Choking recovery: threats and opportunities in an expanding fish stock

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Choking recovery: threats and opportunities in an expanding fish stock

Alternative title:

From a recovering stock to a 'choke' species: the example of northern hake

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Running title:

Recovering fish stock and choke species

Abstract

Many commercial fish stocks are beginning to recover under more sustainable exploitation regimes. In this study we document the temporal and spatial changes in one remarkable example of stock recovery: northern European hake (*Merluccius merluccius*). Analysing data from several scientific surveys, we document a dramatic increase in estimates of biomass between 2004 and 2011 throughout the larger area now occupied by the stock. The largest increase occurred in the North Sea, where hake have been largely absent for over 50 years. Spatio-temporally resolved commercial landings show that high densities occur in the North Sea only between April and September, suggesting a density-dependent seasonal habitat expansion to suitable temperature and depth conditions. These changes have implications for the management of the stock which are discussed. Notably, if discards are banned as part of management revisions, the relatively low quota for hake in the North Sea will be a limiting factor (the so-called "choke" species) which may result in a premature closure of the entire demersal mixed fishery in the North Sea, jeopardising many commercial fisheries in the region. This example of the unforeseen consequences of improved stewardship, highlight the need for a more holistic, regional and responsive approach to managing our marine ecosystems.

Keywords: fish stock recovery, fisheries management, choke species, European hake

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Introduction

Fisheries of the northeast Atlantic were heavily exploited throughout the second half of the 20th century, and many commercial fish stocks experienced a severe decline in biomass by the early 2000s. As a result, the Common Fisheries Policy (CFP) which regulates fisheries in European waters undertook a major reform in 2002 (Daw and Gray 2005) and is currently under further reform (EC 2013). The 2002 reform aimed to reduce fishing pressure on over-exploited stocks by introducing recovery plans to allow depleted fish stocks to recover, and long-term management plans to protect healthy stocks from depletion (Kraak *et al.* 2013). These measures have contributed towards a substantial reduction in fishing pressure for most northern European fish stocks in recent years (Cardinale *et al.* 2013) and a reversal of stock decline, with prospects for recovery (Fernandes and Cook 2013). Among the stocks showing signs of recovery, the northern stock of European hake (*Merluccius merluccius*, Merlucciidae) seems to have experienced one of the largest and fastest biomass increases over the last five years. The latest assessment of this stock undertaken by the International Council for the Exploration of the Sea (ICES) shows a dramatic increase in biomass since 2006, and the spawning stock biomass (SSB) is now well above the recommended level (ICES 2012a). Reported landings have consequently increased, especially for the northern part of the stock (ICES 2012a).

European hake is a large demersal gadoid species found at depths between 70 and 200 m (Kacher and Amara 2005), with a preference for depths between 70 and 100 m (Bartolino *et al.* 2008). It is a Lusitanian species with a preferred temperature of 13.8 °C, plus or minus 2.9 °C (Wheeler 1969). European hake has the most extensive distribution of all gadoid species in the northeast Atlantic and ranges from the tropical coast of Mauritania to the cooler waters of Norway, expanding eastwards in the Mediterranean Sea, the North Sea, and the Skagerrak and Kattegat (Casey and Pereriro 1995). In northeast Atlantic waters, European hake is managed as two distinct stock units, a southern and northern component, separated by the Cap Breton canyon in the Bay of Biscay (ICES 2012a). The northern stock ranges from the southwest coast of France to Norway, covering ICES areas IIIa (Skagerrak and Kattegat), IV (North Sea), VI (West of Scotland), VII (Celtic Sea) and VIIIa,b,d (Bay of Biscay) (ICES 2012a). The stock is, therefore, managed over an extensive area and regional assessments are not carried out. Northern hake are surveyed by five scientific trawl surveys, conducted annually, in the North Sea, the Celtic Sea, the West of Scotland, Irish waters, the Porcupine Bank and the Bay of Biscay. These surveys provide estimates of relative abundance, as well as length- and maturity-at-age estimates, used in the stock assessment. The SSB of this stock peaked in 1980 at 101,917 t, but was then rapidly depleted to a historical low in 1998 at 24,603 t (ICES 2012a). As a result, an emergency plan was implemented in 2001 (EC 2001, 2002) which introduced a reduction in the Total Allowable Catch (TAC) as well as stipulating a minimum mesh size (100 mm) in the cod-ends of trawl nets; a recovery plan followed in 2004 (EC 2004). These multi-annual plans led to a reduction in the exploitation rate and SSB has since increased to a new high of 131,075 t in 2010 (ICES 2012a).

Fish stocks experiencing an increase in abundance often show a concurrent increase in the area they occupy, a mechanism known as density-dependent habitat selection (MacCall 1990; Hinz *et al.* 2003; Hiddink *et al.* 2005). According to the ideal free distribution theory (Shepherd and Litvak 2004), individuals expand to suitable habitats in order to avoid high densities and maximise their fitness, a response which has been observed in gadoid stocks (Marshall and Frank 1995). Given the large increase in biomass, an expansion of the area occupied by the northern hake stock is likely to have occurred, providing that suitable habitats are available in adjacent areas. Warming sea temperatures have also been linked to changes in the distribution of fish stocks such as shifts towards the poles or deeper waters (Hiddink and ter Hofstede 2008; Dulvy *et al.* 2008). In the northeast Atlantic several examples of Lusitanian species expanding their distribution northward have been reported such as European anchovy (*Engraulis encrasicolus*, Engraulidae), European pilchard (*Sardina pilchardus*, Clupeidae), Atlantic horse mackerel (*Trachurus trachurus*, Carangidae) and Atlantic mackerel (*Scomber scombrus*, Scombridae) and are now prevalent in new areas (Beare *et al.* 2004; Petitgas *et al.* 2012). However, both a change in the area occupied and a shift in distribution have yet to be documented for the northern stock of European hake.

Changes in the area occupied by a stock can result in changes to the potential catch and can offer new fishing opportunities depending on the area and/or the species considered (Cheung *et al.* 2012). Typical examples in the northeast Atlantic region include northward expansion of the Atlantic mackerel (ICES 2013). Such changes are likely to affect fisheries regulation and exploitation patterns, but also fish prices and economic performance of fishing fleets (Cheung *et al.* 2012). The northern hake stock is of great economic importance (Alvarez 2004) especially for Spanish and French fleets which historically have accounted for 60% and 25% of the landings respectively; fleets from the U.K., Denmark, Ireland, Norway, Belgium, Netherlands, Germany and Sweden have contributed to the remaining 15% (ICES 2012a).

In the North Sea there is an additional management concern relating specifically to hake which could affect the entire demersal fishery. The latest CFP reform (EC 2013) includes a ban on discards due to be phased in over the next 5 years. Hake in the North Sea is caught in a mixed demersal fishery including cod, haddock, whiting and other fish species. However the TAC of hake in this area is very small compared to other species, simply because it was not abundant when catch shares were being allocated. In the presence of a discard ban this fishery will be closed once the smallest quota (hake) is taken and fishermen will not be able to catch other species even though their quotas may not have been reached. This scenario is commonly referred to in the USA as the "choke species" concept (Schrope 2010): a species with the lowest quota in the mixed fishery "chokes" the opportunity to catch the quotas of other species. In Europe this has been examined in mixed fishery models (Ulrich *et al.* 2011) but hitherto the choke species in the North Sea is expected to be cod. It is, therefore, important to assess the increase in regional biomass of hake and document the concomitant changes in distribution which are likely to occur in order to better understand the dynamics of this stock and any repercussion on fisheries. Improving our knowledge of the intra-stock dynamics of northern hake is particularly important since this pan-European stock is assessed over a large area.

In this study, fisheries independent data are analysed to document the regional increases in the northern hake stock and investigate the potential implications for fisheries management. Local abundance estimates are determined to investigate the distribution of the increasing biomass and whether the area occupied by European hake has expanded amid the observed increase in global biomass. Commercial landings data are used to compare seasonal changes in distribution with local changes in sea temperature. Regional biomass estimates are calculated to quantify the increase within ICES areas of the northern hake stock. Particular attention is given to the North Sea where the TAC is much lower than in other areas of the stock. Finally, the increase in biomass and expansion of spatial distribution is discussed in relation to quota allocation, to highlight the opportunities and challenges presented by a recovering stock in the context of the proposed management changes (CFP reform).

Methods

Data

Data from scientific trawl surveys were obtained from ICES for the five regions covering the northern stock area: North Sea, West of Scotland, Celtic Sea, Porcupine bank and Bay of Biscay. Data for European hake were available in sufficient quantity over the period 1978-2011 for the North Sea and West of Scotland, 1978-2008 for Ireland, 2001-2011 for the Porcupine Bank and 1985-2010 for the Bay of Biscay. Additional data from Scottish (1978-2007) and French (1985-2002) surveys were obtained from Marine Scotland Science (MSS) and IFREMER, respectively. Available maturity-at-length data were extracted from the same database. Northern hake stock estimates of total stock biomass (TSB), SSB, fishing mortality and recruitment were taken from the latest stock assessment report (ICES 2012a). North Sea landings of European hake from 1903 to 2010 were obtained from the Food and Agriculture Organisation. Landings of European hake into Scottish ports and the associated discards values for 2011 were obtained from MSS (Alastair Pout, MSS, personal communication). Monthly European hake landings per ICES statistical rectangle of Scottish (from 2005 to 2011) and Danish (from 2000 to 2011) fleets, the two main nations targeting European hake in the North Sea (ICES 2012a), were obtained from MSS (Rui Catarino, MSS, personal communication) and the Danish National Institute of Aquatic Resources (Henrik Degel, DTU aqua, personal communication) in order to perform spatial analyses. Monthly sea surface temperature (SST) values in °C were obtained from the British Atmospheric Data Centre for the northern hake stock area. SST values were available on a 1° latitude by 1° longitude grid extrapolated from the Met Office Hadley Centre data (Rayner 2003). Bathymetry data for the North Sea were obtained from the National Oceanic and Atmospheric Administration.

Analyses

Data for each trawl haul included: date, longitude and latitude, depth, distance covered (a measure of the maximum length sampled by the trawl), haul duration, speed over ground, door spread (a measure of the maximum width sampled by the trawl) and numbers-at-length. For each survey, the number-at-length values were corrected to account for the differences in sampling procedures between surveys: whenever sub-sampling occurred, the values were adjusted by the corresponding raising factor. Data from each survey were then compiled in one standardised dataset for further analysis. The weight of hake in each haul was estimated by summing up the weight at each length-class as follows:

$$(1) \qquad w_h = \left(\sum_h^l (a * l^b) * n_l\right)/1000$$

where w_h is the weight of hake caught in haul h in kg, l is the length-class in cm, n_l is the number of individuals in length class l in haul h, and a and b are the coefficients of the hake weight to length relationship obtained from Coull *et al.* (1989) with $a = 0.0047$ and $b = 3.099$. The relationship between depth and door spread was estimated by fitting the following equation to survey data for which both depth and door spread were recorded:

$$(2) \qquad ds = \frac{\sigma * dp}{\beta + dp}$$

where ds is the door spread, dp the depth and α and β are the estimated unitless coefficients. Equation 2 was then used to estimate missing door spread values. Missing distance values were estimated by multiplying haul duration by speed over ground. The area sampled by each haul was calculated by multiplying door spread (width) with distance (length). Using door spread provides a conservative measure of density since it corresponds to the largest area sampled: the estimates can, therefore, be considered as minimum values in the context of whole gear selectivity which affect absolute abundance estimates. For each haul, densities in weight (kg.km^{-2}) were determined by dividing the weight of fish caught by the area sampled. These density estimates were plotted spatially by year and quarter from 2001 to 2011. Average densities were also estimated for each survey, taking into account null observations (i.e. hauls where no hake were caught).

In order to estimate the biomass in each ICES area included in the northern hake stock, the time series of total biomass from each survey was estimated by multiplying the mean density by the area covered by the corresponding survey. The total northern hake survey biomass tsb_{TOT} was estimated by summing up the regional survey estimates tsb_{AREA}. The survey catchability q was calculated as the ratio of the total northern hake survey biomass tsb_{TOT} to the northern hake TSB estimates TSB from the reported stock assessments (ICES 2012a): $q=tsb_{TOT}/TSB$. Regional TSB estimates TSB_{AREA} were then determined by multiplying the survey biomass in each area tsb_{AREA} by the inverse of the survey catchability: $TSB_{AREA}=tsb_{AREA}*q^{-1}$. A maturity ogive for the northern hake stock was fitted to the maturity-at-length data available from ICES and the length at 50% maturity (L_{50}) was estimated at 31.2 cm. SSB was then estimated as the fraction of the TSB for which the length of individuals was greater than L_{50}.

To investigate changes in the northern hake stock distribution area, a threshold was defined as the maximum density determined in the North Sea prior to the implementation of the 2004 hake recovery plan. The percentage of ICES rectangles surveyed in which densities greater than this threshold were determined was calculated for each year. This proxy of relative spatial occupation differs from the positive area (the area where fish densities are strictly positive) used by Woillez *et al.* (2009) to investigate fish distribution and was employed to assess the magnitude of the change in the area occupied by hake. This proxy was estimated for all surveys between 1985 and 2011 to ensure sufficient data in all regions with the exception of Porcupine Bank where data were available from 2001 only. To assess changes in regional distribution, the centre of gravity (Woillez *et al.* 2007) of the observed densities (i.e. the mean location of the population) was calculated for each survey from 2001 to 2011. In addition, the overall centre of gravity was calculated using only years sampled by all surveys (2001-2008) and averaged both before (2001-2004), and after (2005-2008), the implementation of the 2004 hake recovery plan.

To investigate changes in distribution in the North Sea throughout the year, Scottish and Danish monthly hake landings per ICES statistical rectangles were aggregated over all available years and plotted on monthly maps. Monthly mean SST values averaged across 2001-2011 as well as the 100 m depth contour were added to the maps to compare the distribution of hake with these environmental variables. Generalised Additive Models (GAMs) were employed to investigate statistical relationships between hake distribution and the corresponding temperature and depth as follows:

(3) $g(\text{landings}) = c + s(\text{SST}) + \text{Depth} + \varepsilon$

where g is the Gaussian link function, c a constant, s a smoother, and ε a random error term. Depth was set as a discrete variable with 50 m classes. GAMs were applied to the whole dataset (2000-2011), and to landings recorded before (2000-2004) and after (2005-2011) the 2004 hake recovery plan to assess whether the increase in abundance affected the relationship between distribution and environmental variables.

Results

Estimates of biomass from the northern hake stock assessment reveal that the biomass was declining for most of the 1978-2010 period until a significant increase in recent years. TSB (Fig. 1a) and SSB (Fig. 1b) time series exhibit a steady decline from the late 1970s to the late 1990s followed by a slight increase until the mid-2000s. From 2006 the biomass increased dramatically, to reach a historical high in 2010 (Fig. 1a and 1b). Estimates of recruitment declined steadily over the majority of the time series reaching a historical low in 2009, apart from a slight increase in the mid-2000s concurrent with the start of the increase in TSB (Fig. 1a). Average estimates of fishing mortality show concurrent and opposite trends to SSB (Fig. 1b). After a rapid increase in the 1980s, F remained high until a sharp decrease occurred from 2005 to 2010, which was concurrent with the increase in SSB. Northern hake landings show similar patterns to the biomass time series apart from a slight increase in the 1980s (Fig. 1c). However, there are differences between the various areas occupied by the stock. Landings in the Bay of Biscay declined by 50% between the 1980s and 2000s with a slight increase in recent years, while landings from the Celtic Sea have remained constant. Landings from the West of Scotland and North Sea, although much lower in comparison, have experienced a proportionally larger increase in the last 5 years and are now half the size of the landings in the Bay of Biscay and Celtic Sea, respectively (Fig. 1c).

Density estimates from trawl surveys showed a significant increase across the northern hake stock area between 2001 and 2011, although there were differences between regions (Fig. 2). From 2001 to 2004, the largest densities were observed on the western continental shelf between the Bay of Biscay and the West of Scotland with the highest densities recorded on the Porcupine Bank and West of Scotland (Fig. 2). Low densities were recorded in the Skagerrak and Kattegat, and very few positive values were estimated in the North Sea (Fig. 2). In 2005, there was an increase in samples of low density in the northern North Sea around Shetland, while densities in other regions remained similar (Fig. 2). From 2006 to 2011, densities estimated in the northern North Sea exhibited a rapid increase reaching the largest estimated values in 2010 and 2011 while densities in other regions increased steadily except in Skagerrak and Kattegat (Fig. 2). Contrary to other regions, the densities observed in the North Sea were much larger in quarter 3 (Q3) than in quarter 1 (Q1, Fig 2). Overall the mean density quadrupled in all regions except the North Sea, where it quintupled.

The percentage of ICES rectangles with densities higher than the maximum estimated in the North Sea prior to the implementation of the 2004 hake recovery plan (85.7 kg/km^2) increased in all five regions demonstrating an expansion of the northern hake stock (Fig. 3a). The increase in area of occupation was most pronounced from 2005 to 2011, with the largest expansion observed in the North Sea, followed by West of Scotland (Fig. 3a). Summing up the indicator of spatial occupation across all regions shows that the area occupied by northern hake has quintupled over the last decade (Fig. 3a). Over this period, the centre of gravity of the estimated densities within each survey has remained unchanged with the exception of the North Sea where it shifted north-westward, from the northern tip of Denmark in 2001, to the northern North Sea in 2011 (Fig. 3b). Densities in the northwest North Sea increased from 2005 onward, while densities in the Skagerrak and Kattegat remained low (Fig. 2), so the shift in centre of gravity actually advocates for an eastward expansion into the North Sea. The overall centre of gravity before and after the implementation of the 2004 hake recovery plan shows a northeast displacement, supporting the hypothesis of an eastward expansion into the North Sea (Fig. 3b).

In the North Sea the dichotomy between the high densities in Q3 and low densities in Q1 suggests that European hake are not present in the North Sea throughout the year (Fig. 2). Spatially resolved landings data from the Scottish and Danish fishing fleets (the predominant fleets in the area) show that from January to March (Q1) hake are mostly located west of Shetland, along the 8°C temperature isotherm to the north and west of Scotland (Fig. 4). In April, as sea temperature rose, landings increased in the northern North Sea around the 100 m depth contour. From May to August, as landings increased, the distribution expanded eastward into the North Sea along the 100 m depth contour as temperatures increased to their maximum (Fig. 4). From September to December a reverse pattern was observed as the landings distribution gradually retreated back to the North of Scotland as temperatures declined. There was a significant relationship between the distribution of landings and temperature and depth for all periods tested (Table 1). Landings increased with temperature (between 5 and 17°C) and depth (until 150 m) and this pattern was observed both before and after the 2004 recovery plan, although the relationship with depth was less clear for the 2000-2004 period due to fewer data available (Fig. S1). The spatial monthly landings data infer that hake undertake seasonal migrations as temperatures become suitable, expanding from the North of Scotland into the North Sea and back out in the course of the year. This is supported by the difference in survey density between Q1 and Q3. Landings were restricted mainly to areas where waters were deeper than 100 m and none were from the southern North Sea despite suitable temperatures, suggesting that migrations are driven by both temperature and depth.

Regional SSB estimates for the period encompassing the increase in northern hake (2001-2011) were calculated for the four ICES areas included in the stock for the first (Q1 and Q2) and second (Q3 and Q4) half of the year. SSB increased in the second half of the 2000s in all regions (Fig. 5a-d). The largest proportional increase, from 4,494 to 59,273 t, occurred in the North Sea in the second half of the year (Fig. 5a). The highest SSBs were estimated in the West of Scotland (84,177 t) (Fig. 5b) and Celtic Sea (86,282 t) in 2011 (Fig. 5c). A dichotomy between the first and second half of the year was observed in both the North Sea, where the increasing SSB in 2011 reached 59,273 t in the second half (c.f. 12,423 t in the first half, Fig. 5a), and the West of Scotland, where SSB in 2011 was only 19,913 t in the second half contrasting with 84,177 t estimated in the first half (Fig. 5b). This supports the hypothesis that individuals migrate in and out of the North Sea in the year, and suggests that much of the SSB present in the North Sea in the second half of the year comes from the West of Scotland. SSB estimates suggest that the rise observed in the North Sea is unprecedented. However, historical landings in the late 1940s and early 1950s (≈ 7,800 t) were similar to those achieved nowadays (7,631 t in 2009), attesting that high biomasses previously occurred in the North Sea (Fig. 5e).

Discussion

An increase in fish stock biomass can be associated with three factors, occurring independently or in combination: higher recruitment success, faster body growth rate, or a reduction in mortality, which in a heavily exploited stock is largely due to fishing (Hilborn and Walters 1992). In the case of the northern hake stock, an increase in the recruitment success resulting from improved environmental conditions between the late 1980s and mid-2000s has been suggested (Goikoetxea and Irigoien 2013). However, declining recruitment estimates towards historical low values in the late 2000s suggest that recruitment is unlikely to be the cause of the recent increase observed in biomass. A possible increase in body growth rate, albeit not explored in this study, is unlikely to generate an increase in biomass of such a magnitude, particularly when associated with the changes in distribution observed here, although it could have contributed. Trends in fishing mortality estimates on the other hand mirror those in biomass, with the highest values corresponding to the lowest biomass levels. The fact that the drop in fishing mortality following the 2004 recovery plan coincides with the sudden rise in biomass strongly suggests that the reduction in fishing mortality is the most probable cause behind the biomass increase currently observed. In the North Sea the highest landings were recorded in the late 1940s immediately after World War II which prevented commercial fishing for six years. This period of reduced harvest has been linked to rapid increases in fish stock abundance with a faster response from older individuals (Beverton and Holt 1957; Beare *et al.* 2010). Overfished stocks can experience rapid recovery providing that a sufficient reduction in harvest rate is applied (Neubauer *et al.* 2013). It is likely that the recent increase in northern hake biomass resulted from the decline in fishing pressure enforced by the recovery plan. The recent observed increase in the proportion of stocks with rising biomass trends (and concomitant decreasing fishing mortality trends) in the northeast Atlantic has been attributed to such multi-annual plans which also included controls on fishing capacity (days-at-sea and vessel power) (Fernandes and Cook 2013).

The recent increase in northern hake biomass has also resulted in an increase of the overall area occupied by the stock, with a striking expansion into the North Sea over the last ten years. Both the biomass increase and the spatial expansion are proportionally higher in the North Sea, showing the growing importance of northern hake in that particular area. The fact that the centre of gravity of survey-based densities has remained unchanged in all areas but the North Sea, advocates against a climate-induced northward distribution shift and suggests instead an expansion of European hake into the North Sea. The northeast displacement of the overall centre of gravity is most likely due to higher densities occurring in the North Sea. These invasions are seasonal, as shown by both survey-based and commercial data, and driven by both temperature and depth which is consistent with the density-dependent habitat selection hypothesis and suggest that European hake expand to suitable habitats when available (MacCall 1990). Northern hake landings realised in the North Sea in the late 1940s and early 1950s were similar to current levels before declining throughout the 1960s and 1970s, probably as a consequence of a decreasing biomass resulting from overexploitation (Goikoetxea and Irigoien 2013). The high values of these historical landings show that high levels of biomass previously occurred in the North Sea when the fishing pressure was low (Beare *et al.* 2010). This suggests that, providing that the current fishing mortality remains low, the high levels of biomass experienced in the North Sea could become a permanent feature.

The increase in biomass combined with an expansion of the area occupied by the stock suggest that, if these two characteristics become permanent features, the northern hake stock could offer new fishing opportunities. Under the current CFP, the distribution of the annual TAC for the northern hake stock among ICES areas remains unchanged from year to year so that each area and country is allocated the same proportion of the TAC every year, a policy known as Relative Stability. This quota allocation key is based on historical catch records and was set when the CFP was first adopted in 1983 (Symes 1997). At that time, hake landings in the North Sea (area IV) were negligible, resulting in a strong west-east imbalance. The TAC is now distributed as follows: 37% to the Bay of Biscay (area VIII) and 56% to the West of Scotland and Celtic Sea (areas VI and VII respectively); while the North Sea (area IV) and Skagerrak and Kattegat (area IIIa) are allocated just 4% and 3% respectively (ICES 2012a). The findings from this study show that European hake undertake seasonal migrations between areas VI and IV and are now present in the North Sea in large quantities during summer months only. Survey-based SSB estimates for 2011 suggest that while the North Sea and Skagerrak and Kattegat only contribute to 7% of the biomass in the first half of the year (when West of Scotland, Celtic Sea and Bay of Biscay account for 44%, 46%, and 3% respectively); they contribute to 34% of the biomass in the second half of the year when West of Scotland, Celtic Sea and Bay of Biscay account for 12%, 50%, and 4% respectively. This reveals a problematic aspect of the northern hake biomass increase: the quota allocation no longer reflects the regional abundances. In the summer, when the fishery is active, the North Sea has 34% of the entire stock SSB, but only 7% of the TAC.

The mismatch between allocated quotas and the regional abundance of commercial species can result in major management challenges and unfavourable economic consequences. For instance, a change in the timing of the migration in the Northeast Atlantic mackerel stock in 2009 led to the under-utilization of quotas worth over 100 M € as fishes were absent from areas with allocated quotas (Jansen *et al.* 2012). The same mackerel stock has also been the subject of a reduction in fishing pressure in the last decade (ICES 2012b). Like hake, this has led to the expansion of its distribution to the west of northern Europe (ICES 2013). Mackerel now appear more prominently in Icelandic & Faroese waters leading those nations to unilaterally increase their allocation of catches. In 2005, Iceland caught 363 t of mackerel (0.1% of the TAC): by 2011 this had risen to 155,000 t (17% of the TAC). The Faroe Islands also unilaterally increased their quota from 2.4% (10,000 t) in 2005 to 13% (150,000 t) in 2011. These increases have since pushed the exploitation rate of mackerel beyond sustainable limits and resulted in significant political disagreements between the EC (and Norway), and Iceland and the Faroe Islands. In the case of European hake in the North Sea, the discrepancy between available biomass and allocated quotas has led to the practice of extensive discarding (Fernandes *et al.* 2011).

Discarding is a key issue for mixed-fisheries (Ulrich *et al.* 2011). In the North Sea, European hake shares its habitat with other gadoid species and is caught as part of the North Sea demersal mixed-fishery (Casey and Pereriro 1995). Being of similar size of other target species and fished using the same gear, it is extremely difficult for fishermen to avoid catching hake; especially if this species is present in large quantities as is the case today. Under the current CFP it is possible for fishermen to trade quotas between ICES areas (Valatin 2000) should they need it to land a species for which the quota in the area where they are operating is exhausted. In 2011, a quota of 1,935 t (corresponding to 4% of the northern hake TAC of 55,105 t) was allocated to the North Sea, 348 t of which were distributed to the United Kingdom (ICES 2012a). By acquiring quotas from other areas, Scottish fleets alone were able to land 3,035 t of hake caught in the North Sea, corresponding to almost nine times the quota allocated for all British fleets. However, despite the trading of quotas the large mismatch between low quotas and higher biomass still results in extensive discarding occurring in the North Sea. While Scottish fleets landed 3,035 t of hake in the North Sea in 2011, 4,993 t were discarded, bringing the total catches to 8,028 t which is more than four times the TAC allocated to the whole North Sea and over 20 times the UK quota.

Such figures emphasize the difficulties created by a quota allocation scheme put in place under markedly different ecological conditions.

The example of the northern hake stock shows that the management measures introduced by the 2002 reform of the CFP can be successful in restoring depleted stocks' biomass providing that good stewardship is applied. However, while offering new fishing opportunities a recovering stock can also result in unexpected management issues, as shown in this study. In the case of the northern hake stock in the North Sea, regional quotas do not reflect the regional abundance of the increasing and expanding biomass, resulting in high discards. Such issue challenges the relevance of the Relative Stability policy and the lack of flexibility in adjusting regional quotas. The CFP is currently under reform in order to improve fish stock conservation and achieve long-term economic viability of the fishing industry (EC 2013). This revision includes a move towards a discard ban meaning that all fish caught at sea will have to be landed: an option to ensure that this policy is realised is to close the fishery when the quota of a given stock is reached. Atlantic cod (*Gadus morhua*, Gadidae) has previously been identified as the "choke" species of the North Sea demersal mixed-fisheries for which the quota would be exhausted first (Ulrich *et al.* 2011). However, the current level of biomass and distribution of European hake in the North Sea documented here and the associated low TAC suggest otherwise. If the increased levels of northern hake biomass reported here persist, European hake is likely to be the "choke" species which effects a premature closure of the entire demersal mixed-fishery in the North Sea.

The consideration of solutions to this problem lies beyond the scope of this paper, however it is clear that a regional approach to management, which is included in the proposed reforms, will help. Elements of co-management (Holmes *et al.* 2011) and new approaches to dealing with a potential discard ban (Kindt-Larsen *et al.* 2011) will be needed if the potential of our recovering fish stocks is not to be "choked" by inflexible management approaches which fail to take into account the dynamic ecology of the oceans.

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References

Alvarez, P. (2004) Distribution and abundance of European hake Merluccius merluccius (L.), eggs and larvae in the North East Atlantic waters in 1995 and 1998 in relation to hydrographic conditions. *Journal of Plankton Research* **26**, 811–826.

Bartolino, V., Ottavi, A., Colloca, F., Ardizzone, G.D. and Stefansson, G. (2008) Bathymetric preferences of juvenile European hake (Merluccius merluccius). *ICES Journal of Marine Science* **65**, 963–969.

Beare, D., Hölker, F., Engelhard, G.H., McKenzie, E. and Reid, D.G. (2010) An unintended experiment in fisheries science: a marine area protected by war results in Mexican waves in fish numbers-at-age. *Die Naturwissenschaften* **97**, 797–808.

Beare, D.J., Burns, F., Greig, A., *et al.* (2004) Long-term increases in prevalence of North Sea fishes having southern biogeographic affinities. *Marine Ecology Progress Series* **284**, 269–278.

Beverton, R.J.H. and Holt, S.J. (1957) *On the dynamics of exploited fish populations*. Fisheries Investigations, London, Ser. 2. 19:533 pp.

Cardinale, M., Dörner, H., Abella, a., *et al.* (2013) Rebuilding EU fish stocks and fisheries, a process under way? *Marine Policy* **39**, 43–52.

Casey, J. and Pereriro, J. (1995) European hake (M. merluccius) in the Northeast Atlantic. In: *Hake, Fisheries, Ecology and Markets*. (eds J. Alheit and T.J. Pitcher). Chapman and Hall, London.

Cheung, W.W.L., Pinnegar, J., Merino, G., Jones, M.C. and Barange, M. (2012) Review of climate change impacts on marine fisheries in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems* **22**, 368–388.

Coull, K.A., Jermyn, A.S., Newton, A.W., Henderson, G.I. and Hall, W.B. (1989) Length-weight relationships for 88 species of fish encountered in the North East Atlantic. Scottish Fish. Res. Rep. **43,** 1–80 pp.

Daw, T. and Gray, T. (2005) Fisheries science and sustainability in international policy: a study of failure in the European Union’s Common Fisheries Policy. *Marine Policy* **29**, 189–197.

Dulvy, N.K., Rogers, S.I., Jennings, S., Stelzenmller, V., Dye, S.R. and Skjoldal, H.R. (2008) Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. *Journal of Applied Ecology* **45**, 1029–1039.

EC (2013) Amendement proposal for a regulation of the European Parliament and of the Council on the European Maritime and Fisheries Fund. *Communication from the Commission to the European Parliament , the Council, the European Economic and Social Committee and the Committee of the Regions* Brussels, 22.4.2013 COM(2013) 245 final.

EC (2001) Commission Regulation (EC) No. 2602/2001 of 27 December 2001establishing additional technical measures for the recovery of the stock of hake in ICES subareas III, IV, V, VI andVII and ICES Divisions VIIIa,b,d,e. *Official Journal of the European Communities.* L 345: 49.

EC (2002) Commission Regulation (EC) No. 494/2002 of 19 March 2002 establishing additional technical measures for the recovery of the stock of hake in ICES subareas III, IV, V, VI andVII and ICES Divisions VIIIa,b,d,e. *Official Journal of the European Communities.* L 77: 8.

EC (2004) Council Regulation (EC) No. 811/2004 of 21.4.2004 establishing measures for the recovery of the Northern hake stock. *Official Journal of the European Union.* L 150:1.

Fernandes, P.G. and Cook, R. (2013) Reversal of fish stock decline in the Northeast Atlantic. *Current Biology* **23**, R661–R662.

Fernandes, P.G., Coull, K., Davis, C., *et al.* (2011) Observations of discards in the Scottish mixed demersal trawl fishery. *ICES Journal of Marine Science* **68**, 1734–1742.

Goikoetxea, N. and Irigoien, X. (2013) Links between the recruitment success of northern European hake (Merluccius merluccius L.) and a regime shift on the NE Atlantic continental shelf. *Fisheries Oceanography* **22**, 459–476.

Hiddink, J.G. and ter Hofstede, R. (2008) Climate induced increases in species richness of marine fishes. *Global Change Biology* **14**, 453–460.

Hiddink, J.G., Jennings, S. and Kaiser, M.J. (2005) Do haddock select habitats to maximize condition? *Journal of Fish Biology* **67**, 111–124.

Hilborn, R. and Walters, C.J. (1992) *Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty*. Chapman and Hall, New York.

Hinz, H., Kaiser, M.J., Bergmann, M., Rogers, S.I. and Armstrong, M.J. (2003) Ecological relevance of temporal stability in regional fish catches. *Journal of Fish Biology* **63**, 1219–1234.

Holmes, S.J., Bailey, N., Campbell, N., Catarino, R., Barratt, K., Gibb, A. and Fernandes, P.G. (2011) Using fishery-dependent data to inform the development and operation of a co-management initiative to reduce cod mortality and cut discards. *ICES Journal of Marine Science* **68**, 1679–1688.

ICES (2013) Report of the Ad hoc Group on the Distribution and Migration of Northeast Atlantic Mackerel (AGDMM). *ICES CM 2013/ACOM: 5 8.* 211 pp.

ICES (2012a) Report of the Working Group on the Assessment of Southern Shelf Stocks of Hake, Monk and Megrim (WGHMM). *ICES CM 2012/ACOM: 11.* 617pp.

ICES (2012b) Report of the Working Group on Widely Distributed Stocks (WGWIDE). *ICES CM 2012/ACOM: 15.* 931 pp.

Jansen, T., Campbell, A., Kelly, C., Hátún, H. and Payne, M.R. (2012) Migration and fisheries of north east Atlantic mackerel (Scomber scombrus) in autumn and winter. *PloS one* **7**. (doi:10.1371/journal.pone.0051541).

Kacher, M. and Amara, R. (2005) Distribution and growth of 0-group European hake in the Bay of Biscay and Celtic Sea: a spatial and inter-annual analyses. *Fisheries Research* **71**, 373–378.

Kindt-Larsen, L., Kirkegaard, E. and Dalskov, J. (2011) Fully documented fishery: a tool to support a catch quota management system. *ICES Journal of Marine Science* **68**, 1606–1610.

Kraak, S.B.M., Bailey, N., Cardinale, M., *et al.* (2013) Lessons for fisheries management from the EU cod recovery plan. *Marine Policy* **37**, 200–213.

MacCall, A.D. (1990) *Dynamic geography of marine fish populations*. Washington Sea Grant Program, Seattle.

Marshall, C.T. and Frank, K.T. (1995) Density-dependent habitat selection by juvenile haddock (Melanogrammus aeglefinus) on the southwestern Scotian Shelf. *Canadian Journal of Fisheries and Aquatic Sciences* **52**, 1007–1017.

Neubauer, P., Jensen, O.P., Hutchings, J.A. and Baum, J.K. (2013) Resilience and recovery of overexploited marine populations. *Science (New York, N.Y.)* **340**, 347–349.

Petitgas, P., Alheit, J., Peck, M., *et al.* (2012) Anchovy population expansion in the North Sea. *Marine Ecology Progress Series* **444**, 1–13.

Rayner, N. A. (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research* **108**, 4407.

Schrope, M. (2010) What's the catch? *Nature* **465**, 540–542.

Shepherd, T.D. and Litvak, M.K. (2004) Density-dependent habitat selection and the ideal free distribution in marine fish spatial dynamics: considerations and cautions. *Fish and Fisheries* **5**, 141–152.

Symes, D. (1997) The European Community's common fisheries policy. *Ocean & Coastal Management* **35**, 137–155.

Ulrich, C., Reeves, S.A., Vermard, Y., Holmes, S.J. and Vanhee, W. (2011) Reconciling single-species TACs in the North Sea demersal fisheries using the Fcube mixed-fisheries advice framework. *ICES Journal of Marine Science* **68**, 1535–1547.

Valatin, G. (2000) Quota Trading Systems in EU Fisheries. *Review of European Community & International Environmental Law* **9**, 296–306.

Wheeler, A.J. (1969) *The Fishes of the British Isles and north-west Europe*. Michigan State University Press, East Lansing, MI.

Woillez, M., Poulard, J.-C., Rivoirard, J., Petitgas, P. and Bez, N. (2007) Indices for capturing spatial patterns and their evolution in time, with application to European hake (Merluccius merluccius) in the Bay of Biscay. *ICES Journal of Marine Science* **64**, 537–550.

Woillez, M., Rivoirard, J. and Petitgas, P. (2009) Notes on survey-based spatial indicators for monitoring fish populations. *Aquatic Living Resources* **22**, 155–164.

Tables

Table 1. Summary table of the Generalised Additive Models (GAMs) used to investigate statistical relationships between North Sea hake landings, sea surface temperature (SST) and depth (in 50 m depth classes). GAMs were performed using all available data (2000-2011), and using data recorded before (2000-2004) and after (2005-2011) the implementation of the 2004 hake recovery plan (see methods) (*edf*: estimated degrees of freedom, *F*: F-ratio statistic).

Period	Deviance explained	*edf*		*F*		*P*-value	
		SST	Depth	SST	Depth	SST	Depth
2000-2011	18.8%	7.839	10	166.3	212.4	<0.001	<0.001
2000-2004	24.3%	5.519	9	98.24	74.15	<0.001	<0.001
2005-2011	20.9%	8.135	10	104.4	191.1	<0.001	<0.001

Figure legends

Figure 1. Summary of the northern hake stock assessment estimates. (a) total stock biomass (TSB) together with recruitment (Rec). (b) spawning stock biomass (SSB) together with the average fishing mortality (F). (c) Total landings for the northern hake stock, along with the landings for each ICES area composing the stock: North Sea (area IV), West of Scotland (area VI), Celtic Sea (area VII) and Bay of Biscay (area VIII).

Figure 2. Maps of the north east Atlantic displaying the spatial distribution of estimated densities of northern hake from 2001 to 2011 showing the expansion of the stock into northern areas and the North Sea. The chosen time series encompasses the increase in northern hake densities observed over the last 10 years. Densities are colour coded by quarter (blue: Q1, green: Q2, orange: Q3, red: Q4). Survey data were not available for the Celtic Sea and Bay of Biscay in 2011.

Figure 3. Statistics of the spatial occupation of northern hake showing expansion and changes in distribution. (a) The percentage of ICES rectangles surveyed where densities greater than the maximum North Sea hake density observed prior to the 2004 recovery plan (85.7 kg/km^2) were recorded. This is a proxy to assess changes in the area occupied by the stock. (b) Centres of gravity of hake densities observed in each survey from 2001 to 2011, labelled 1 to 11. The overall centres of gravity for the northern hake stock calculated for years sampled by all regional surveys (2001-2008, see methods) are averaged prior (2001-2004) and after (2005-2008) the 2004 recovery and are also represented by a black circle and a black triangle respectively. The 100 m depth contour is displayed in grey.

Figure 4. Monthly maps of the British Isles showing Scottish and Danish hake landings per ICES rectangle between 2000 and 2011 by month (data for Scottish landings were available from 2005 onwards). The proportion of Scottish and Danish landings are displayed in blue and red respectively. The coloured background corresponds to monthly sea surface temperature (°C) averaged from 2000 to 2011. The 100 m depth contour is displayed in black.

Figure 5. Estimates of European hake spawning stock biomass (SSB) calculated from survey data for each ICES area included in the northern hake stock (a-d), and historical landings from the North Sea (e). For each area, SSB estimates calculated for the first (dark grey) and second (black) half of the year, according to data availability, are displayed from 2001 to 2011. (e) The historical North Sea landings from 1903 to 2010 (grey histogram) from FAO are displayed along the North Sea SSB estimates.

Figures

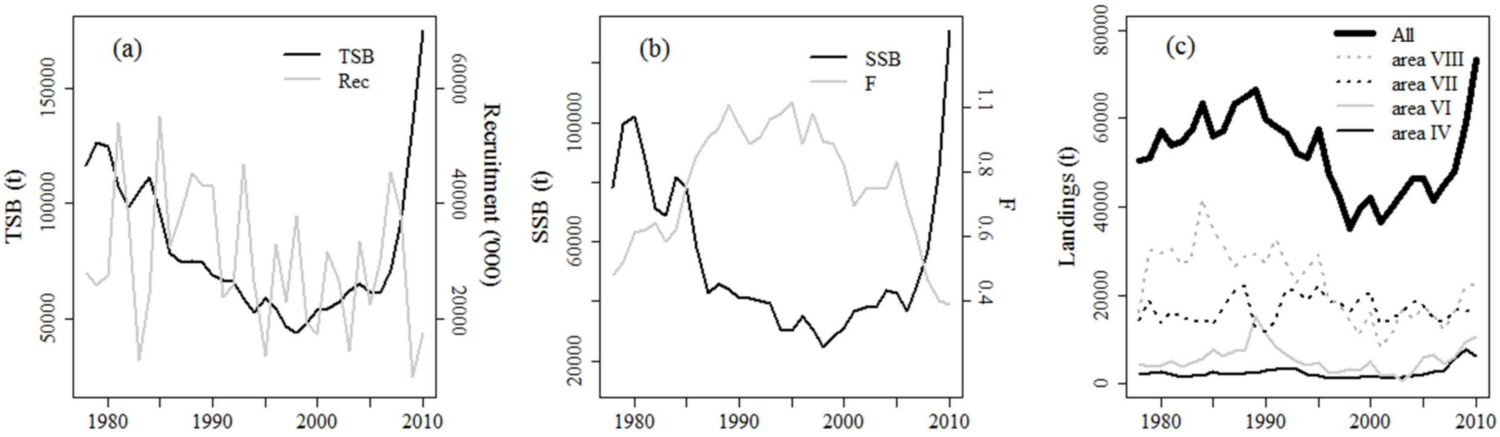

Figure 1.

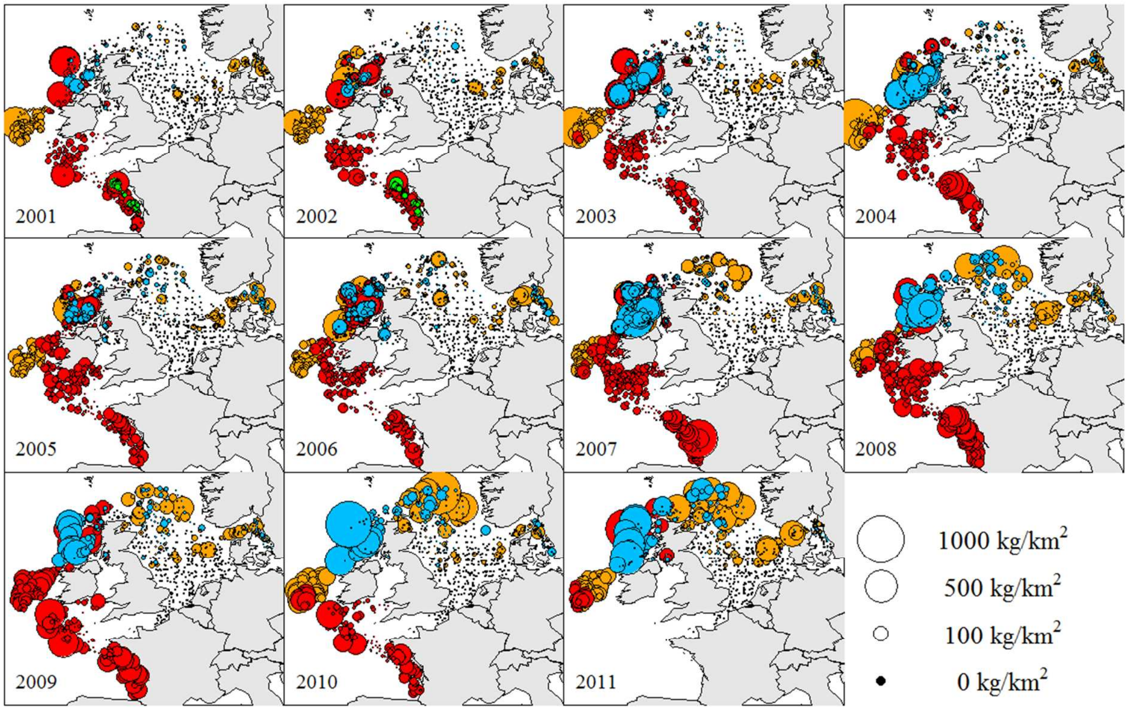
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
1000 kg/km²
500 kg/km²
100 kg/km²
0 kg/km²

Figure 2.

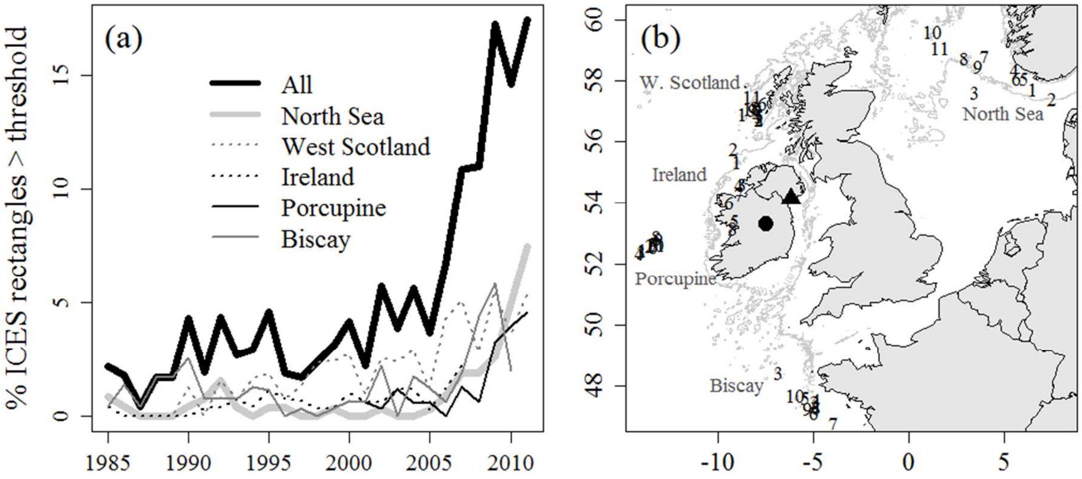
(a)
% ICES rectangles > threshold
0
5
10
15
1985
1990
1995
2000
2005
2010
All
North Sea
West Scotland
Ireland
Porcupine
Biscay
(b)
W. Scotland
Ireland
Porcupine
Biscay
North Sea
60
58
56
54
52
50
48
-10
-5
0
5

Figure 3.

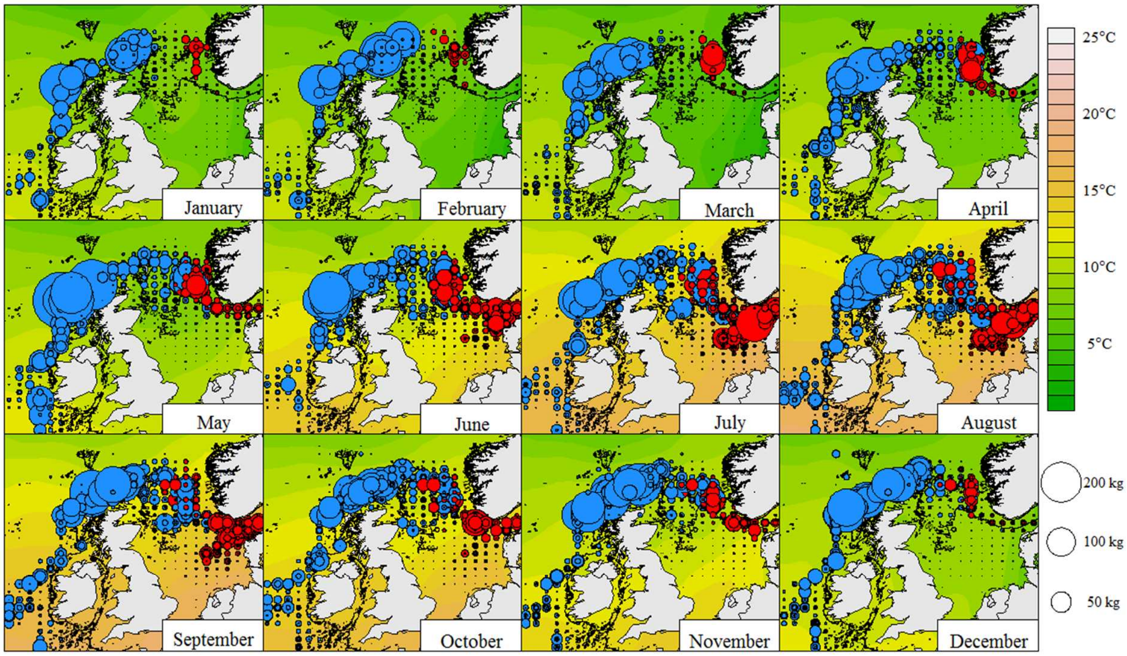
January
February
March
April
May
June
July
August
September
October
November
December
25°C
20°C
15°C
10°C
5°C
200 kg
100 kg
50 kg

Figure 4.

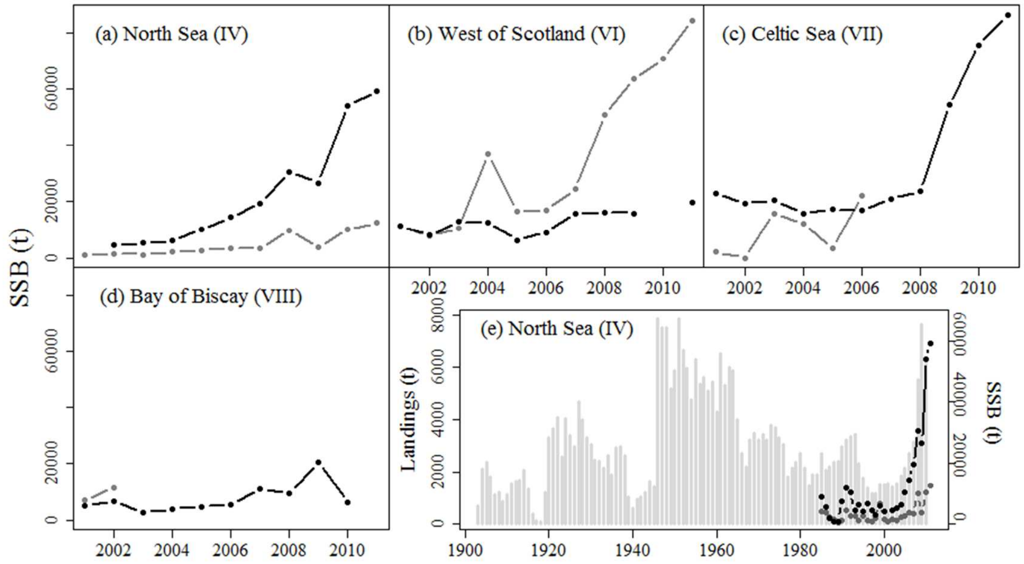
(a) North Sea (IV)
(b) West of Scotland (VI)
(c) Celtic Sea (VII)
(d) Bay of Biscay (VIII)
(e) North Sea (IV)
SSB (t)
Landings (t)
SSB (t)
0
20000
60000
0
2000
4000
6000
8000
0
20000
40000
60000
2002
2004
2006
2008
2010
1900
1920
1940
1960
1980
2000

Figure 5.

Supporting information

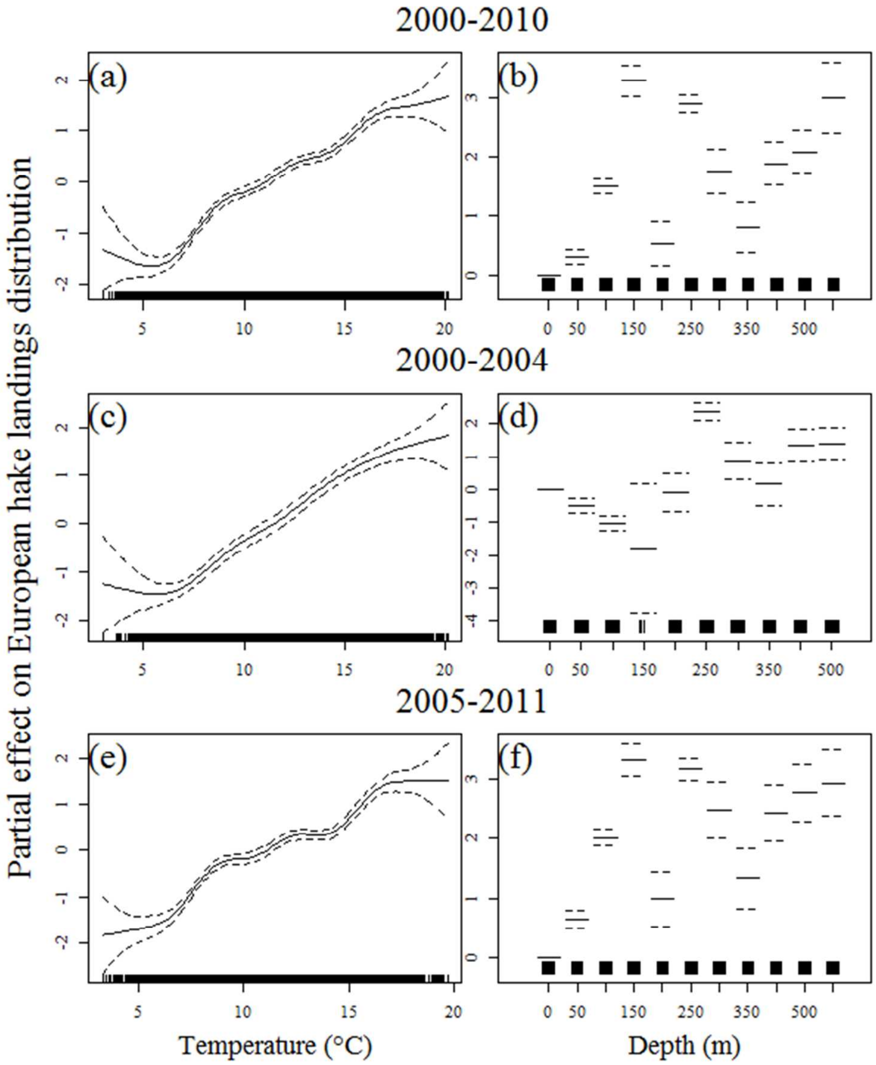

Figure S1. Results from Generalised Additive Models (GAMs) used to investigate statistical relationships between the distribution of North Sea hake landings and the variables temperature and depth. GAMs were performed using all available data (2000-2011, panels (a) and (b)), and using data recorded before (2000-2004, panels (c) and (d)) and after (2005-2011, panels (e) and (f)) the implementation of the 2004 hake recovery plan to assess potential impact of an increase in abundance on the relationship between hake distribution and environmental variables. The continuous and dashed lines show the model fits and 95% confidence intervals respectively. The tick marks on the *x*-axis indicate the data availability.