable way. Stopping deep-sea fishing in the high seas (the areas beyond national jurisdiction) has been suggested to be more "equitable, and environmentally and economically sensible" [13]. In European deep seas, another report suggested that "sustainable levels of exploitation are probably too low to support an economically viable fishery" [14]. On the other hand, deep-water fisheries can provide regional socioeconomic benefits, most notably in remote areas. In the northeast Atlantic, the major fishing area for deep-water bottom trawl fisheries lies west of Scotland and Ireland out to the Rockall and Hatton Banks [15]. Deep-water fish stocks were first exploited in this area in the early 1970s, but the fishery only became regulated in 2003 after it was recognized that most target species were being exploited outside of safe biological limits [16]. The introduced management measures included setting total allowable catch (TAC) limits for listed commercial species and effort restrictions on days at sea and required vessels to hold fishing licenses. Despite this, there have been difficulties: TACs were often not complied with [9], and high proportions of catches were being discarded [10]. Of particular concern were species with low productivity, such as deep-sea sharks and rays (Elasmobranchii), some of which were estimated to have declined by up to 90% [17]. In addition, incomplete information on fishing effort, landings, and discards due to under-reporting [18] and limited scientific surveys [19] generates much uncertainty in the scientific advice for management. With European Union (EU) regulations such as the Common Fisheries Policy (European Commission [EC] no. 1380/2013) [11] and Marine Strategy Framework Directive (2008/56/EC) [12] now requiring the implementation of an ecosystem approach to marine management, the question has been raised as to whether a better management strategy would be to impose a maximum fishing depth limit. Such a limit might reflect the depth at which the commercial benefits derived from fishing start to be outweighed by potentially negative consequences for sustainable management, ecosystem health, and the preservation of biodiversity.

In this study, we examined the trends of catch composition indices taken from scientific trawl surveys with depth to determine whether consistent patterns could be found. The data were collected from trawl surveys between the depths of 240 and 1,500 m in the northeast Atlantic (Figure 1). Surveys used different gear types at different locations and spanned different periods of time between 1978 and 2013 (for details, see Table S1). The indices calculated from the trawl data were (1) Simpson's diversity index, (2) the ratio of "discarded" to commercial biomass, (3) the ratio of Elasmobranchii to commercial biomass, and (4) the value per square kilometer of each trawl in Euros. Demersal fish species with no commercial value were deemed "discarded" and those with a value, excluding Elasmobranchii, were classed as "commercial." The generalized additive mixed model (GAMM) function (R package Mixed GAM Computation Vehicle [mgcv] [20]) in R statistical software [21] was used to

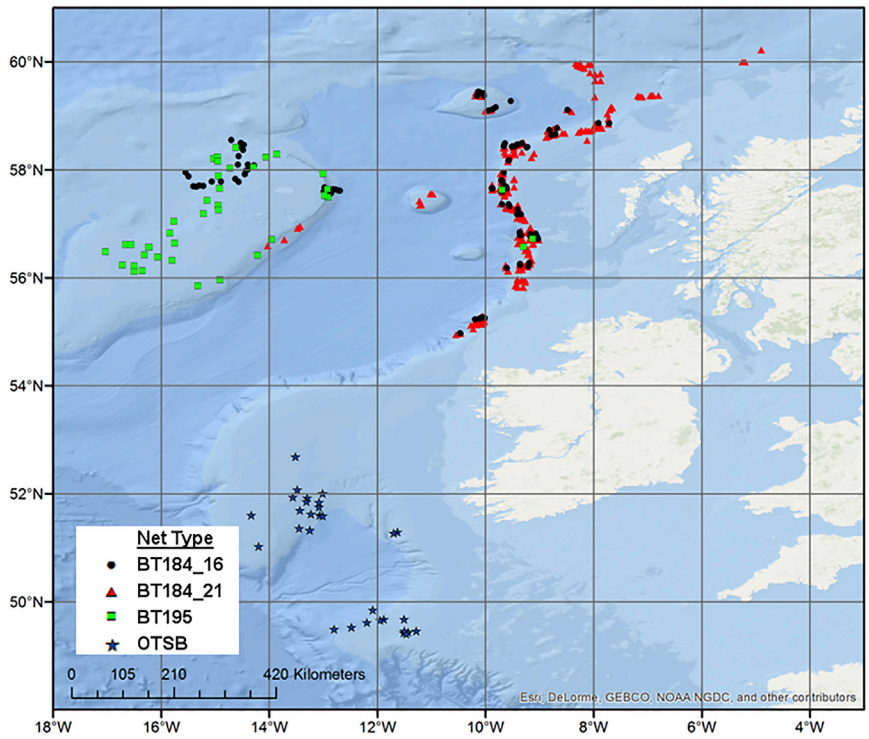

Figure 1. Map of the West Coast of the UK and Ireland

Different-colored symbols indicate locations of trawls conducted by each gear type.

determine the relationship between each index and depth, with depth included as a smoother term. As the surveys were conducted in different locations and with four different gear types, "survey" was included as a random effect. The first derivatives of the modeled trends were then calculated to identify depth ranges where the rate of change of the smoother was significantly different from zero.

Fish biodiversity increased between depths of 400–1,000 m (Figure 2A), suggesting that the deeper that trawls are deployed, the greater the potential impact on biodiversity. Based on estimates of depth distribution for each species, Table 1 shows that approximately 18 additional species are encountered for every 100 m increment in depth. This is clearly relevant to the EC's Marine Strategy Framework Directive, which requires fishing activity to be managed to meet conservation objectives, one of which is "the maintenance of biodiversity." Even though a recent study in the northeast Atlantic suggested that there has been no detectable impact of deep-sea fishing on fish diversity [2], there have been significant declines in abundances of some commercially important species [6, 8], leading to commercial extinction in some cases [7]. When interpreting the lack of effect of deep-sea fishing on biodiversity [2, 8, 22], caution should be taken, as it may take a longer time period (decades) for the effects of fishing to become fully apparent.

Over the range of 600–800 m, the proportion of discarded nontarget species (Figure 2B) increased. The ratio of discarded to commercial biomass significantly increased with depth from 0.3:1 at 600 m to a peak of 1.6:1 at ~1,300 m (Figure 2B). The commercial value per unit effort significantly decreased between depths of 400–700 m, indicating decreasing returns per unit effort of fishing over this depth range. The value per trawl then remained constant between 700 and 900 m before rising again at ~1,300 m (Figure 2D), reflecting the dominance of the commercial species *Coryphaenoides rupestris* at these depths [23]. The high proportion of discarded biomass caught by all net types in this study corroborates with other studies in which scientific observers on commercial fishing vessels recorded that discard biomass was almost equal to landings biomass and discard rates increased with depth [10]. In those studies previously referred to, the increase in discard rate with increasing depth was driven by a change in the length-frequency distribution of the commercial catch, as smaller commercial fish were caught and subsequently discarded [24]. There is no legal minimum landing size for any deep-sea commercial species, but for economic reasons small individuals of commercial species are discarded to maximize the total value of the landings (high grading). Within the present study, commercial fish of all sizes were classed as "commercial biomass," and our estimates of commercial biomass in this study are therefore likely to be conservative as in reality the landed biomass of commercially valuable fish would be lower. Three of the four trawl nets (OTSB, BT184_16, and BT184_21) used in this analysis were scientific nets, with a smaller mesh size and smaller width than commercial nets, raising the issue of how representative these results are of commercial fishing operations. However, the fourth net used was a commercial fishing gear, and the catch ratios derived from the scientific nets were similar (Figure 2), suggesting that this issue is not of major concern.

Between 500 and 600 m, the ratio of Elasmobranchii biomass to commercial biomass significantly decreased before increasing significantly between 600–800 m and eventually peaking at 1,300 m (Figure 2C). The conservation of the deep-sea sharks taken as bycatch is a specific management concern of deep-water fisheries. Deep-sea species of sharks are extremely vulnerable to exploitation [25] and have been documented to typically exhibit more "K-dominated" life-history traits with increasing depth [26]. Surveys conducted in the late 1990s showed that catch rates of Elasmobranchii had decreased by an order of magnitude since the start of the fishery to the west of Scotland [27]. A zero TAC was introduced for sharks in 2010 [15], but that does not prevent them getting caught as bycatch in a mixed fishery [28].

Together, these results show that collateral ecological impacts are increasing significantly between the depths of 600 to 800 m, while commercial gain per unit effort at depths greater than 600 m (until 1,300 m) is decreasing. In the EU, attempts have been made to overcome the problems of discards and reduce

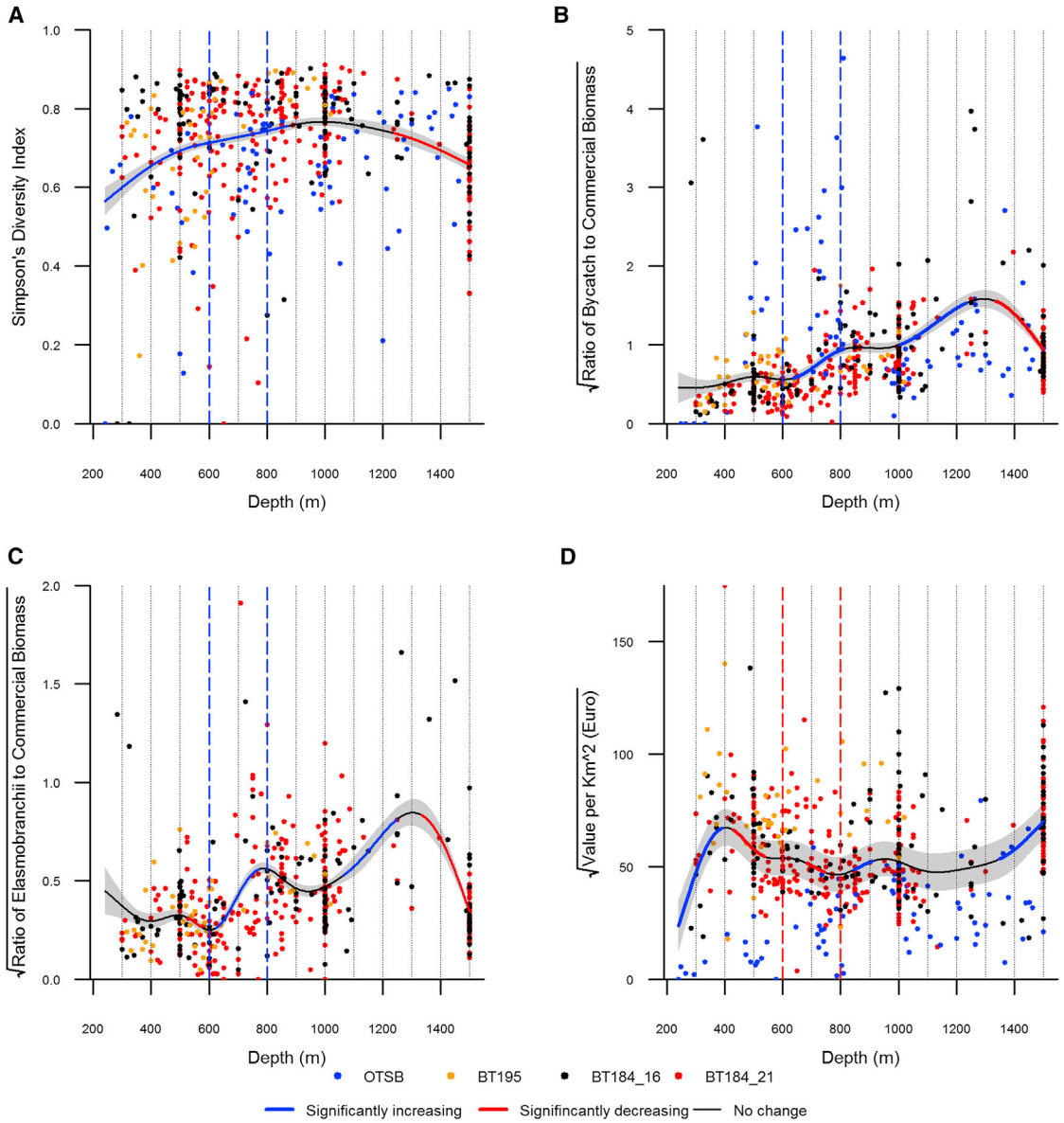

Figure 2. The Trend of Each Catch Composition Index versus Depth

(A) Simpson's diversity.

(B) Square root of the ratio of discarded to commercial biomass.

(C) Square root of the ratio of Elasmobranchii to commercial biomass.

(D) Square root of the value of 1 km^2 trawl (Euros).

Each response variable is fitted with a general additive mixed-effect model versus depth. The fitted line is black, and 95% confidence intervals are shaded in gray. First derivatives were calculated; significant increases are colored blue, and significant decreases are colored red. Each point is a trawl, and the different gear types are colored differently: blue is OTSB, orange is BT195, black is BT184_16, and red is BT184_21.

the exposure of vulnerable fish and habitats to deep-sea fisheries. However, although the introduction of management measures for deep-sea fish stocks may have prevented further stock declines, they have not allowed for recovery [23]. New measures to protect deep-water ecosystems from fishing are currently being considered by the EU. One of the most controversial proposals calls for a ban on trawling at depths greater than 600 m. The present study suggests that prohibition of bottom trawling at depths >600 m may help meet the criteria of multiple European legislations. These include achieving good environmental status for at least two descriptors (biological diversity and marine food webs) required under the Marine Strategy Framework Directive and the implementation of an ecosystem approach to fisheries management under the Common Fisheries Policy. Progress has been made in the management of our shelf seas in the north-east Atlantic, resulting in the majority of fish stocks now providing a sustainable and secure food source [29]. In order to achieve a similar status for Europe's deep-sea fish stocks, a

Table 1. The Number of Demersal Fish Species Whose Putative Home Range Is Deeper Than the Proposed Depth-Limit Scenarios

	Depth Limit						
	300 m	400 m	500 m	600 m	800 m	1,000 m	1,200 m
Number of species excluded from fishing range	180	139	119	80	49	29	11

restriction of bottom-trawling to less than 600 m could be a solution that now has a stronger scientific basis. Although the depth ranges identified in this study as being indicative of an appropriate depth limit to trawling may be particular to the northeast Atlantic, the methodology could be applied globally to generate region specific management advice.

EXPERIMENTAL PROCEDURES

Survey Methods

Details on each of the four survey methodologies can be found in the references provided in Table S1. For all surveys, all fish were identified to species level wherever possible. Using the Fishbase [30] database, we classified all species as demersal or bathypelagic. Only demersal species were used in the analysis. Individual lengths were measured to the closest 1.0 or 0.5 cm accuracy. For the Outer Hebrides surveys, the total weight of each species for each catch was recorded to within 0.1 kg, and subsamples of individuals were weighed to an accuracy of 1.0 g. For the Porcupine Seabight surveys, no weights were obtained in the earlier surveys (1979–1989), whereas in the later (1997–2002) surveys all animals were wet weighed to a precision of 1.0 g [22]. Length-weight relationships were calculated by fitting a linear model to the logarithm (base 10) of length and weight for each species separately from the west coast of Scotland and the west coast of Ireland surveys. Using the output from these models, we calculated the weights for all other individual fish from their known lengths. Simpson's diversity metric ($1 - \lambda'$) was calculated for each trawl and used in the analysis [31].

Calculation of Commercial Value

Data on the value of each demersal fish species landed in the UK, Ireland, France, and Spain were aggregated from the EuroStat website [32]. The value for each species in Euros per ton was taken as the average value for the four countries (the UK, Ireland, France, and Spain), taken over a 10 year period between 2003 and 2012. If a fish species was landed and identified as having a value, it was classed as being commercial (Table S3). All demersal fish species not found to have an attached value were deemed discarded. An exception was made for the species *Alepocephalus bairdii*, which, although landed in some parts of the Atlantic, is discarded by the main fisheries operating in the Rockall Trough area [10]. Elasmobranchii were all classed as discarded as these fisheries have been closed since 2010. Due to the known vulnerability of Elasmobranchii to exploitation, we assessed changes in the ratio of their biomass to commercial biomass with depth.

Calculation of Indices

The weights of all demersal fish species were aggregated to give a total biomass per trawl. Then the weights for all commercial species, discarded species, and Elasmobranchii were aggregated per trawl. The following metrics were calculated: the ratio of discarded to commercial biomass, the ratio of Elasmobranchii to commercial biomass, and the value of commercial biomass per square kilometer. Very few Elasmobranchii were caught in the Porcupine Seabight trawls, so these were excluded from the analysis. It should be noted that most of the data used in this study were collected after deep-sea fisheries had commenced and therefore do not reflect a pristine ecosystem; abundances and biomass have been depleted [8]. Therefore, indices used are representative of the current state of the ecosystem and could change in the future.

Data Analysis

GAMMs were used to model the relationship between the selected metrics and depth, with depth included as a smoother term (Equation 1). As trawls were conducted in different locations and with four different gear types, "survey" was included as a random effect:

$$Y_i = \beta_0 + f_1(\text{depth}_i) + \varepsilon_i + a_i; \varepsilon = N(0, \sigma^2); a_i = N(0, \sigma_a^2), \quad \text{(Equation 1)}$$

where Y_i is the response variable (the individual catch metrics), depth_i is depth in meters (200 m to 1,500 m), β_0 is a constant term, and ε_i is model's residuals.

The depth smoother and number of degrees of freedom were calculated during model fitting using penalized splines and generalized cross validation (GCV). This was conducted using the "gamm" function from the mgcv package [20] in R statistical software [21]. Penalized splines using GCV allowed for model selection to be selected back to a single degree of freedom equaling a linear trend if that was determined to be the best fit.

The ratio indices and the value of commercial biomass index were square-root transformed to reduce the right skewness and normalize the data. All catch metrics were then modeled using the Gaussian distribution with an identity link function. Model validation was carried out by visual examination of plots of the normalized residuals versus the fitted values from each of the models. Any models that violated assumptions of homogeneity of variance were refitted with different variance structures using the "VarFunc" command. Model selection was conducted using Akaike's information criterion (Table S2).

To interpret the fitted trends and identify whether there were any depth ranges that showed significant rates of change, we calculated first derivatives along with 95% simultaneous confidence intervals. When the 95% confidence intervals of the first derivatives do not include zero, this indicates a significant increase or decrease in the rate of change of the response variable. The model's fitted values were calculated at 200 equally spaced points and were calculated again at a point 1×10^{-7} m along the trend line and the model refitted. The difference between the two sets of fitted values was divided by the difference in depth to give a predictor matrix of the slope of the spline at the 200 equally spaced points. This predictor matrix was then multiplied by the coefficients of 10,000 random simulations from the posterior distribution of the model. This method of sampling from the posterior distribution producing simultaneous confidence intervals for the entire trend is a more rigorous assessment of uncertainty than using pointwise confidence intervals [33]. From these, the 95% confidence interval of the first derivatives was calculated by taking the two extreme quantiles of the distribution.

SUPPLEMENTAL INFORMATION

Supplemental Information includes three tables and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2015.07.070.

AUTHOR CONTRIBUTIONS

F.N. and D.B. conceptualized the idea for the paper and the indices for analysis. R.M. critiqued and assisted with the statistical analysis and graphical presentation. J.C. analyzed the data and wrote the paper. All authors discussed the results and commented on the manuscript.

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