Investigations into closed area management of the North Sea cod

for

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C2465

INVESTIGATIONS INTO CLOSED AREA MANAGEMENT OF THE NORTH SEA COD

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Closed areas have been proposed as one of a range of potential management approaches that could be applied to control the exploitation rate of the North Sea cod stock. However, although theoretical studies of the potential effects of closed area are numerous, they are of limited use for providing practical management advice, because they are not case-specific. The aim of this project was to bring together fishers' knowledge of current and potential future North Sea fleet fishing activity with research on the spatial movement of fleets, cod population biology and the impact of fishing on benthic biodiversity, in order to provide practical advice on the impact of closed area management in the North Sea. Research is required to aid the provision of advice on the potential impact of closed area management on cod population dynamics, habitat diversity and the economics of the North Sea fleets.

Examples of closed area management regimes for the North Sea cod were simulated, and the impact on the catches of cod, mixed gadoids and benthic productivity and diversity was evaluated. Funding and the time available for the study was limited, so the work examined three example scenarios: two evaluating the impact of large, broad-scale, North Sea closures, and at a more detailed scale, the effect of a local closure on the cod fishery off the northeast coast of England.

The outcome of the predicted changes in the dynamics of North Sea fleet effort distributions on the benthos and the cod stock is described. Conclusions are drawn with respect to the potential impact of the closures, including comparisons with other management actions or technical measures that could be employed to manage the stock; the design of closed areas for restricting access to stocks; and the effectiveness of the modelling approaches.

The research has led to improved understanding of the potential impact that closed areas could have on the English and international fleet yields and the population dynamics of cod, especially recovery rates to biological reference points. The analyses have also highlighted areas where the science and knowledge base is limited and where further industry input and additional data analyses are required to provide a rapid response to managers and stakeholders when closed areas are proposed.

The studies have been collated as a series of papers, each presented as an independent section. Key points by relevant subject area are summarized below.

General points

1) Removal from a fishery of the effort directed into a closed area results in the most significant impact from a closure. If effort is allowed to relocate into areas remaining open, the impact of the closed area is reduced substantially and, in some of the cases examined, mortality on the stock could be increased. Similarly any derogation to fish in a closed area will reduce the area's impact. Consequently, closed area management cannot be used in isolation from quota and effort regulation and may require lower levels of both.

2) Closed areas are designed to make fishers less efficient at catching protected species. Fishers prevented from accessing local stocks will move into areas that they may not have fished before, resulting in conflict, inefficiency and reduced income. The incentive to provide biased landings and effort data will be greater. Quality of catch and effort data is likely to become even more uncertain, until the stock recovers and pressures are relieved.

3) The approach used by fishers to relocate effort displaced from a closed area is a critical determinant to the effectiveness of a closure. Therefore, case-specific dialogue with fishers during the design process, with regard to potential changes in effort distribution resulting from a closure, is considered to be an important factor in reducing the uncertainty associated with expected returns.

4) Seasonal migration and movement can have a significant impact on the effectiveness of a closed area. Closed areas must be designed to be robust to temporal variability in stock distribution; boundaries may have to be moved during the year or, alternatively, permanent closures may need to be expanded in order to maintain their effectiveness.

The North Sea cod fishery

5) At a time of increasing uncertainty in resource status resulting from bias in catch data, closed areas can remove some of the cod stock from exploitation, protecting at least a portion of the resource. For instance, temporary closures to protect juveniles, if implemented quickly, are an effective way of reducing mortality rates.

6) In all cases, removal from the fishery of the effort directed into the closed areas had by far the most significant effect on reducing mortality of North Sea cod. If effort is allowed to relocate into areas remaining open, the reduction in mortality rates reduces substantially and may increase.

7) Closed areas that deliver "guaranteed" protection and reductions in cod mortality without reducing current levels of effort would require the closure of substantial parts of the North Sea. The impact of displacing significant proportions of the effort into areas remaining open would be considerable, and it could result in many traditional fishing grounds being closed as well as numerous conflicts of interest. Catches recorded from the North Sea cod fishery have spatial structure within them, indicating possible sub-stock structure. This study has not evaluated the impact that this situation might have for each sub-unit. Closure of an area containing one sub-unit may completely protect it from exploitation while forcing effort onto a second sub-unit, making it more vulnerable to exploitation.

8) The effectiveness of a closed area is conditional on its design with respect to the decisions that fishers must make when they redistribute effort. If fishers target cod with effort displaced from closed areas, the current designs of closed areas suggested by the EU Commission could increase cod fishing mortality rates substantially. Closed area designs based on potential catch rate and total catch are more robust to the way in which effort is relocated.

9) If redesigned, then closed areas of the magnitude suggested by the EU Commission can reduce fishing mortality on cod. However, the estimated reductions in mortality rate are relatively small and, at best, will only stabilize the decline in stock size; they will not result in recovery of spawning stock biomass to safe biological levels.

Alternative management strategies

10) The international North Sea fishery selection-at-age estimated by the 2004 ICES Working Group approximates to that of a 90 mm mesh, well below the 120 mm legal minimum mesh for boats targeting cod. Although boats directing fishing effort at gadoids in the North Sea are required to use 120 mm mesh, those deploying a wide range of gear types catch and discard or land cod; the combined effect is a much lower effective mesh selection.

11) The use of 120 mm mesh throughout all of the fisheries catching cod would have the same impact as the reduction of discards to zero, and for an unchanged level of effort results in growth of the stock to B_{lim}. Use of 140 mm mesh increases biomass to between B_{lim} and B_{pa}, and use of 160 mm allows the stock to recover to above B_{pa}. The analysis assumes that effort does not increase in order to compensate for the loss of smaller species and the initial losses of small cod from the catch. Larger mesh sizes would result in significant losses of the whiting and haddock from the catch.

Mixed fishery aspects

12) Relocating fishing effort away from concentrations of cod will impact on the catch of other species. The small example area on the northeast coast of England for which appropriate data were available gave increased catches of *Nephrops* throughout the year and whiting and haddock in the first and fourth quarters.

13) Seasonal migration and movement of cod have a significant impact on the catch. Increase in catch rates of associated species will have a strong impact on discard rates if additional quota is not available for displaced boats.

Impact on the benthos

14) Closure of fishing grounds will move fishers away from traditional fishing areas, resulting in increased effort and seabed disturbance in areas that were previously relatively lightly fished.

15) There will therefore be a net reduction in diversity and biomass across the North Sea before any increases within the closed areas have had time to accrue. In the simulations, total benthic community biomass start to recover only after more than 10 years.

16) Removing fishing effort displaced by the closed areas always has a positive effect on benthic community biomass and production.

Document references

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REPORT ON

INVESTIGATIONS INTO CLOSED AREA MANAGEMENT OF NORTH SEA COD

January–May 2005

This report is not to be quoted without prior consultation with Cefas

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Raison d'être

The study was designed to develop a collaborative structure for providing practical scientific advice on the effects of closed area management of North Sea fisheries. It brings together scientific expertise in modelling the impact of fisheries on biological systems with fishing industry experience of the dynamics of the United Kingdom (England and Wales) fleets fishing for North Sea cod.

Studies are currently being funded within other groups aimed at reviewing the scientific literature published on closed area management of finfish stocks (SFCD Ref. 14) and the potential economic impact of closing areas of the North Sea (SFCD Ref. 16). Therefore, this study highlights relevant documentation, but it has not extended into a detailed literature review and has not considered economics within its remit.

Both funding and time available for the study were restricted Therefore, the research group chose to demonstrate the relevance of the lines of research by examining three closed area scenarios. The areas were selected to provide insight into how best to support the provision of advice on current management issues at a broad international scale and at a finer, more-detailed UK-centric scale, and also to gain greater understanding of the problems involved in evaluating closure proposals. All closed area scenarios examined have been outlined in discussions between the Commission of the European Union (EU Commission) and North Sea resource managers or from a subset of the areas proposed.

Predictions from models simulating the impact of closed areas on the spatial distribution of the effort directed by North Sea fishing fleets were used to provide plausible effort-relocation scenarios in response to the closure scenarios. The effort relocation scenarios were then used within:

- a model evaluating the impact of fishing on benthic community diversity and production;
- a model of the effect of fishing on a simulated North Sea cod population;
- a model of the effect of effort redistribution on catches made by North Sea fleets.

The outcome of the predicted changes in the dynamics of North Sea fleet effort distributions on the benthos and the cod stock is described. Conclusions are drawn in terms of the potential impact of the closures, including comparisons with other management actions or technical measures that could be employed to manage the stock, the design of closed areas for restricting access to stocks, and the effectiveness of the modelling approaches.

1 Introduction

1.1 Spatial management of fish stocks

Fisheries management employs spatial management at all levels, explicitly and implicitly.

Explicit spatial management of fisheries is utilized at its broadest scale in the definition of stock boundaries; the geographic ranges of species are divided into management areas in an attempt to define population units. For instance the International Council for the Exploration of the Seas (ICES) defines the North Sea cod stock (cod in IV, VIId and IIIa) as cod located within the area covering the whole North Sea, the Eastern Channel and the northern part of the Skagerrak. There is some movement of fish between this area and others, but generally the magnitude of emigration from and immigration into the area is relatively low compared with the removals resulting from fishing and natural mortality. Losses by emigration and gains through immigration are therefore assumed to be minimal, and the stock is considered to be a “biological” unit. Conversely, within the ICES definition of the area containing the North Sea stock, there is some evidence for sub-stock structure, based on genetic isolation distances and tagging studies. The detailed information required to separate catches and to manage at a sub-stock level would increase uncertainty considerably, and the impracticality ensures that sub-stock structure is also assumed to have no significant implications for management.

Implicit spatial management is also inherent within the management regulations affecting North Sea fisheries. Beam trawlers targeting flatfish in the North Sea are restricted to using meshes larger than 80 mm. The species exploited by the North Sea beam trawl fleet (primarily sole and plaice) are located in the southern North Sea, so the spatial distribution impact by this gear type on the sea bed is restricted.

The most common control measures for fisheries exploitation rates are either input controls that regulate the amount or type of activity, such as limitations on effort or gear type, or output controls that regulate quantity and composition of catch, such as quotas or minimum landing sizes. The restrictions may have a spatial component within their implementation, designed to protect vulnerable species, ages, or times in the life cycle. Some examples are presented in Figure 1.1.1, which illustrates historic and current spatial regulation of the amount of effort entering the fisheries around Ireland and Shetland, the exploitation of juvenile North Sea plaice and Western Approaches mackerel, and the herring boxes established to protect spawning grounds.

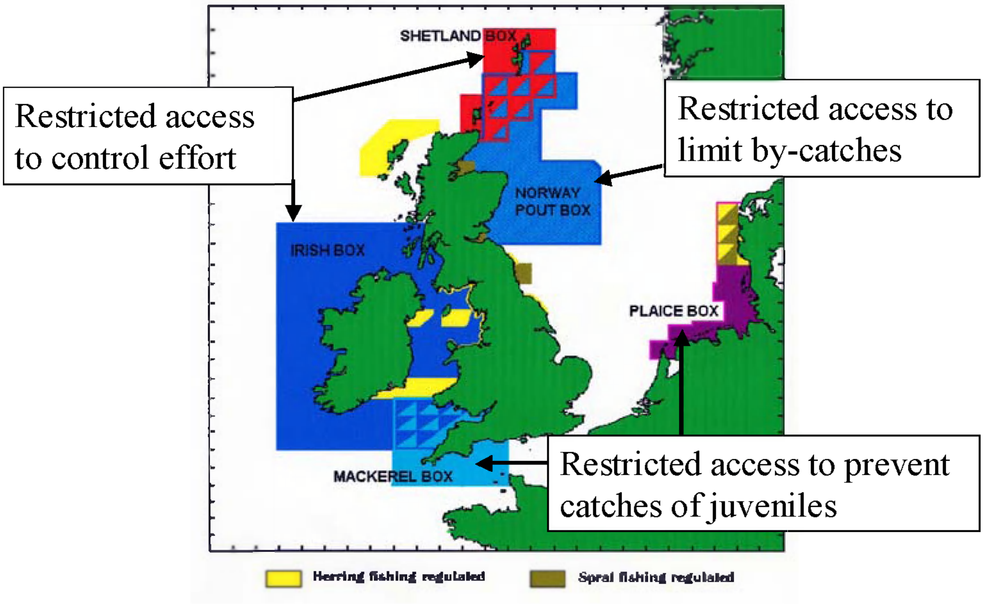


Figure 1.1.1 Historic and current spatial restrictions on effort entering the fisheries around Ireland and Shetland, designed to limit catches of juvenile plaice and mackerel, disturbance of spawning herring and by-catches of juveniles of other species of gadoids in the Norway pout fishery.

Although the concept of using harvest refugia (Marine Protected Areas, MPAs; No-Take Zones, NTZs; Marine Fisheries Reserves, MFRs) to manage fish stocks seems relatively simple, but the definition, design and evaluation of management strategies that utilize areas restricting access to resources are extremely complex (Jones, 2002; NRC, 2001). Consequently, theoretical studies of the potential effects of simplified closed areas are numerous (Polacheck, 1990; Lauck *et al.*, 1998; Stefánsson and Rosenberg, 2004). Unfortunately, the models are of limited use for providing practical management advice on the consequences of closing specific areas, because they generally consider single species and single age systems with even redistribution of displaced effort.

In practice, areas that restrict access to the marine environment have been utilized for protection of sensitive marine habitats, conservation of biodiversity, and protection of depleted or rare organisms and of critical life stages (Novaczek, 1995; NRC, 2001). They have been most successful at achieving their objectives for species that have limited mobility or are highly territorial, for example tropical reef communities (Roberts *et al.*, 2001; Willis *et al.*, 2003). When used for the management of finfish stocks, areas that restrict access have been successfully used to restrict the amount of effort directed into local waters, to reduce bycatches and to protect juvenile concentrations (Horwood *et al.*, 1998; Piet and Rjinsdorp, 1998). They have been less successful when they have been applied with the objective of reducing fishing mortality on mature, more mobile ages (STECF, 2003; Murawski *et al.*, 2005). This is because the degree of success is directly proportional to the propensity of the species to disperse or migrate and the size of the reserve (Beverton and Holt, 1957; Polacheck, 1990; NRC, 2001), and the closed areas have been too small to contain a significant proportion of the stock.

Relocated effort was able to compensate by catching fish outside closed areas (STECF, 2003). Even for apparently successful applications of closed areas, such as the large areas closed on the Georges Bank that may have resulted in an increase in the haddock stock (Murawski *et al.*, 2000, 2005), the underlying cause of subsequent increases in stock biomass could be attributed to other management restrictions imposed at the same time (a 50% cut in effort, days-at-sea restrictions through trip limits, a ban on new entrants and a restriction to use of 160 mm trawl mesh; Mace, 2004).

Although there are no unambiguous results from practical examples that demonstrate the benefits of closed area management for finfish stocks, the subject has recently received greater attention because it is accepted that the current conventional systems of management, especially total allowable catches (TACs), lead to biased landings data and greater uncertainty around the true status of stocks. A consequence of the greater uncertainty is an increased risk that fishing and management actions will lead to further declines in stock biomass. Theoretical studies have shown that in the face of uncertainty it is better to conserve part of the stock within a no-take zone, exploiting only part of the stock and protecting the rest (Lauck *et al.*, 1998; Stefánsson and Rosenberg, 2004).

1.2 Closed area management of North Sea fish stocks

The management measures and studies that have examined the impact of closed areas on the North Sea cod stock and fishery dynamics are listed below.

1.2.1 The 1987 North Sea cod box

The North Sea cod box was introduced in 1987 (EC4034/86). It was intended to protect the large 1985 cod year class as 2-year-olds and was located in the coastal areas of the Southern and German Bights defined by {the Danish coast at 55°N; 55°N 7°E; 54.30°N 7°E; 54.30°N 6°E; 53.30°N 6°E; 53.30°N 4°E; the Dutch coast at 4°E}. The box relocated vessels that used meshes <100 mm during the first and fourth quarters of the year. The implementation of the box was considered to be too late to have a significant conservation effect.

1.2.2 The North Sea cod task force

In 1993 a North Sea task force (North Sea Task Force, 1993) was established by the European Commission to advise on management measures for cod, including closed areas. They examined the effects of annual closures of four large areas (the roundfish reporting areas) under the assumption that the effort displaced from the box would be redeployed in the remaining open areas. The analysis was based on two data sets, one containing catch by rectangle data for 1989 and the other for 1991. Based on an analysis of the 1989 data, closure of the northeast North Sea for a full year resulted in a long-term increase in spawning stock biomass (SSB) of 25%. Closure of other areas had very little impact. However, if the 1991 data were used for the same analysis, closing the same area had no beneficial effects. The distribution of cod was not sufficiently stable over time to make useful predictions about the value of specific boxes.

1.2.3 The 2001 cod closed area

Two boxes were closed in the North Sea in 2001 between 14 February and 30 April (Figure 1.2.1). The boxes were introduced in response to ICES advice to reduce fishing mortality. They were not part of the ICES advice but were introduced as part of emergency measures, in the absence of an agreement to reduce fishing effort directly (EU259/2001). The rationale for the closed areas was that cod aggregated at spawning time and that as many as possible should be allowed to breed in that year, increasing the probability of better recruitment. The areas were also thought to be a supportive measure for the reduction in fishing effort associated with a lower TAC. The box was identified largely on the basis of where 80% of the cod had been caught in quarters 1 and 2 of 1999. No attempt was made to renew the box by the Commission in for 2002 or 2003. STECF (2003) evaluated the impact of the seasonal closure and concluded that it had an insignificant effect upon either the spawning potential for cod in 2001 or fishing mortality. There were several reasons for the lack of impact. The redistribution of the fishery along the edges of the box coupled with the increases in proportional landings prior to and subsequent to the closure negated any potential benefits the box may have had. The conclusion from that study was that the box would have to be extended in both space and time to be more effective.

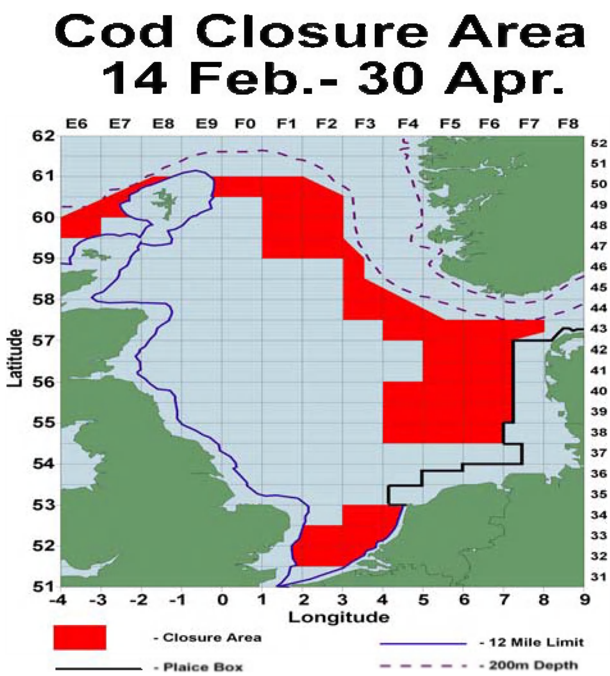


Figure 1.2.1 The 2001 cod box closed area introduced with the aim of protecting spawning fish.

1.2.4 The 2003 STECF Cod Assessment and Technical Measures Report

The 2003 STEFC working group (STECF, 2003) developed two models for evaluating the effects of closed area on the dynamics of the North sea cod fishery: a) a single species model, b) a mixed fishery, fleet-based model. They used the models to investigate the impact on cod mortality of an annual closure of four areas:

1) the ICES rectangles containing 80% of the average 2000-2002 IBTS survey adult cpue;
2) the ICES rectangles containing 80% of the IBTS survey juvenile cpue;
3) the ICES rectangles specified in the 2001 emergency measures described in EU259/2001;
4) an area located east of Scotland (a UK industry suggestion for an area in which haddock could be taken at low cod bycatch rates).

Scenarios 1 and 2 were in response to the Term of Reference "*Evaluate the areas which would need to be closed in order to remove 80% of the fishing possibilities for cod in the North Sea*".

In all cases removal of effort from the fishery was calculated to have a larger influence on fishing mortality than that achieved when effort was redistributed. The expected benefits of a closure were reduced by about 15–40% for scenarios 1 and 2 if effort was redirected. Similarly, redirection of effort negated any potential benefit of the 2001 closure (scenario 3): adult fish were caught elsewhere during the spawning closure and in the box area prior to and after closure.

The group concluded that closed areas could be used to benefit management of fish stocks. However, experience with the North Sea cod box and the 2001 emergency measures box illustrates that they may also be ineffective if additional management constraints are not imposed concurrently. For instance, if effort is removed from the fishery at the time of closure (and not reallocated), the effects on the reduction in fishing mortality are generally of significantly greater magnitude. The redistribution of effort can lead to no beneficial and sometimes significant negative effects on unprotected age groups and species. Discussions with fishers with regard to the potential changes in effort distribution would be required before a full modelling evaluation of any box could be carried out.

1.3 Closed area scenarios

Three North Sea closed area scenarios were examined, each based on areas defined within previous studies:

a) 2001 closure – permanent closure of the area closed during the period between 14 February 2001 and 30 April 2001 to protect spawning cod (Figure 1.3.1);
b) STECF closure – closure of the area estimated by the STECF (2003) meeting to be that from which 60% of the international catches of cod were taken in 2002 (STECF, 2003; Figure 1.3.2)
c) northeast coast closure – closure of two ICES statistical rectangles located on the northeast coast of England that were apparent in the 60% area from the STECF report (cf. scenario (b); Figure 1.3.3).

The selected areas provided two broad-scale scenarios that allowed the potential impact of spatial closures on the international fisheries for cod to be modelled along with a smaller area impacting an important coastal fishery for which more detailed spatial and temporal information was available.

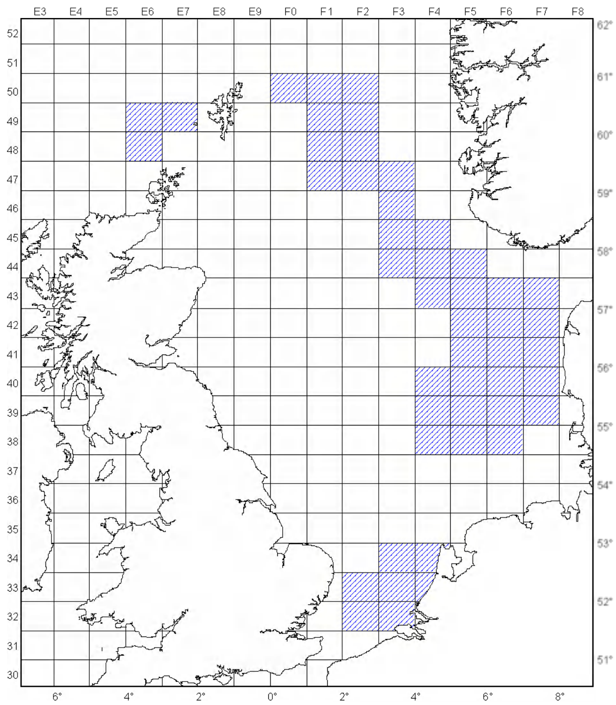


Figure 1.3.1 Example closed area based on the cod closure imposed during the period between 14 February 2001 and 30 April 2001 with the aim of protecting spawning cod.

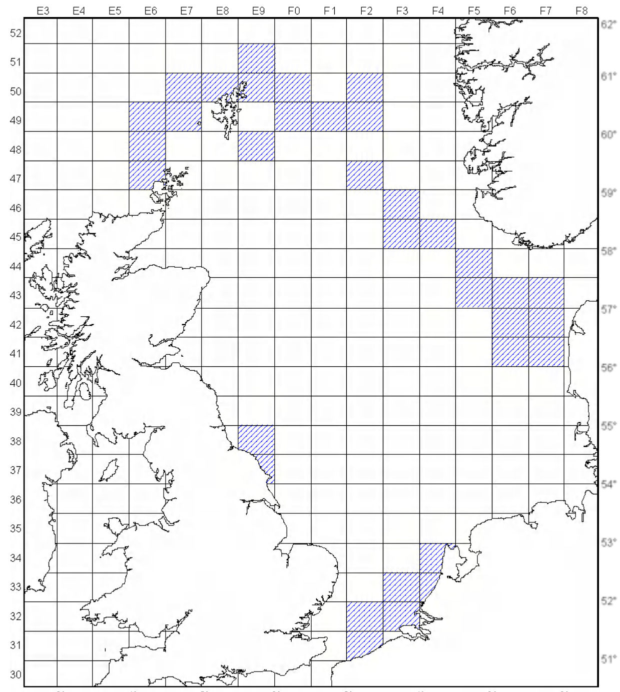


Figure 1.3.2 The example of a closed area based on the area estimated by STECF (2003) to be that from which 60% of the international catches of cod were taken in 2002.

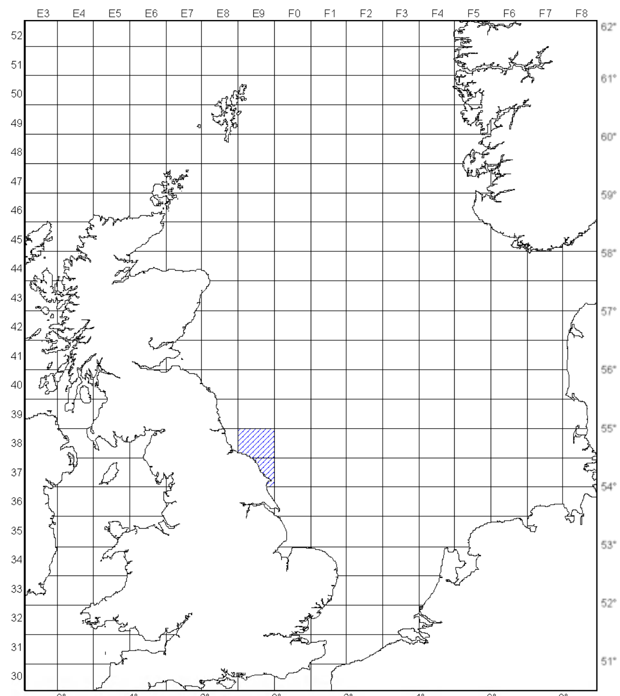


Figure 1.3.3 Example closed area based on an area located on the northeast coast of England that were apparent in the 60% area from the STECF report (cf. scenario in Figure 1.3.2) and which cover a locally important mixed gadoid fishery.

2 Spatial distribution of North Sea fishing effort

Trevor Hutton, Chris Darby and Doug Beveridge

2.1 English fleet effort

Individual trip catch and effort data, recorded within EU logbooks by English beam trawlers and otter trawlers fishing in the North Sea in 2003, were extracted from the Defra Fishing Activities Database (FAD) and aggregated for each ICES rectangle.

2.1.1 English otter trawl

There were 4183 English otter trawl trips recorded in 2003 for vessels fishing in the North Sea and landing into English ports. The number of vessels was 172, of which 106 fished more than 5 times per year and 66 fished fewer than 5 times per year. Records from vessels recording a low frequency of trips were retained on the assumption that the trips formed an important component of vessel effort and income. Figure 2.1.1 illustrates the distribution of effort (total hours fished in each ICES rectangle); most vessels fished in 6 ICES rectangles adjacent to the northeast coast.

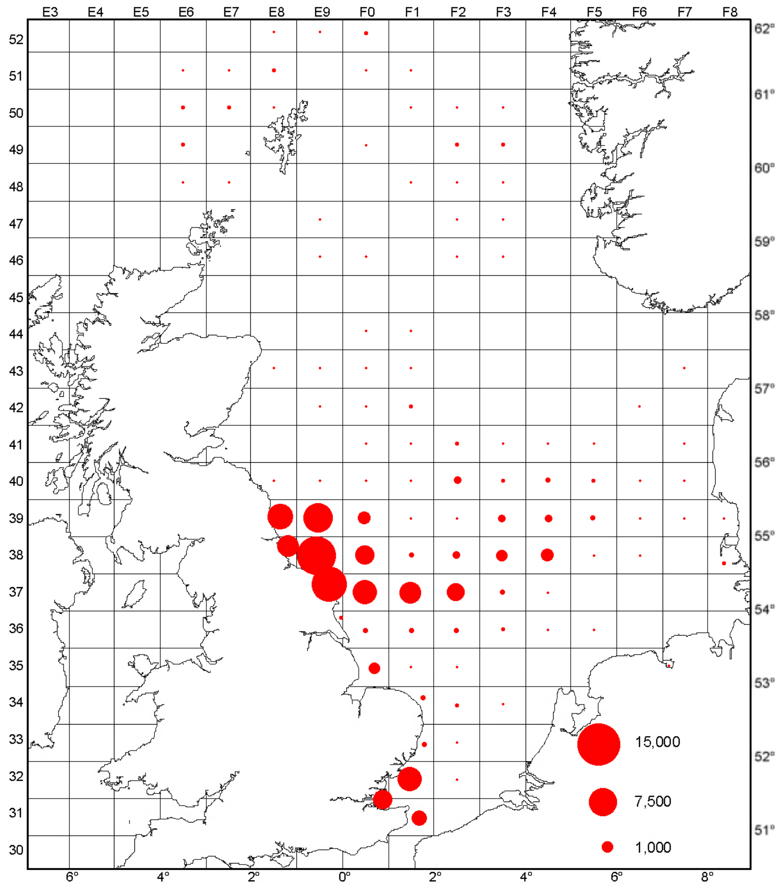


Figure 2.1.1 Spatial distribution of effort (total hours fished in each ICES rectangle) of English otter trawlers fishing in the North Sea in 2003.

2.1.2 English beam trawl

Strictly, this fleet should be termed beam trawl vessels that fish against a UK (England and Wales) quota. The total number of recorded North Sea trips during 2003 was 1584. Of the total of 71 vessels, 41 were English-registered vessels landing into ports in the Netherlands and 30 were foreign-registered vessels fishing with UK quota and landing into ports in the Netherlands. The recorded fishing effort was therefore representative of the effort required to land the UK quota. Figure 2.1.2 shows the spatial distribution of effort (total hours fishing in each ICES rectangle) for these vessels. Most vessels fished about 60 ICES rectangles in the North Sea between 37F1 (near the English coast) and 43F7 (off the Danish coast).

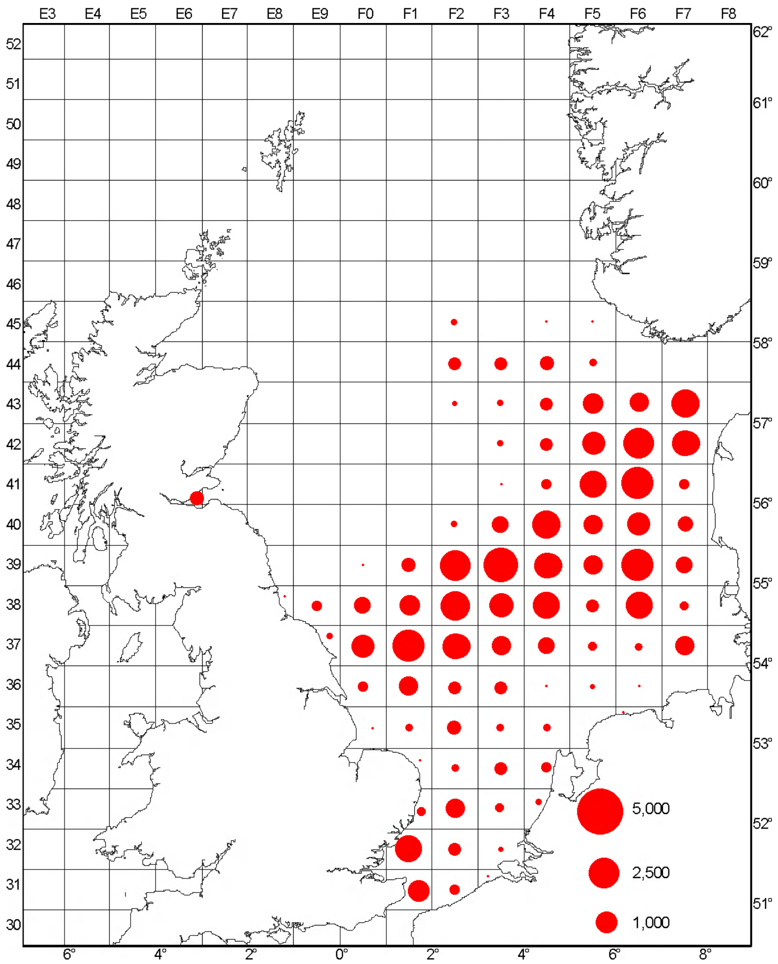


Figure 2.1.2 Spatial distribution of effort (total hours fished in each ICES rectangle) of English beam trawlers fishing in the North Sea in 2003.

2.2 English fleet effort redistribution in response to closure

2.2.1 Background

A simplified spatially structured simulation model that utilizes catch and effort data (individual trip) from the Fishing Activity Database (FAD) was developed. The model computes the total catch and effort for each vessel fishing in a North Sea ICES rectangle (logbook data are collected at this scale) and can, consequently, be used to model effort redistribution in response to potential spatial closures that are either temporary or permanent at that spatial scale.

The model assumes that total fishing effort and catch rates of each species of the fleet will not vary significantly from year to year. This assumption is not unrealistic, because the model is used principally to predict one year ahead. Distance to port is assumed not to play a major role in influencing a decision of where to fish (based on the results in Mardle *et al.*, 2004) for the beam trawl fleet).

The model has been used to predict the response of the English beam trawl fleet to the closure of the North Sea in early 2001 (Hutton *et al.*, 2004). It has the characteristic of simplicity in its assumptions (skippers will fish in areas where previously they had high catch rates, e.g. boxes per haul), and also complexity in that it captures individual variation. Each vessel is included in the model and predictions are based on assumed decisions by each skipper.

The assumption that fishers will base their choice of location on past catch rates was validated by comparison with the results of an analysis based on a Random Utility Model (RUM). The RUM is a discrete choice model: where the utility (benefit) of making a choice is defined as a combination of explanatory variables (e.g. catch, value of landings, catch rates) and a stochastic error (random) component. Hutton *et al.* (2004) included the following variables in the RUM: trip length (days), effort (hours fishing), total value of the catch (£), total weight (value-weighted; kg), cpue or value per unit effort (vpue; £ per hour); and variables for past activity: cpue or vpue (£ per hour). In terms of past activity, vpue (or cpue) was the significant variable in explaining location choice, forming the basis for an important assumption used within this study.

2.2.2 Method: model structure and assumptions

The model simulates the effect (of closing areas) on a vessel-by-vessel basis for each month and for each spatial unit (an ICES statistical rectangle), in the series of steps outlined below.

1st stage

1. Each vessel's effort distribution is computed from individual trip logbook records, to obtain the total effort (h) per spatial unit per month per vessel.

2. Each vessel's spatial distribution of catch rate is computed to obtain the average catch rate (kg per h) per spatial unit per month per vessel for all species.

3. Some spatial units are closed (assuming the closure is in the next year), and the total effort in all the closed areas for each vessel for each month is computed. This effort is the effort to be redistributed.

4. Based on the assumption that vessels will obtain the largest net benefits per trip if they fish in the spatial units with the highest catch rates in a previous year (or years), the effort is distributed in proportion to the average catch rate per spatial unit per month per vessel in the base year (for spatial units that are not closed).

5. The redistributed effort is added to the total effort per spatial unit per month per vessel of the open spatial units, and a predicted total effort per spatial unit per month per vessel is obtained.

Thus, the predicted effort (E') in the following time period (t + 1) is

$$E'_{r,t+1,v} = E_{r,t,v} + \sum_{a=1}^{A} E_{a,t,v} \left(cpue_{r,t,v} \Big/ \sum_{r=1}^{R} cpue_{r,t,v} \right) \quad \text{given} \quad \sum_{r=1}^{R} E'_{(r,t+1,v)} = \sum_{r=1}^{R} E_{(r,t,v)}$$

for a particular combination of spatial unit/rectangle (r, that is still open), time period (t), fishing unit (v) and closed area (a). The effort of the fleet can be obtained by summing over all vessels.

2nd stage

In situations where the closed area encapsulates the total fishing ground of a vessel, the first stage of the model will predict that the vessel will remain in port. However, fishers do not remain in port, but rather follow other vessels to fish in other areas. Therefore, the second stage of the model redistributes this effort to ICES rectangles using a simple rule, assuming that they follow other vessels that were also subject to the closure.

2.2.3 Scenarios

The analysis uses 2003 data for the English otter trawl and beam trawl fleets, and models three scenarios for closed areas for a future time period (e.g. 2004 in this case). The default assumption is that they base relocation decisions on the previous year's cpue (Y_{-1}), when the alternative is to assume that they base decisions on a longer time period (e,g, the average over the last 2 or the last 5 years). Basing the decision on the average of the last 2 years would not make a large difference because the year-on-year shifts in effort are small. Using longer time periods such as 5 years could be invalid for the beam trawl fleet, because there have been major shifts in effort to different fishing grounds as a consequence of vessels becoming flag vessels, as well as changes in landing port that can indirectly influence location choice. In addition, if the vessel skipper has changed, this will also invalidate this assumption because information would have been lost. Therefore, a decision was made to use the previous year only (2003, in this case).

The three scenarios modelled are:

a) *2001 closure*: 47 rectangles were closed permanently in the North Sea (where such a closed area represents, as nearly as possible, the area closed by the EU Commission in 2001 as part of the North Sea cod management strategy);

b) *STECF closure*: 34 four rectangles were closed permanently in the North Sea (where this closed area represents, the area noted by STECF (2003) to be that from which 60% of the international catches of cod were taken in 2002);

c) *NE Coast closure*: closure of two ICES statistical rectangles located on the northeast coast of England that were apparent in the 60% area from the STECF report.

2.2.4 Results

The amount of effort relocated at each stage of the modelling process, as a result of the closure covered by each of the three scenarios, is shown in Table 2.2.1. The 1st stage redistributes the effort of vessels that already fished within the open areas prior to closure; it is assumed that relocation of displaced effort is in proportion to the vessels' prior catch rates in the open area. The effort redistributed in the 2nd stage is the effort of fishing vessels that the closed area excludes from their entire fishing grounds. It is assumed that they follow the others and redistribute their effort in a similar proportion to the vessels displaced in the 1st stage, rather than returning to port.

Otter trawlers

The spatial distributions of effort resulting from relocation as a result of the three scenarios modelled are presented in Figures 2.2.1–2.2.3.

Figure 2.2.1 shows the results for the *2001 closure* (47 rectangles closed permanently, i.e. for a whole year, in the North Sea). The impact on the fleet is small. Just 5% of the effort is redistributed, and visually the difference is not easily noticeable.

Figure 2.2.2 shows the results for *STECF* closure (34 rectangles closed permanently, i.e. for a whole year, in the North Sea). The potential impact of this scenario is similar to that of the third scenario mentioned below, because it includes the two rectangles of the NE Coast closure. A significant proportion of effort is redistributed to the surrounding ICES rectangles (34% of the effort, or 24 760 fishing hours).

Figure 2.2.3 shows the results for the *NE Coast* closure. A significant proportion of effort is redistributed to the surrounding ICES rectangles (33% of the effort, or 23 930 fishing hours).

Beam trawlers

The spatial distributions of effort resulting after relocation as a result of the three scenarios modelled are presented in Figures 2.2.4–2.2.6.

Figure 2.2.4 shows the results for the *2001 closure*. The impact on the fleet is highly significant, more than 51% of the fleet having to redistribute its effort.

Figure 2.2.5 shows the results for the *STECF closure*. The potential impact on the fleet in this scenario is relatively large, up to 23% of the effort having to be redistributed. However, the impact is smaller than the previous scenario because a large part of the fishing ground is still open.

Figure 2.2.6 shows the results for the *NE Coast closure*. The impact on the fleet is small, just 1% of the effort being redistributed; visually the difference is negligible.

2.2.5 Discussion

The results of the effort relocation modelling indicate that the NE Coast closure scenario and the portion of the STECF closure scenario located in that region have a significant impact on the UK (England and Wales) otter trawl fleet but a negligible impact on the beam trawl fleet. The 2001 closure scenario has a relatively light impact on the otter trawl fleet, but a significant impact on the beam trawl fleet. An important factor to consider is the large amount of effort redistributed under the second stage of the model in the case of otter trawlers (for the NE Coast and STECF closure scenarios), indicating that a significant portion of this fleet is subject to a closure that encapsulates their entire fishing ground and therefore has to redistribute its effort to other fishing grounds by following other vessels.

Table 2.2.1 Results from the three scenarios for each of the fleets (otter and beam), showing the total number of hours of fishing effort, without a closure and under the three scenarios outlined in text (note, the effort redistributed at each stage of the model is also shown). The values Total % are the totals redistributed in both stages.

Scenario	Stage	Otter	Beam
No closure		72514	57207
2001-closure	1st	3194	13995
	2nd	715	15207
	Total %	**5**	**51**
STECF closure	1st	6924	6609
	2nd	17836	6278
	Total %	**34**	**23**
Northeast coast closure	1st	6214	273
	2nd	17719	94
	Total %	**33**	**1**

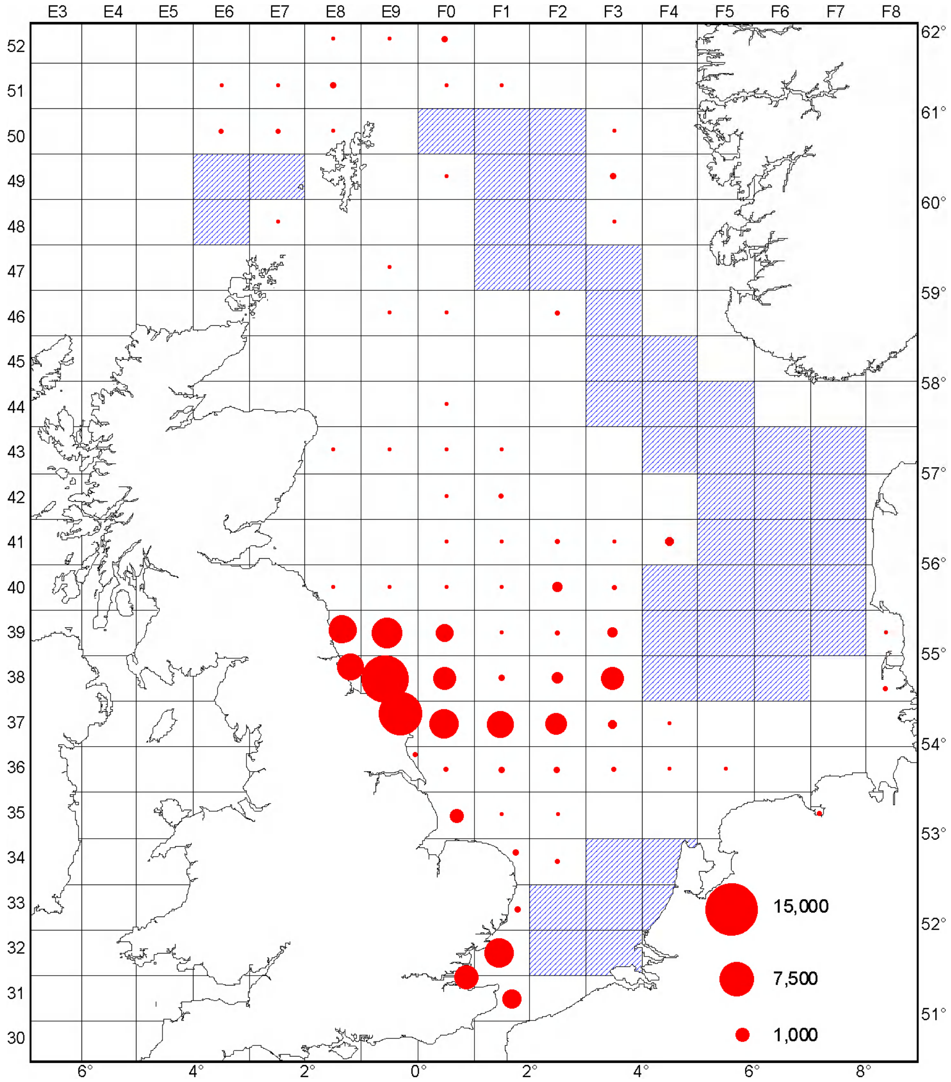


Figure 2.2.1 Estimated spatial distribution of effort (total hours fishing in each ICES rectangle) of English otter trawlers fishing in the North Sea following the *2001 closure* scenario ICES rectangles

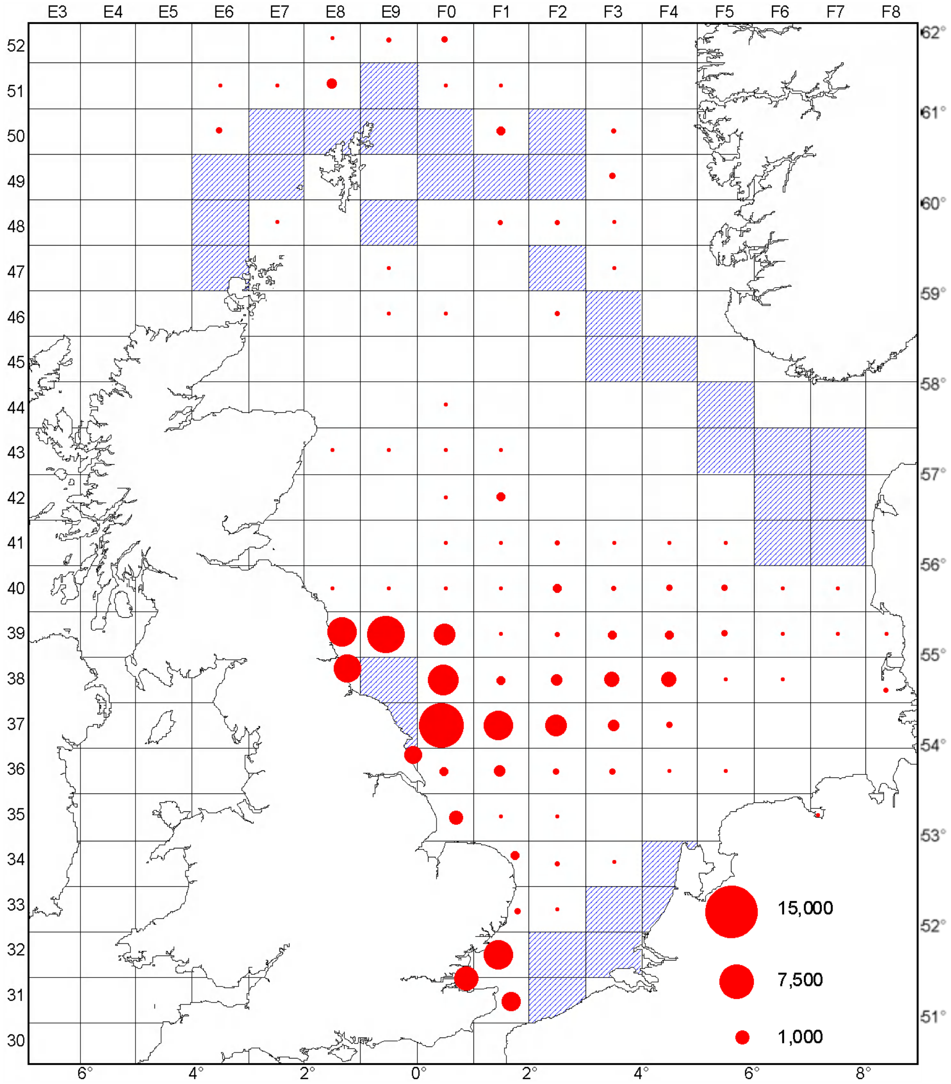


Figure 2.2.2 Estimated spatial distribution of effort (total hours fishing in each ICES rectangle) of English otter trawlers fishing in the North Sea following the *STECF closure* scenario ICES rectangles

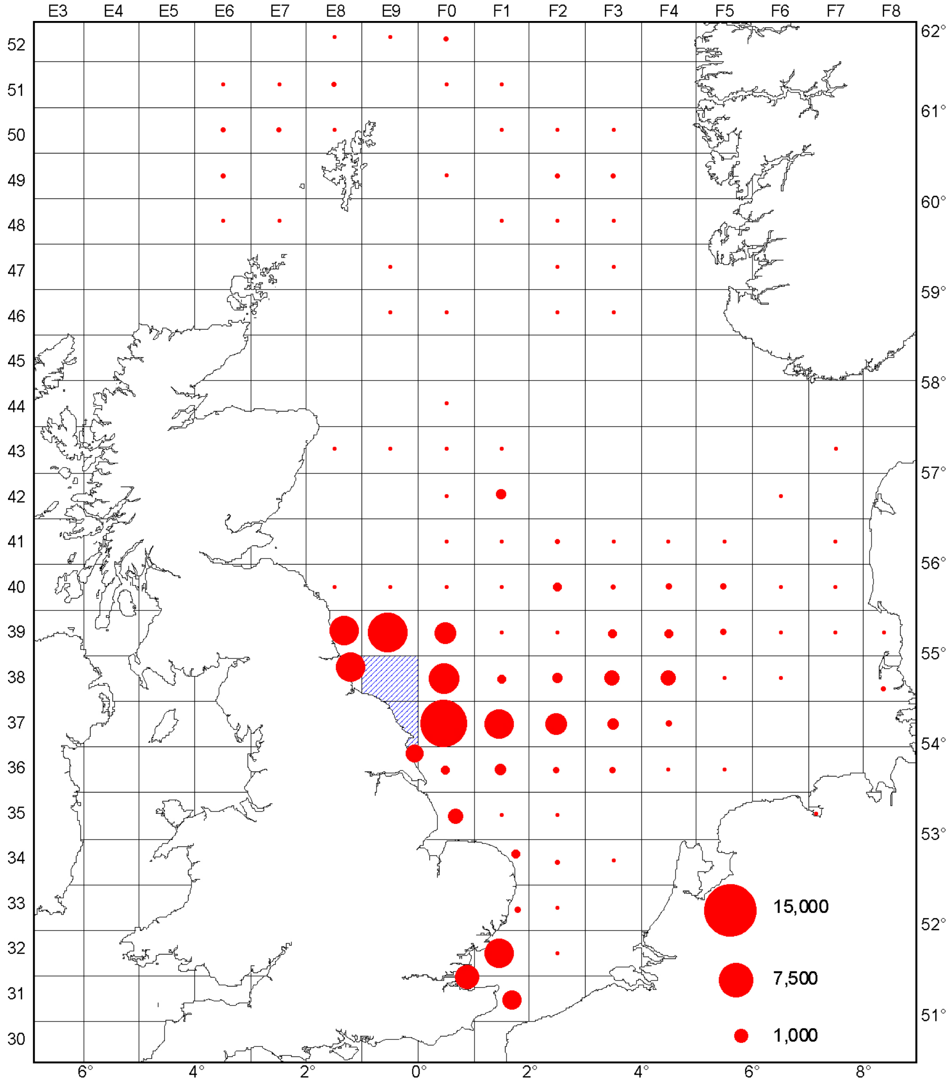


Figure 2.2.3 Estimated spatial distribution of effort (total hours fishing in each ICES rectangle) of English otter trawlers fishing in the North Sea following the *NE Coast closure* scenario ICES rectangles

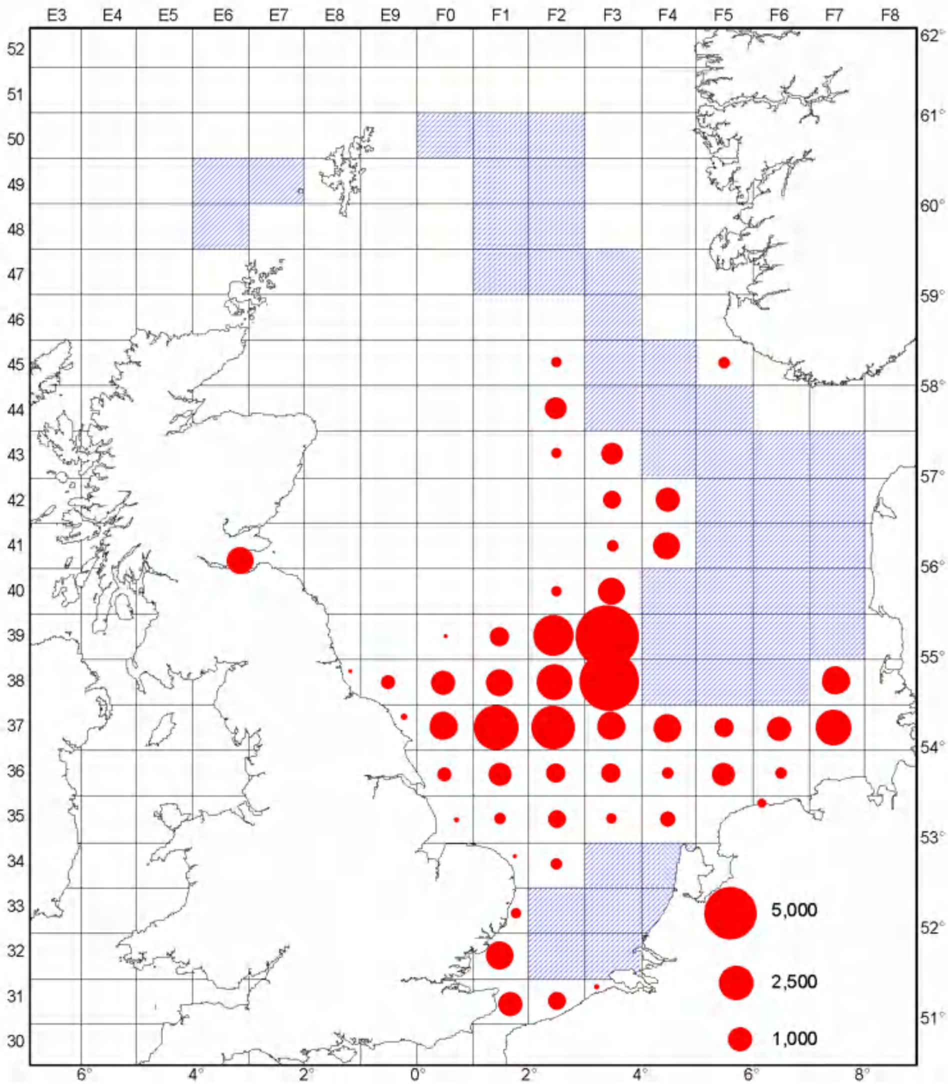


Figure 2.2.4 Estimated spatial distribution of effort (total hours fishing in each ICES rectangle) from "UK (England and Wales)" beam trawlers fishing in the North Sea following the *2001 closure* scenario ICES rectangles

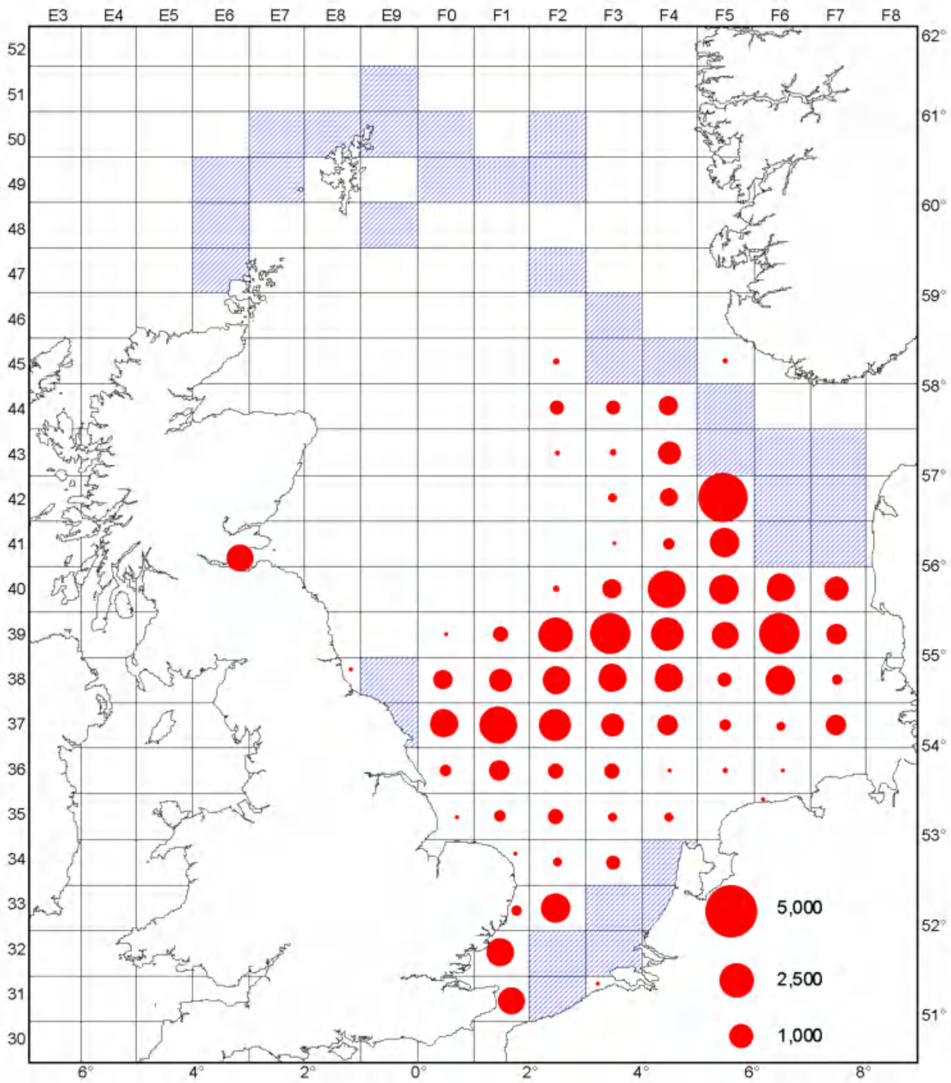


Figure 2.2.5 Estimated spatial distribution of effort (total hours fishing in each ICES rectangle) from "UK (England & Wales)" beam trawlers fishing in the North Sea following the *STECF closure* scenario ICES rectangles

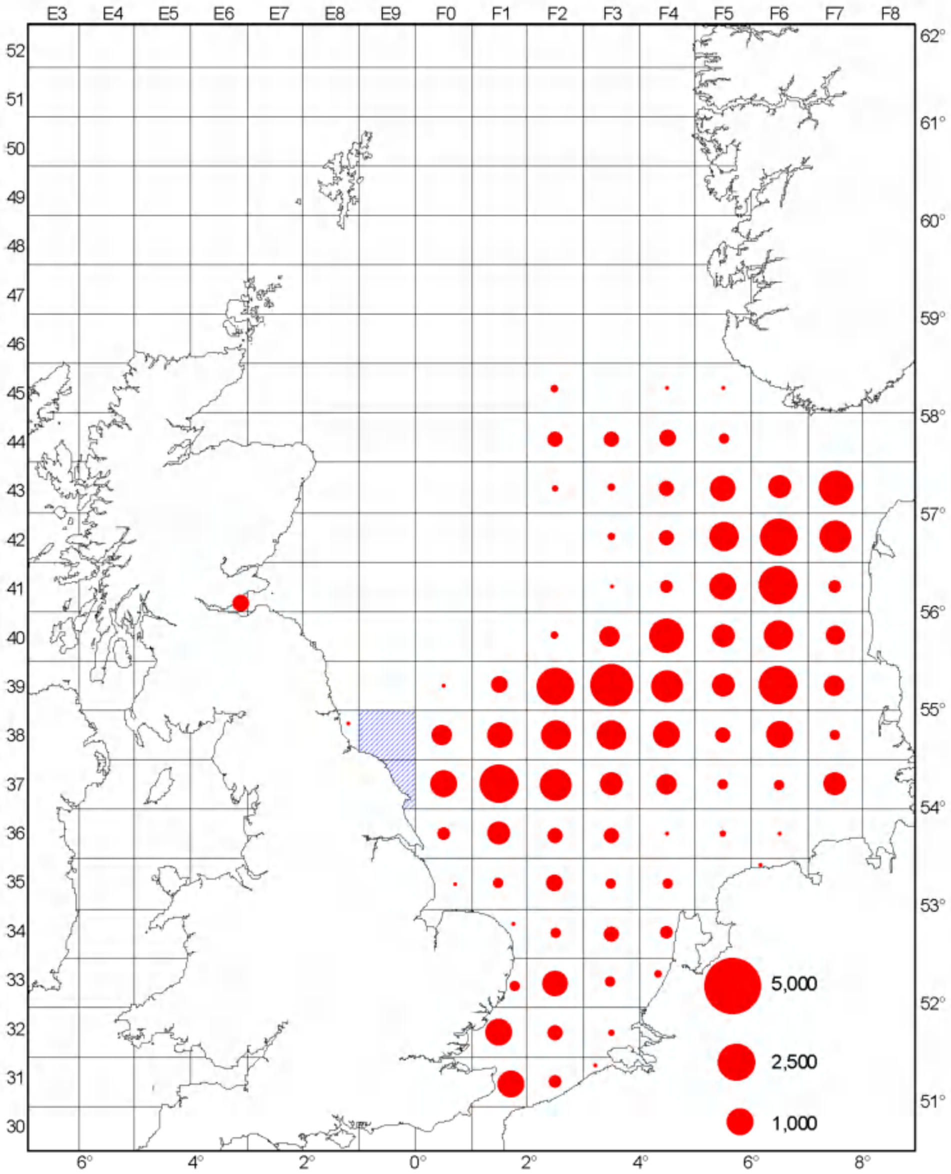


Figure 2.2.6 Estimated spatial distribution of effort (total hours fishing in each ICES rectangle) from “UK (England & Wales)” beam trawlers operating in the North Sea following the *NE Coast closure* scenario ICES rectangles

2.3 International effort

Reliable measures of international effort could not be obtained for all major fleets fishing on North Sea cod owing to the lack of an agreed data source. Therefore, a proxy for the spatial distribution of international effort was calculated from the commercial landings and a catch per unit effort (cpue) series under the assumption that:

Effort proxy = ICES rectangle international catch / cpue proxy

International catch per unit effort

It was assumed that the spatial pattern of the cpue of cod at ages 2 and older recorded by the ICES International Bottom trawl Survey (IBTS 1st and 3rd quarters) is representative of the annual spatial distribution of cpue resulting from commercial fishing.

STECF (2003) compared the spatial trends in standardized commercial and IBTS survey catch rates for cod averaged over the years 1999–2002. The comparison established that although the absolute values of the catch rates differed, the relative spatial distributions of the IBTS survey catch rates exhibit good spatial correlation with the available commercial information. The IBTS data can therefore be used as a relative index of the spatial distribution of commercial cpue.

Unfortunately, the IBTS survey does not extend into the deep water north of Scotland or south into the Channel, so the cpue model does not cover the entire distribution of North Sea cod stock distribution.

Effort

Data were collated at the 2003 STECF meeting on the spatial distribution of commercial cod landings (without discards) by statistical rectangle for the major cod-catching countries.

Under the assumption that the spatial distribution of the IBTS survey cod cpue can be used as a proxy for the spatial distribution of commercial cpue, the spatial distribution of commercial effort was derived using the ratio of landings and IBTS cpue. Several rectangles at the extremes of the distribution have landings data but no survey cpue information; they represent a small proportion of the rectangles, so were excluded. The derived distribution of effort (Figure 2.3.1) shows concentrations along the Dutch and Danish coasts and also along the east coasts of Scotland and England. Lower levels of effort were estimated for the central North Sea.

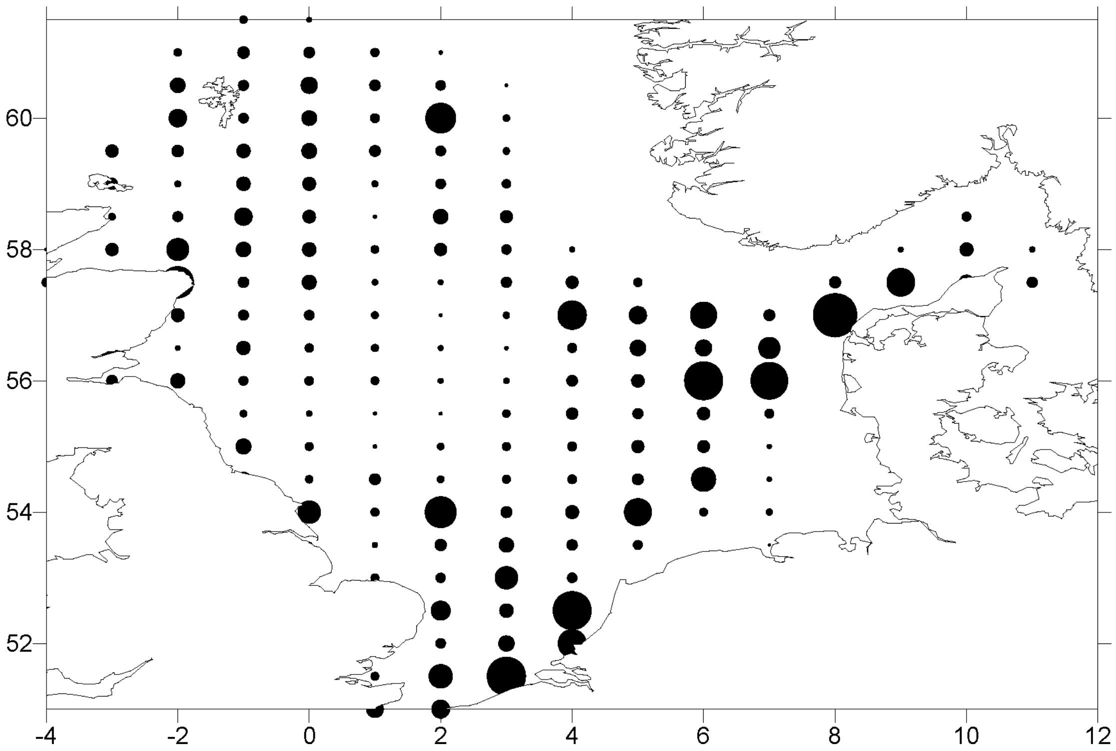


Figure 2.3.1. Spatial distribution of the derived North Sea cod effort proxy calculated from international landings and survey catch per unit effort.

2.4 International effort redistribution in response to closure

Closed area models were specified such that ICES statistical rectangles were either open to fishing or closed in total. Three scenarios were examined for the relocation of effort displaced from each closed area:

1) total removal of the effort from the fishery;
2) relocation within the open areas based on historic effort distributions;
3) relocation within the open areas based on historic cpue distributions.

Effort was redistributed within the open rectangles in either the proportion of either effort or cpue within that rectangle in comparison with all other open rectangles.

3 Modelling the effects of closed areas on the North Sea cod fishery using models based on simplified assumptions

Chris Darby

The effects of spatial closures on the relocation of fishing effort directed at cod were examined at two levels of complexity. Section 3.1 presents a single species investigation of the potential benefits/losses that could occur after restricting the international fishery for North Sea cod. Section 3.2 examines the effects of a local closure on the English mixed gadoid fishery located on the adjacent to the northeast coast of England.

3.1 A closed area model for catches of North Sea cod

The impact of closing areas of the North Sea to prevent the fishing of cod was examined using an enhanced version of the spatially structured model developed at the 2003 meeting of the STECF (STECF, 2003). The model is similar to those examined by the North Sea Task Force (1993; SEC93/2119) and Horwood *et al.* (1998). It simplifies a complex interaction between the fishing fleets and the cod population by assuming a constant equilibrium state for catch rates. It has been used explore the sensitivity of the expected impact of closed areas to the decisions that fishers have to make when redistributing effort.

3.1.1 Model description

In order to simulate the impact of closed areas on the absolute level of North Sea cod catches, data would be required on the detailed spatial distributions of commercial catch per unit of effort (cpue) and effort for all gear types and vessel sizes. Such detailed international data are unavailable at the required scale of spatial and temporal disaggregation.

If, however, the impact of closed areas is evaluated as relative changes in catch or fishing mortality, model complexity is reduced considerably. This is because absolute data are not required, only the level relative to other areas. This approach, using standardized spatial indices of cpue (based on survey data) and commercial effort, was used to provide advice by the STECF at their May 2003 meeting (STECF, 2003). The model has been developed further within this study.

The method assumes that average annual catch rates and effort distributions provide sufficient information to determine the effectiveness of a closed area during all seasons. In other words, seasonal shifts in the spatial patterns of the population (migration) or the fishery do not negate its effects. For species that exhibit local-scale movements, the assumption will hold, but for highly mobile or migratory species, which can be fished outside the closed area, closures will be less effective.

The model was developed to utilize data aggregated to the scale of the International Council for the Exploration of the Seas (ICES) statistical rectangle. Effort displaced from closed rectangles is re-allocated into open areas under the assumption that there will be no change in catch rates attributable to increased local exploitation. The product of the revised distribution of effort and the constant spatial distribution of catch rates of juvenile (ages 1 and 2) and adult (3+) cod, cpue values are summed to calculate the expected total catch. The impact of closing an area is presented as the resulting proportional change in adult and juvenile catches, a figure considered to be equivalent to proportional changes in fishing mortality rates.

Juveniles are modelled separately from adults because of differences in their spatial distribution. As juvenile cod are distributed more to the south in the North Sea, closed areas in the south would offer them greater protection than closed areas in the north. There is no allowance for increased or decreased levels of discards associated with increased catches of juveniles in the model calculations.

3.1.2 International effort relocation

The impact of closing areas of the North Sea was examined by calculating the effect of reducing the effort within specified ICES statistical rectangles to zero and either removing or redistributing effort into areas remaining open. Displaced effort was then redistributed within open areas using three potential scenarios for relocation:

1) removal of displaced effort from the fishery;
2) redistribution in proportion to the effort located within the open rectangles prior to closure;
3) redistribution in proportion to the cpue of cod located within the open rectangles.

The first scenario is considered to represent a management action; the other two are decisions that would have to be taken by fishers. Assumptions (2) and (3) are open to the criticism of oversimplification, in that fleets based primarily in one area may not have prior information on effort or catch rates in others, and would require a “learning time” before optimizing their relocated effort. The choice of rectangle to fish may also be based on the catch rates from a mixture of species (Section 3.2). During the first months (years) of relocation, the catch rates of displaced vessels are likely to be lower than those of vessels using similar gears that have historical experience of the area.

It is assumed that the total amount of effort available to the fleets is capped, i.e. that there is no allowance within the redistribution algorithm for increases in effort in the areas to which effort is relocated to compensate for lower initial catch rates. Changes in behaviour, to compensate for the economics of effort displacement, are not modelled; examples would be vessels changing the port from which they operate if became uneconomic to remain in their home area, thus reducing steaming times.

3.1.3 Closed area scenarios

Three closed area scenarios are examined for their impact on the international catches of cod:

a) 2001 – closure of the 2001 "cod spawning zone" permanently (Figure 1.3.1)
b) STECF – closure of the area estimated by the STECF 2003 meeting to be that from which 60% of the international catches of cod were taken in 2002 (STECF, 2003; Figure 1.3.2)
c) northeast coast – closure of two ICES statistical rectangles located on the northeast coast of England that were apparent in the 60% area from the STECF report (cf. scenario (b); Figure 1.3.3).

Table 3.1.1 presents the percentage of the total modelled North Sea area and the proportion of the total juvenile and adult cpue contained within each of the closed areas.

Table 3.1.1 The proportion of the area of the North Sea spatial effects model and the percentage of the total cpue of juveniles and adults contained within three closed area scenarios.

Closure scenario	2001	STECF	Northeast coast
Proportion of the modelled area	30%	20%	1%
Fraction of cpue contained in area			
Adults	43%	35%	<1%
Juveniles	49%	31%	<1%

3.1.4 The impact of area closure on international catches of cod

Table 3.1.2 presents the results of the calculations for the percentage change in total international landings, of juvenile and adult cod, estimated by the model.

Removal of effort from the fishery has the greatest impact on catches across all model scenarios. The 2001 cod protection area and the STECF closed area reduce fishing mortality by ~50% each when the effort is removed on an annual basis. The two rectangles on the northeast coast of England reduce mortality by around 4%. The reductions are of similar magnitude for adult and juvenile cod.

If effort is redistributed within the model, the impact of a closed area is very sensitive to the way in which effort is reallocated to the open rectangles. If effort is reallocated using the spatial distribution of historical effort, the reduction in fishing mortality is ~14% for the 2001 closed area and ~23% for the larger STECF area. The small northeast coast closed area has a very small impact on fishing mortality, just 2% reduction in cod mortality. Adult and juvenile mortality rates are reduced in similar proportions.

However, if effort is redistributed in proportion to the total (adult and juvenile) cpue of cod in the open rectangles, fishing mortality increases after the introduction of all three closed areas. Adult mortality doubles after closure of the 2001 area and is increased by 70% after closing the STECF area. Juvenile mortality increases by approximately 15% in both scenarios. If displaced effort targets rectangles with high catch rates of cod, the effect of the closures significantly increases the risk of further stock decline.

The increase in mortality is a consequence of the underlying basis for the current distribution of international effort across the North Sea, previously discussed in Sections 2.2 and 2.3. Effort is not distributed within the North Sea according to catch rates of cod, but in proportion to the catch rates of a mixture of species, distance from port, fuel price, etc. The diversity of factors introduces considerable complexity into the modelling process, in that vessels fishing in different locations with the same gear and those fishing in the same location with different gears could attain different species compositions and/or catch rates and therefore elect to move their effort to different areas in response to a closure. When modelling North Sea closures, analysis of international effort redistribution should, if possible, be carried out at the individual boat level, as formulated in Section 2.2, an exercise that becomes very large and requires very detailed data sets.

Table 3.1.2 The percentage change in the catches of North Sea adult and juvenile (ages 1 and 2) cod based on calculations from a closed area model using simplified population and fishery interaction assumptions for three closed area scenarios based on the spatial pattern distribution of catches.

Catch based models	2001	STECF	N.E. Coast
Effort removed			
Change in adult mortality	-54%	-52%	-4%
Change in juvenile mortality	-54%	-53%	-4%
Effort redistribution (historical)			
Change in adult mortality	-13%	-21%	-2%
Change in juvenile mortality	-14%	-23%	-2%
Effort redistribution (cpue)			
Change in adult mortality	98%	67%	3%
Change in juvenile mortality	15%	13%	1%

3.1.5 Closed areas designed on the basis of catch rates

The redistribution of effort according to mixed species catch rates introduces new complexity to the design and modelling of the impact of closed areas.

The potential number of gear and species combinations results in a very large number of scenarios that would require evaluation before a comprehensive study of the possible effects of each closed area can be achieved for each potential relocation choice by fishers.

If the problem of the design of a closed area and its evaluation is reduced to that of trying to estimate the minimum potential impact of the closure on the target species, in this case cod, the problem becomes more tractable. Closure scenarios that have no beneficial effect on the target species mortality rates can be removed from the set of potential management options.

For the two scenarios of effort relocation examined, the minimum impact of the closure on the target species would be achieved if fishers redistribute their effort according to the distribution of catch rates of cod within the open squares. Table 3.1.3 illustrates the catch rate by rectangle of adult cod used within the model; empty cells indicate the STECF closed area scenario. The distribution of values illustrates that although the closed area restricted access to many North Sea rectangles with high catch rates, sufficient rectangles remained open at the edges of the closed areas to permit displaced effort to more than compensate for any loss of catches resulting from the closure. This suggests that robust designs for closed areas aimed at protecting cod should include the additional areas in which catch rates of cod are high.

In order to examine the utility and robustness of designs for closed areas based on catch rates, the rectangles that contained the highest 20, 30 and 40% of the IBTS cpue of adult and juvenile cod were identified. Juvenile cod are distributed in greater abundance in the southern North Sea, adult cod in the northern area; the distributions of the selected juvenile and adult rectangles reflected the spatial differences. In this evaluation exercise, the two sets of rectangles were combined into a single area and the closed area model run to calculate the effect of redistribution of effort. Figures 3.1.1–3.1.3 present the results for the closed areas based on combined juvenile and adult catch rates that enclose 20, 30 and 40% of the cpue values.

In addition to the closed areas containing specified proportions of the catch rates of juvenile and adult cod, the model was altered such that the closed areas defined for the two age groups could be adjusted to achieve a targeted reduction (50%) in the total catches of adults and juveniles. The area is illustrated in Figure 3.1.4.

Table 3.1.4 presents the proportions of enclosed adult and juvenile cpue and the percentage of the modelled North Sea area within the closed areas. Table 3.1.5 presents the reduction in catch estimated by the model under the three effort redistribution algorithms; removal, effort-based and cpue-based.

In common with the estimates from the effort redistribution model (Section 3.1.4), the greatest reduction in catches (mortality) is achieved when the displaced effort is removed from the fishery. Redistribution reduces the impact of the closures. The historical effort redistribution algorithm reduces catches marginally more than redistribution according to the catch rates in a rectangle.

The difference between the impacts of the closed areas designed using catch rates and those defined previously, based on total catches, is that the annual cod catches are reduced under both redistribution algorithms. Designing closed areas according to the proportions of catch rates (a proxy for population distributions) not catches (the product of effort and catch rates) reduces the potential for increasing catches in those rectangles where cod are abundant, after redistribution.

The results of the simulation in which a 50% reduction in fishing mortality (*F*) on adults and juveniles is targeted are also presented in Table 3.1.5. In order to achieve the required reduction, 47% of the modelled area is closed, illustrating that in order to achieve significant reductions in cod fishing mortality, large areas of the North Sea would have to be closed.

Table 3.1.3 The distribution of adult cod cpue by ICES rectangle used within the closed area simulation model for North Sea cod, illustrating areas that remain open and within which there are relatively high catch rates.

Average o	RectE											
RectN	E6	E7	E8	E9	F0	F1	F2	F3	F4	F5	F6	F7
52	0.0	0.0	0.0	1.0	**1.5**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
51	0.0	0.0	**6.5**		**4.2**	**4.4**	**10.4**	0.0	0.0	0.0	0.0	0.0
50	0.0	0.0				**4.4**		**8.0**	0.0	0.0	0.0	0.0
49	0.0		0.5	**2.8**				**2.4**	0.0	0.0	0.0	0.0
48	0.0	**1.7**	0.8		**1.5**	0.9	**1.9**	**3.4**	0.0	0.0	0.0	0.0
47	0.0	0.0	0.6	1.2	1.1	**4.5**		**4.2**	0.0	0.0	0.0	0.0
46	0.0	0.4	0.9	0.5	1.3	**9.3**	0.3		0.0	0.0	0.0	0.0
45	1.3	0.0	0.2	0.7	**1.5**	1.0	0.4			0.0	0.0	0.0
44	0.4	0.3	0.0	0.8	0.8	0.7	0.8	**1.7**	**1.8**		0.0	0.0
43	0.0	0.0	0.2	0.2	0.3	0.3	1.2	0.5	0.3			
42	0.0	0.0	0.4	0.2	0.5	0.2	0.8	1.1	0.7	1.1		
41	0.0	0.0	0.0	0.0	0.2	0.1	0.7	1.1	0.4	1.5		
40	0.0	0.0	0.2	0.3	0.5	1.2	1.1	0.8	0.5	1.3	0.8	1.1
39	0.0	0.0	1.1	1.0	0.3	0.8	0.6	0.7	**1.6**	0.8	1.4	**1.7**
38	0.0	0.0	0.0		1.1	0.1	0.4	0.8	**1.8**	0.7	0.2	0.8
37	0.0	0.0	0.0		0.4	0.8	0.2	1.1	0.6	0.1	**2.1**	0.5
36	0.0	0.0	0.0	0.0	0.5	0.4	0.5	0.4	1.0	1.0	0.0	0.6
35	0.0	0.0	0.0	0.0	0.5	0.1	1.2	0.2	1.0	0.0	0.0	0.0
34	0.0	0.0	0.0	0.0	0.0	0.4	0.4	1.1		0.0	0.0	0.0
33	0.0	0.0	0.0	0.0	0.0	0.2	**2.0**			0.0	0.0	0.0
32	0.0	0.0	0.0	0.0	0.0	0.9			0.0	0.0	0.0	0.0
31	0.0	0.0	0.0	0.0	0.0	0.5		0.0	0.0	0.0	0.0	0.0

Table 3.1.4 The percentage of North Sea catch per unit effort and the proportion of the area of the North Sea spatial model contained within four closed area scenarios based on the spatial pattern distribution of catch rates.

Cpue-based models	20% cpue	30% cpue	40% cpue		50% *F*
Fraction of cpue area closed					
Adult area	19%	32%	40%		71%
Juvenile area	20%	30%	40%		67%
Proportion of the model area closed	5%	10%	20%		47%

Table 3.1.5 The percentage change in the catches of North Sea adult and juvenile (ages 1 and 2) cod based on calculations from a closed area model using simplified population and fishery interaction assumptions for four closed area scenarios based on the spatial pattern distribution of catch rates.

Cpue-based models	20% cpue	30% cpue	40% cpue	50% *F*
Effort removed				
Change in adult mortality	-11%	-21%	-30%	-73%
Change in juvenile mortality	-16%	-25%	-35%	-73%
Effort redistribution (historical)				
Change in adult mortality	-9%	-17%	-24%	-59%
Change in juvenile mortality	-14%	-21%	-29%	-59%
Effort redistribution (cpue)				
Change in adult mortality	-5%	-13%	-17%	-50%
Change in juvenile mortality	-12%	-18%	-22%	-50%

3.1.6 Comparison of the effects of closed area management scenarios

In order to examine and compare the impact of the closed area scenarios on North Sea cod stock dynamics, the model estimates of the change in fishing mortality were considered constant in time, and stochastic projections were used to evaluate the potential effect on spawning stock biomass and yield.

The projections were run under the assumption that the current spatial patterns of effort and cpue would remain stable during the simulated time period (20 years), an unlikely scenario. North Sea cod spatial distribution has changed over time in parallel with decreased abundance. If the cod stock rebuilds, associated changes in distribution would be expected. Consequently, regular reviews and potential revisions of the closed area boundaries would be required to maintain the reductions in mortality rates.

Stochastic projections were run for twenty years using the CS4 program developed by the STECF (STECF, 2002). The principal biological and statistical assumptions used for the projections were that the underlying population dynamics are fixed. Population abundance at age is assumed to be lognormally distributed, with age-specific standard deviation. Recruitment is modelled as a stochastic variable dependent on spawning stock biomass, according to a simplified recruitment model that declines linearly from a point represented by user-defined biomass and geometric mean recruitment over a specified time range, to the origin, and is constant at the geometric mean at spawning stock size above the given biomass. All other population parameters (weights at age, maturity, natural mortality) are assumed known precisely and time-invariant. As with any projection or simulation method, the approach described here does not represent the true uncertainty or the real range of expected outcomes. Real uncertainties are much larger than those represented, so the projected trajectories of the stock can only be used for comparative purposes.

The starting populations, their standard errors, stock and catch weights, maturity, etc. were taken from the most recent assessment of North Sea cod (ICES, 2004). In order to allow comparison between the modelled scenarios and alternative management measures, the fishing mortality was referred to as that at the fully exploited age range for the North Sea cod assessment, i.e. ages 4–6 (average F = 0.99). Recruitment abundance at stock biomasses above the lowest estimated was modelled as the geometric mean of recent low levels, the 1997–2002 year classes at age 1; below the lowest spawning stock biomass, recruitment declines linearly to the origin. Note that this is a pessimistic stock and recruitment model specification. At stock biomasses above the lowest observed, recruitment does not increase, but is maintained at recent low levels. If recruitment does recover with increased stock biomass, recovery rates will be faster and stock abundance will attain higher levels.

Stochastic stock projections were run with the reductions in fishing mortality estimated for the two major closed area scenarios, and compared with a *status quo* projection based on the North Sea assessment results; the results are presented in Figures 3.1.5–3.1.7. In each figure there are eight self-explanatory panels; time trends in yield (catch = landings + discards + under-reporting), SSB and fishing mortality are plotted along with annual percentage changes. The distribution of time in years to recovery (two successive years with SSB above B_{pa}) and the cumulative percentages of recovery in time are also presented.

Figure 3.1.5 illustrates the stochastic results for the *status quo* stock projection, starting at the 2004 working group estimate of stock abundance for 2005. The projection is based on the assumption that recent efforts to reduce catches of North Sea cod have not been effective. At the projected rate of exploitation, SSB is forecast to decline further. Yield and recruitment decrease with biomass, and the stock and fishery situation continues to deteriorate. The bottom two panels of Figure 3.1.5 illustrate that if recent levels of recruitment and rates of fishing mortality continue, there is no prospect of stock recovery to the Precautionary Approach biomass reference levels within 20 years.

Figure 3.1.6 illustrates the stochastic stock and yield trajectories resulting from a reduction in mortality following annual closure of the 2001 cod protection area, based on the redistribution of displaced effort in proportion to the historical effort distribution. Catches are reduced by approximately 14% for both juveniles (1 and 2 years) and adults (3+). The reduction in fishing mortality is sufficient to stabilize the decline in spawning biomass and to maintain yield and recruitment. Maintaining the stock at low levels results in a negligible probability of recovery within 20 years.

Figure 3.1.7 illustrates the stochastic stock and yield trajectories resulting from a reduction in mortality following annual closure of the STECF-defined area that contains 60% of the 2002 catches, based on the redistribution of displaced effort in proportion to the historical effort distribution. Catches are reduced by 21% for juveniles and 22% for adults. The reduction in fishing mortality results in a stabilization of the biomass followed by an increase; yield and recruitment levels are maintained at recent levels. The increase in biomass results in a probability of recovery of <1% after 20 years.

The simulations for both closed area scenarios indicate that if fishers target areas with high catch rates of cod when redistributing displaced effort, the risk of a further decline in the stock is greater than the *status quo* situation (Figure 3.1.5). Therefore, Figures 3.1.6 and 3.1.7 present optimistic outcomes for the stock, and the most probable outcome of closing the two areas would fall between stabilization of the stock at a level below safe biological limits and a further deterioration in its status.

If a North Sea closed area were to be designed around the areas with high survey catch rates, as described in Section 3.1.5, closing the rectangles containing 20–40% of the highest catch rates is estimated to result in catch reductions in the range 9–30%, based on historical effort, and 5–25% if based on cpue redistribution (Table 3.1.5). Both ranges of catch reduction cover the reductions in fishing mortality presented in Figures 3.1.6 and 3.1.7. The estimated impact would be a halt to the decline in the stock with a possible increase in biomass, but not to the required recovery to the reference biomass levels defined for the stock.

Complete removal from the fishery of effort displaced from the closed areas was estimated to have the greatest beneficial effect on reducing mortality rates (Section 3.1.4). The reductions were of the order of 50% for both adults and juveniles. Similarly, Figure 3.1.4 illustrates the closed area, based on catch rates of juvenile and adult cod, estimated to result in a 50% reduction in catches. A corresponding stochastic run with a 50% reduction in fishing mortality at all ages is illustrated in Figure 3.1.8. The reduction in mortality results in increased biomass that rapidly exceeds B_{lim} and stabilizes at a level just below B_{pa}. Yield falls in the short term, but recovers after a few years and rapidly exceeds current estimates. There is a relatively greater (>50%) probability of stock recovery for the scenarios in which effort is removed from the fishery completely.

3.1.7 Comparison with alternative management measures

Management of the North Sea cod fishery using closed areas and effort reductions could lead to rebuilding of the stock if sufficiently large areas are closed or substantial effort restrictions imposed. Attempts at management by the more usual TAC restrictions will, presumably, also be continued. After unrecorded landings, one of the more damaging side effects of TAC management is discarding of undersized, less valuable fish. Discards have recently been included in the assessment of the North Sea stock for the first time (ICES, 2004). Estimated discard mortality rates for recent years are highest at ages 1 (87%), 2 (53%) and 3 (17%).

Reducing the mortality attributable to discarding would have a beneficial effect on the stock. Therefore, in order to allow comparison with the closed area management scenarios, a stochastic simulation of the effect of the reducing discard mortality to zero is presented in Figure 3.1.9. Reducing discards to zero has a similar effect on the stock to that of the STECF closed area (Figure 3.1.7); the projected decline in SSB is reversed and there is an increase to a stable level just below B_{lim}.

A ban on discards is difficult if not impossible to enforce and does not reduce the mortality of juveniles directly; fish are landed rather than being thrown back dead. Overall fishing mortality is reduced when discards are counted against quota. In contrast, changes to mesh size reduce discards through releasing juveniles and are relatively easier to introduce and enforce. The North Sea fishery selection (relative fishing mortality) at age ogive estimated by ICES (2004) was compared with the selection ogive of cod fished with known mesh sizes. The selection ogive (including discards) is approximately congruent with that of a 90 mm mesh, well below the 120mm legal minimum mesh for boats targeting cod. Although boats directing fishing towards gadoids in the North Sea are required to use 120mm mesh, boats using a wide range of gear types catch and discard or land cod; the combined effect is a much lower effective mesh selection.

In order to examine the effect of increasing the realised selection pattern of the North Sea cod fishery and facilitate comparison with the impact of the closed area and effort reduction management scenarios, cod selection ogives were calculated for 120, 140 and 160mm trawl meshes. Relative changes in selection were calculated from 90 – 120/140/ and 160mm meshes and the total mortality resulting from fishing (landings and discards) at age adjusted in accordance. Selection at length was determined from $S_L = 0.5 + 0.5 \tanh(\alpha[L-L_{50}])$ where S_L is the proportion selected by the gear at length L, $\alpha = 0.203$, a shape parameter, set to provide mesh selection characteristics of otter trawl as supplied by the FRS Aberdeen, L_{50} – the length at which 50% of the cod entering the gear are retained, determined from: L_{50} = Selection Factor * Mesh size / 10, where the selection factor = 2.97

It was assumed that the fishery continues with constant effort levels, and that fishing mortality at age, throughout the fishery, was reduced at the youngest ages by increasing mesh sizes across all fleets. Figures 3.1.10 – 3.1.12 present the stochastic runs for the estimated effect of increasing mesh size on the stock trajectories for cod. As would be expected, increasing mesh size reduces mortality at the youngest ages improving the production from juveniles and increased biomass is achieved. The use of 120mm mesh throughout all of the fisheries catching cod would have the same impact as the reduction of discards to zero or the effect of the STECF closed area and for an unchanged level of effort results in growth of the stock to Blim; using 140mm mesh increases biomass to between Blim and Bpa and 160mm allows the stock to recover to above Bpa. The simulations assume that effort does not increase in order to compensate for the loss of smaller species and the initial losses of small cod from the catch.

The simulated stock trajectories are illustrative of the effects of changing mesh size, rather than predictive. It has been assumed that the mixture of meshes taking cod can be summarised by a single mesh and that the impacts of changing mesh are uniform across areas; a gross simplification.

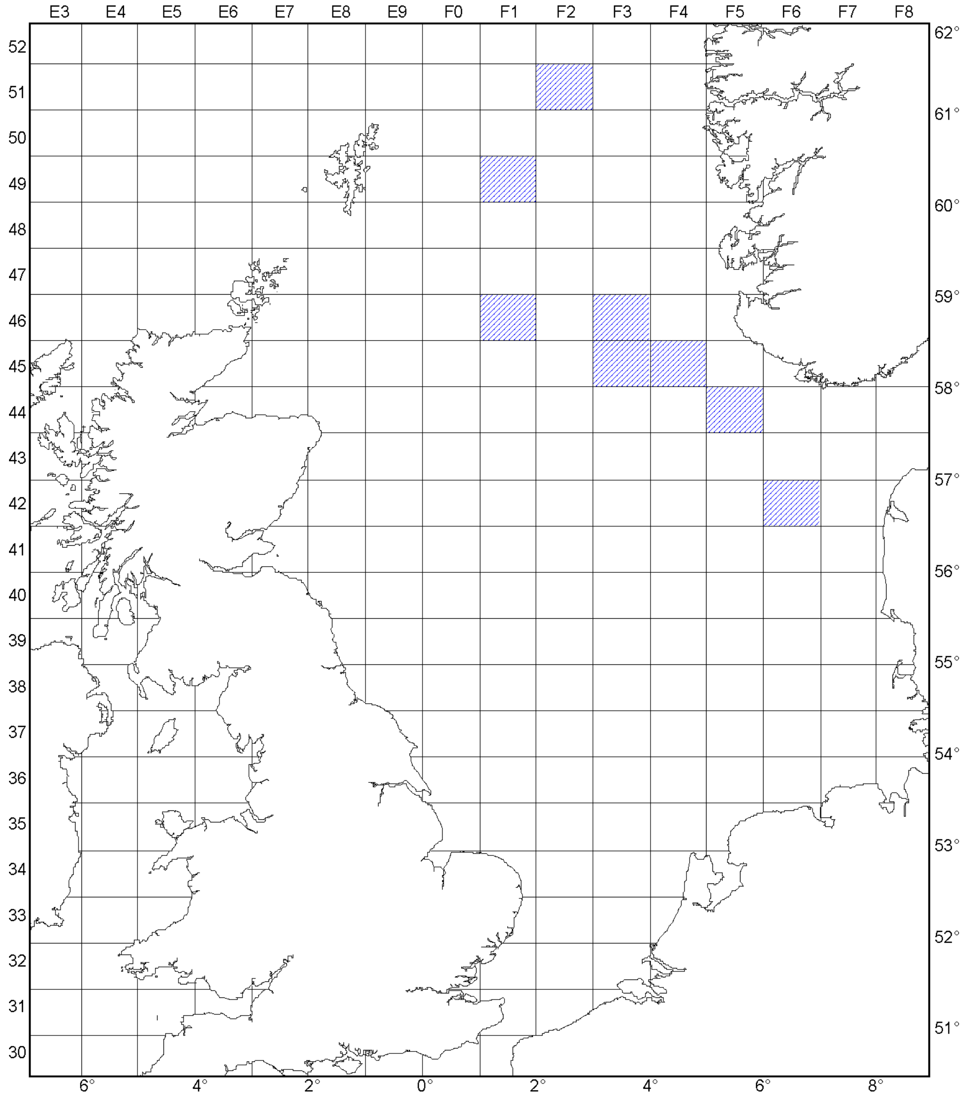


Figure 3.1.1 The area of the North Sea that contains the highest 20% of the IBTS catch rates for adult and juvenile cod.

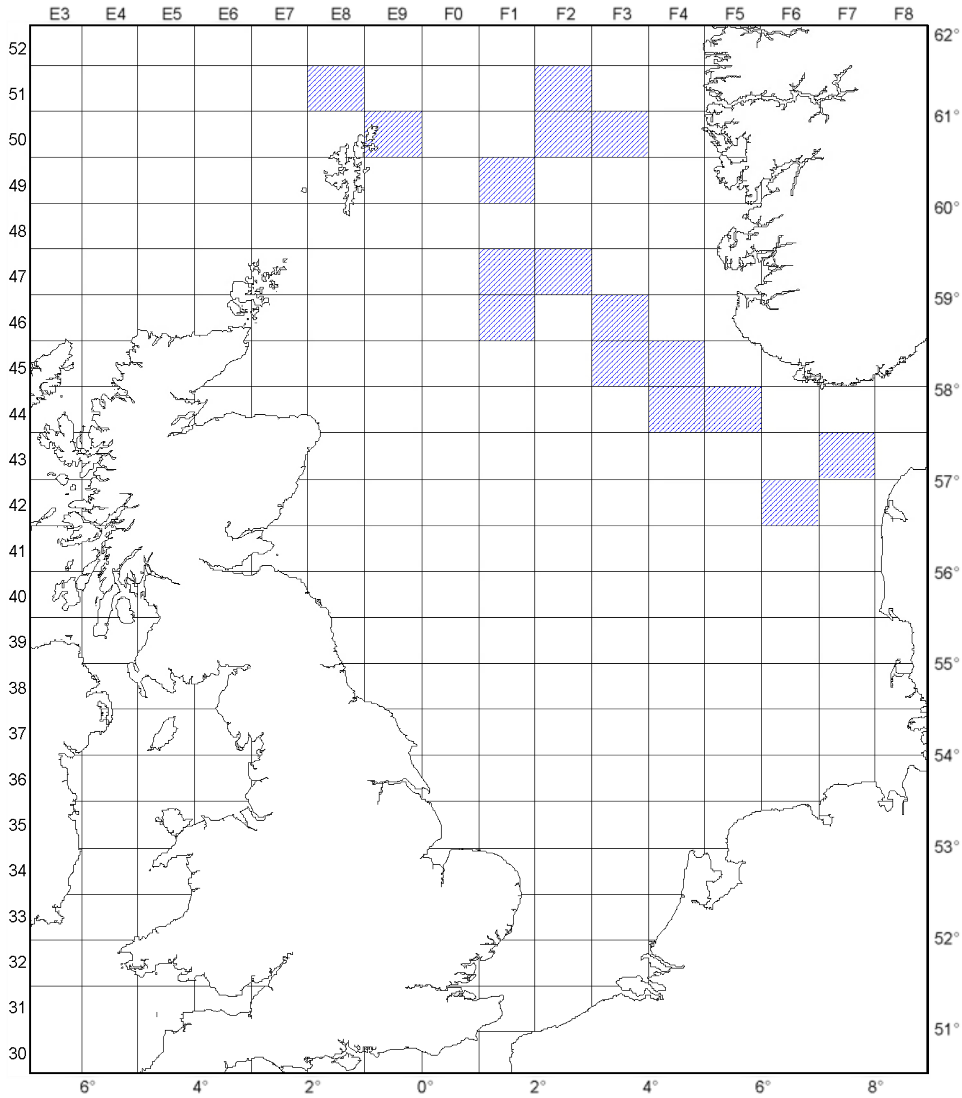


Figure 3.1.2 The area of the North Sea that contains the highest 30% of the IBTS catch rates for adult and juvenile cod.

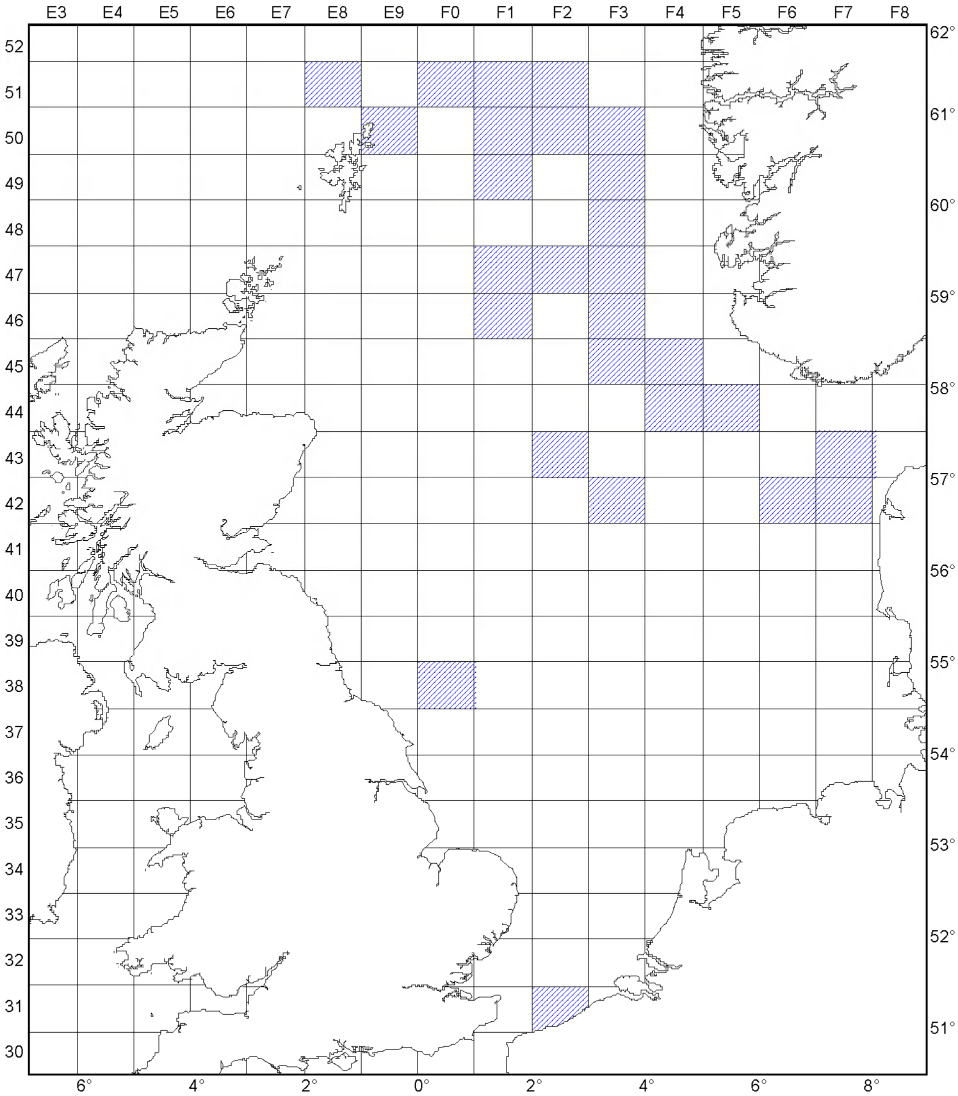


Figure 3.1.3 The area of the North Sea that contains the highest 40% of the IBTS catch rates for adult and juvenile cod.

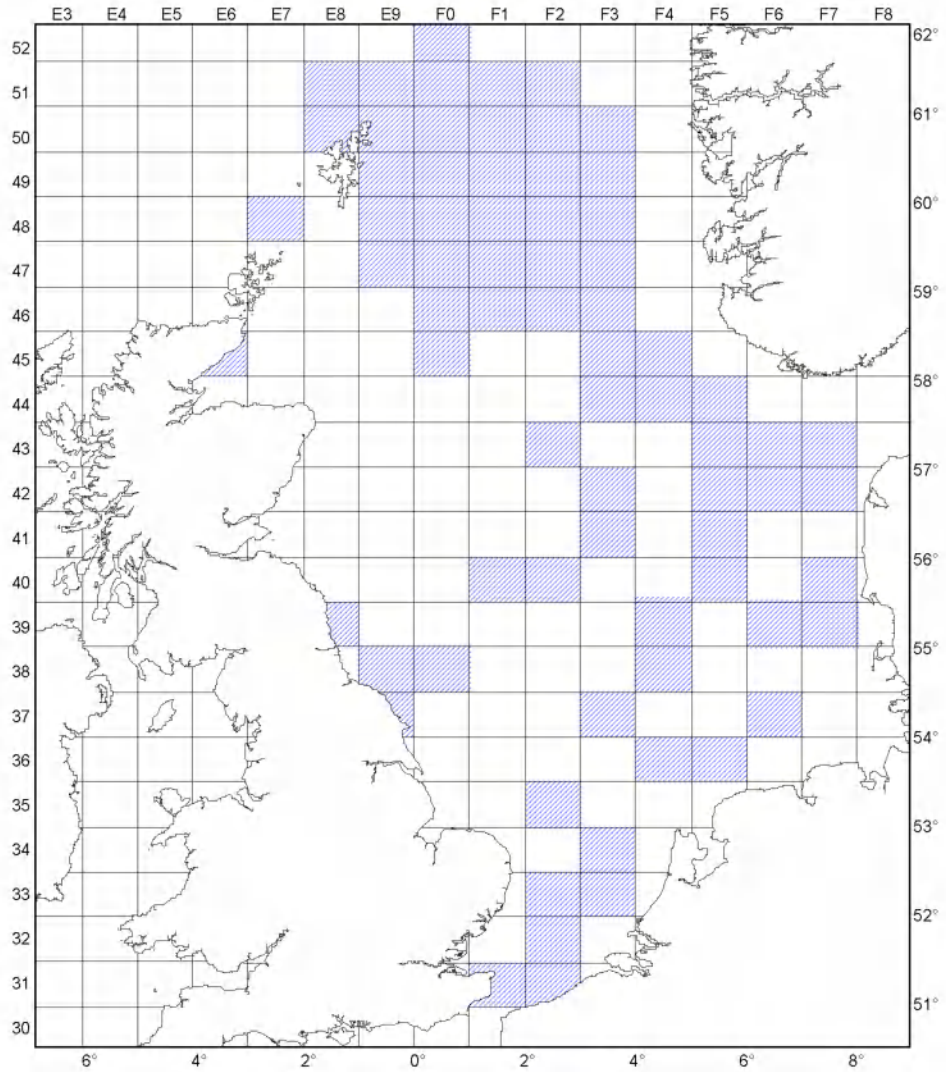


Figure 3.1.4 The area of the North Sea that would be closed to achieve a 50% reduction in fishing mortality based on IBTS catch rates for adult and juvenile cod.

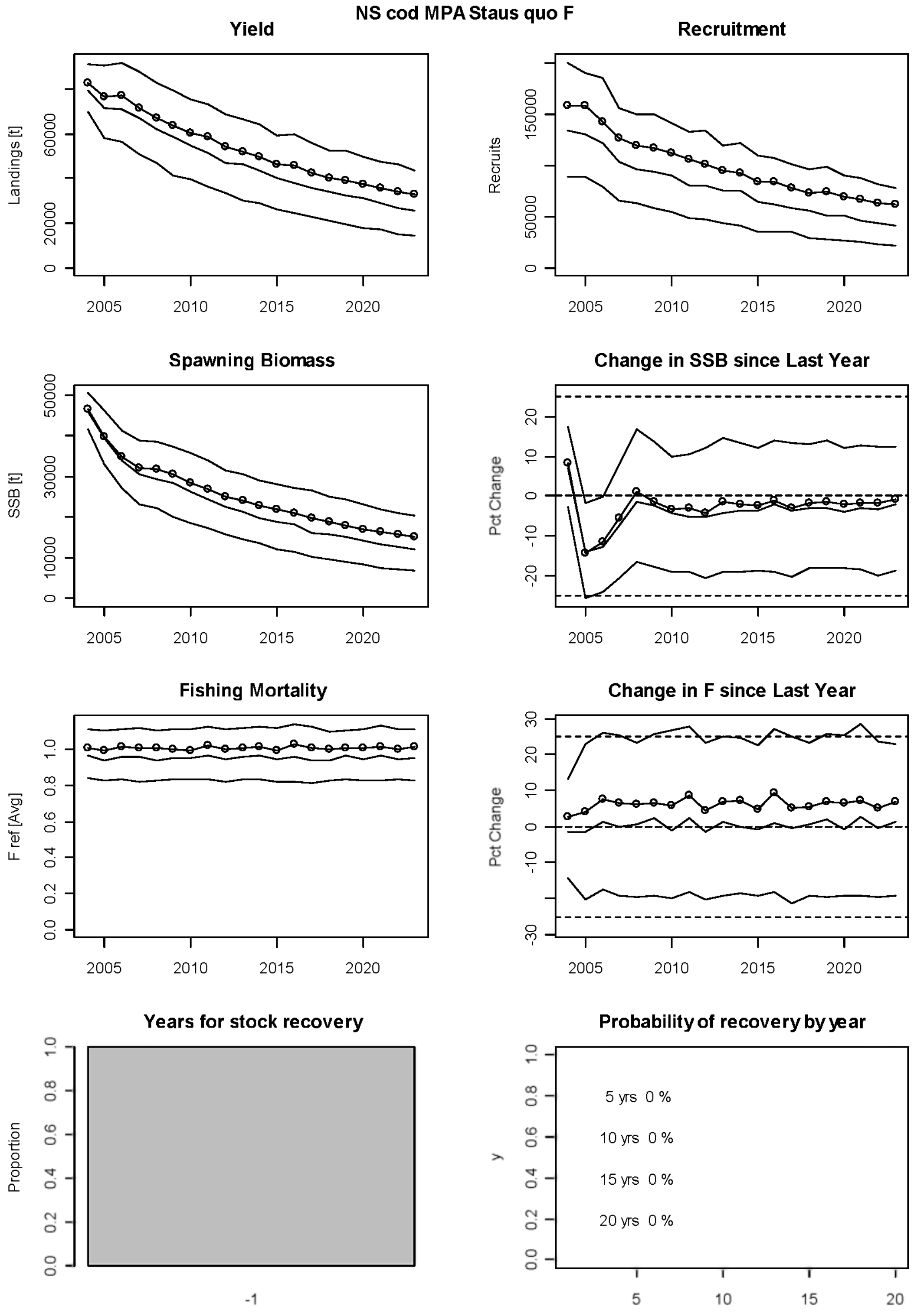


Figure 3.1.5 North Sea cod CS4 stock projection at *status quo* fishing mortality (0.98 at fully selected ages). Refer to Section 3.1.6 for a description of the panels.

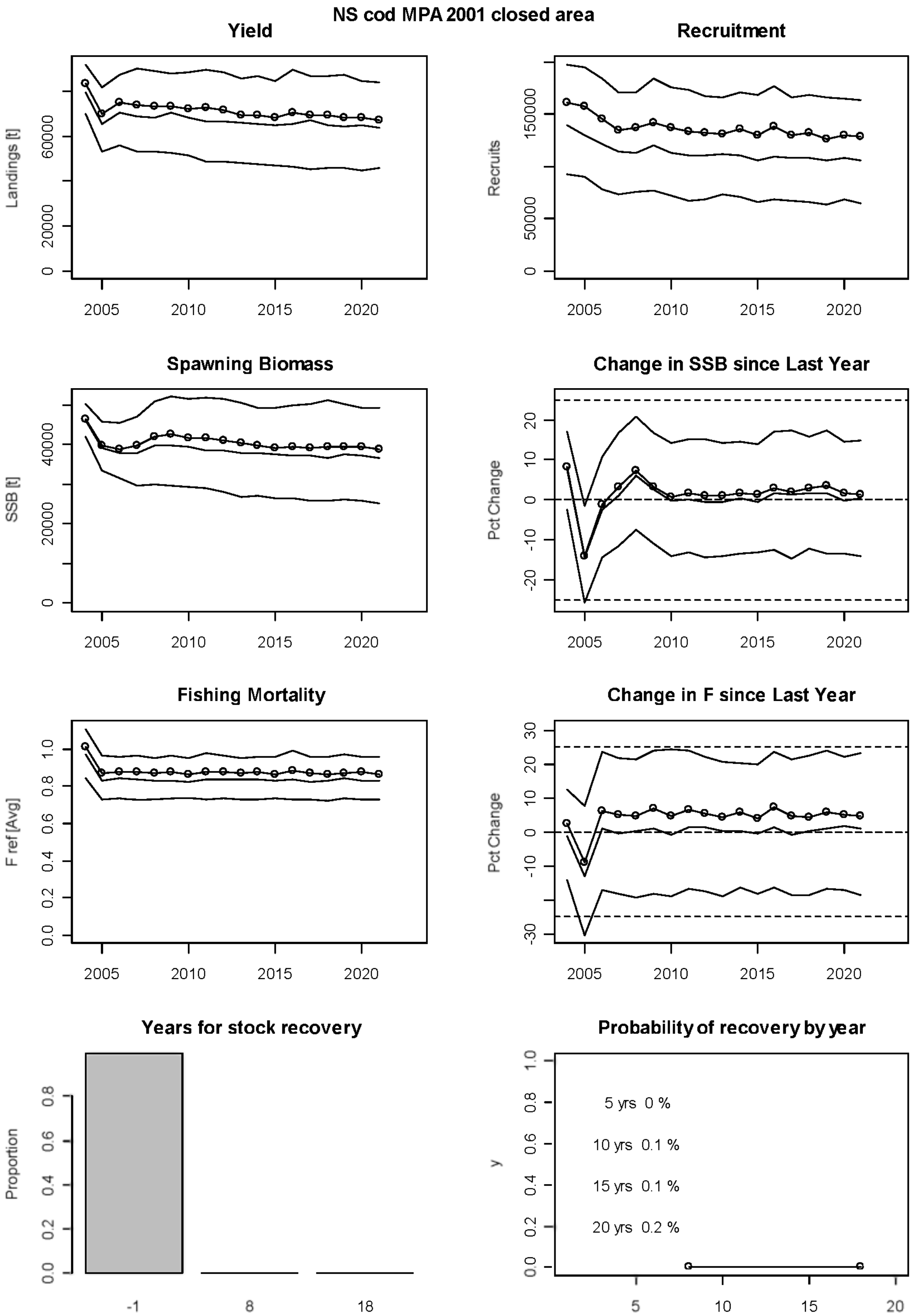


Figure 3.1.6 North Sea cod CS4 stock projection based on the fishing mortality reduction estimated to result from the closure of the 2001 closed area (0.86 at fully selected ages). Refer to Section 3.1.6 for a description of the panels.

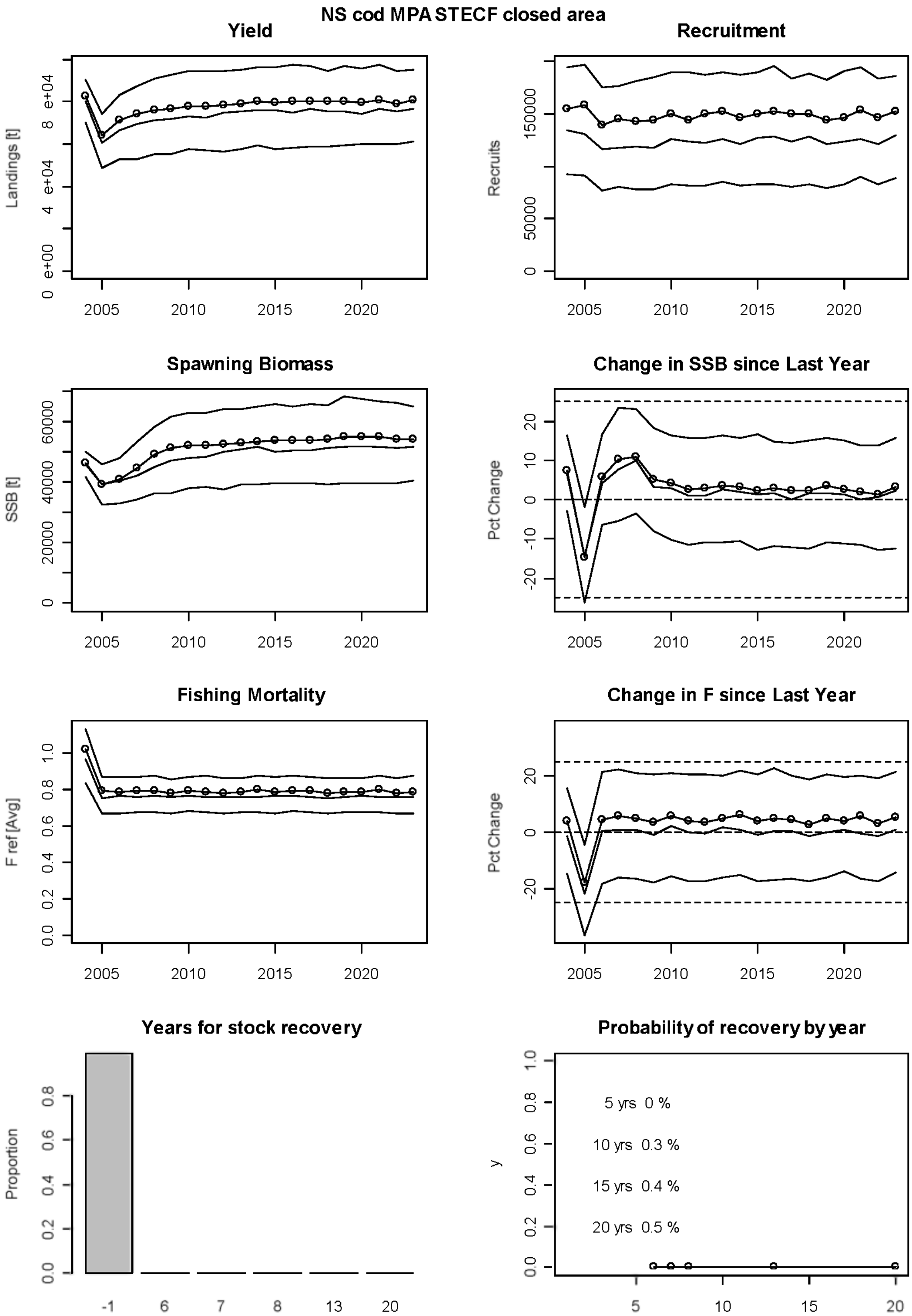


Figure 3.1.7 North Sea cod CS4 stock projection based on the fishing mortality reduction estimated to result from the closure of the STECF scenario (0.78 at fully selected ages). Refer to Section 3.1.6 for a description of the panels.

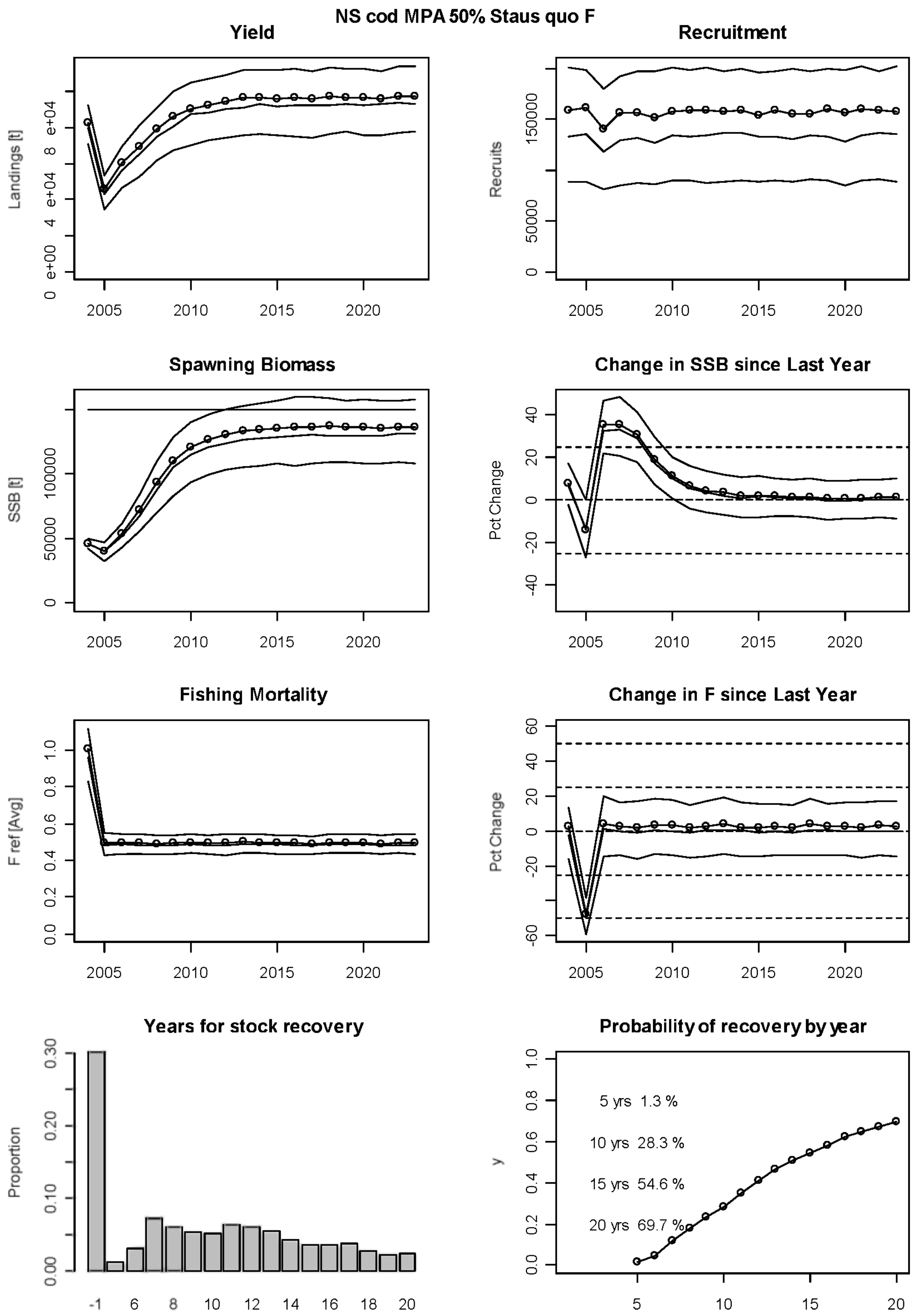


Figure 3.1.8 North Sea cod CS4 stock projection based on a 50% reduction in fishing mortality (0.49 at fully selected ages). Refer to Section 3.1.6 for a description of the panels.

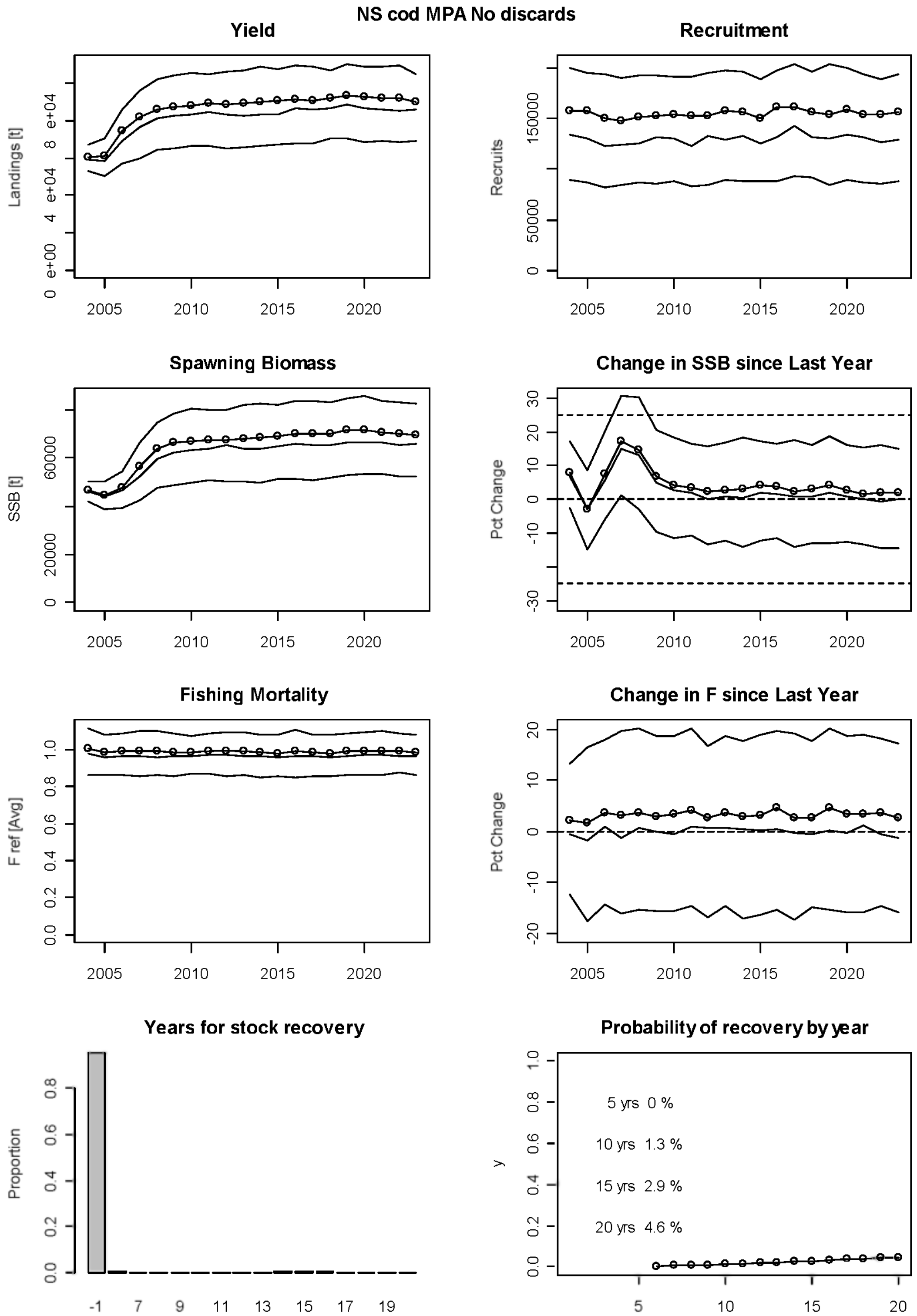


Figure 3.1.9 North Sea cod CS4 stock projection based on the reduction in fishing mortality at the youngest ages resulting from a reduction of discarding to zero for all cod-directed effort. Refer to Section 3.1.6 for a description of the panels.

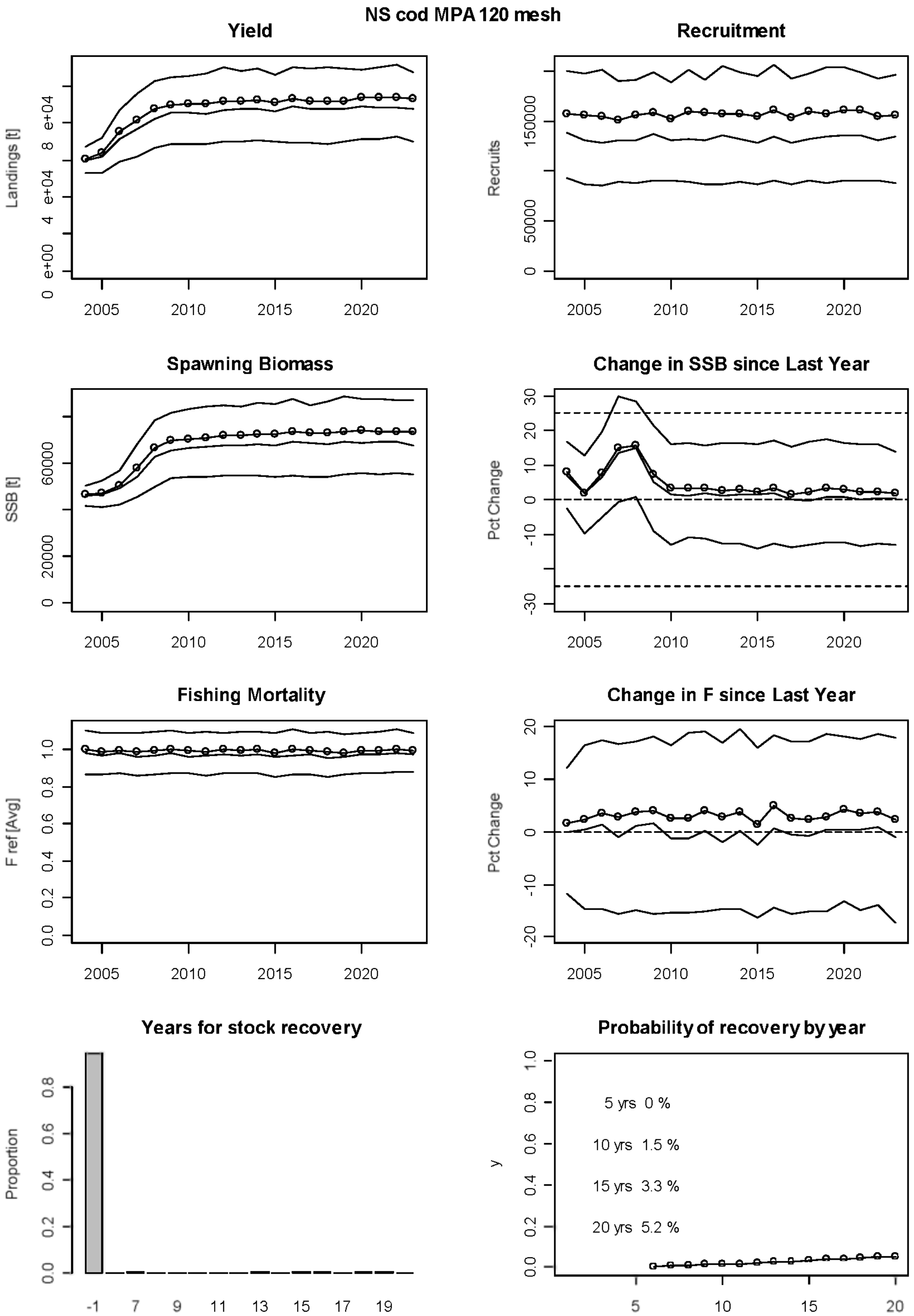


Figure 3.1.10 North Sea cod CS4 stock projection based on the reduction in fishing mortality at the youngest ages resulting from the selection pattern implied by a change to 120 mm trawl mesh for all cod-directed effort. Refer to Section 3.1.6 for a description of the panels.

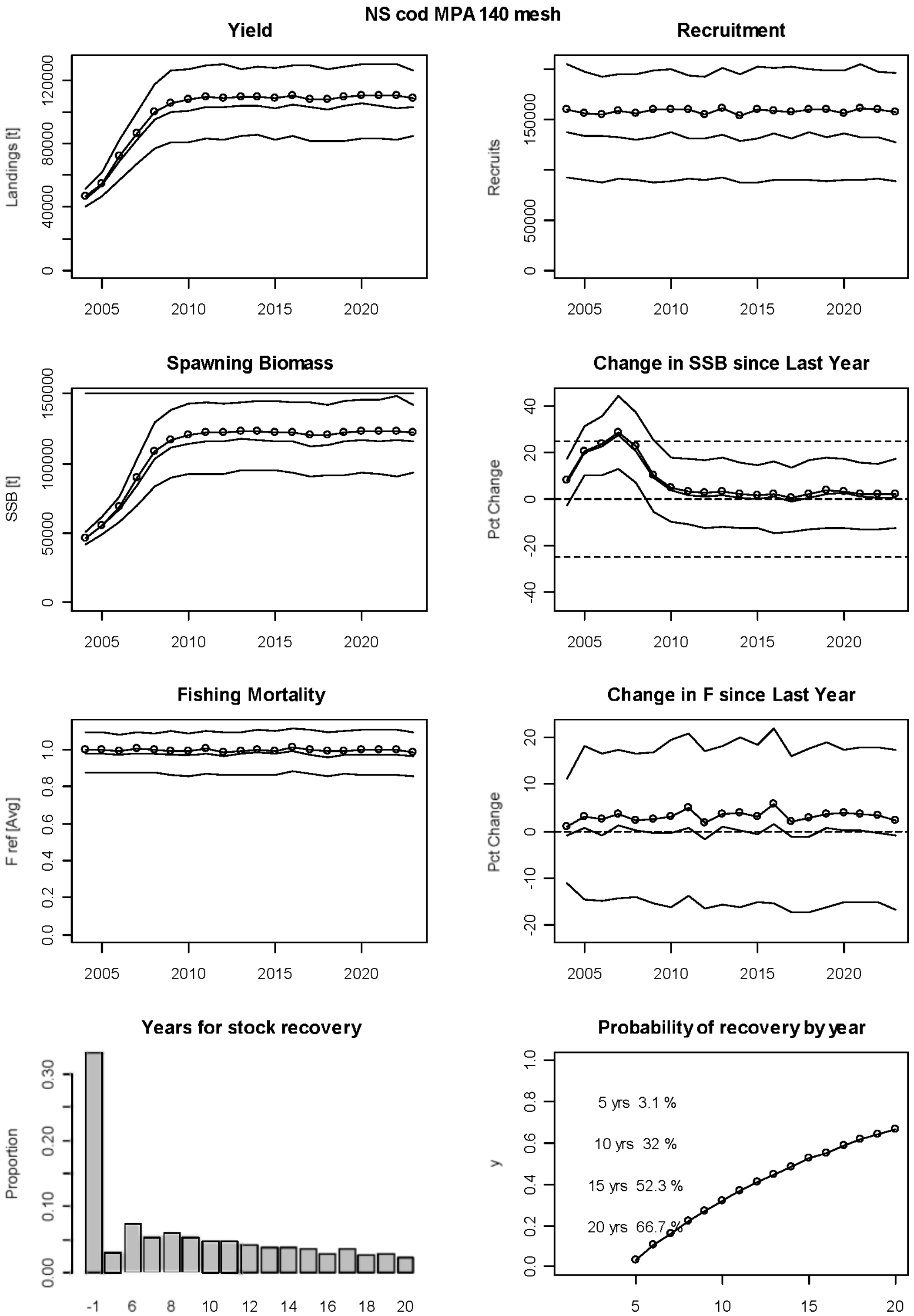


Figure 3.1.11 North Sea cod CS4 stock projection based on the reduction in fishing mortality at the youngest ages resulting from the selection pattern implied by a change to 140 mm trawl mesh for all cod-directed effort. Refer to Section 3.1.6 for a description of the panels.

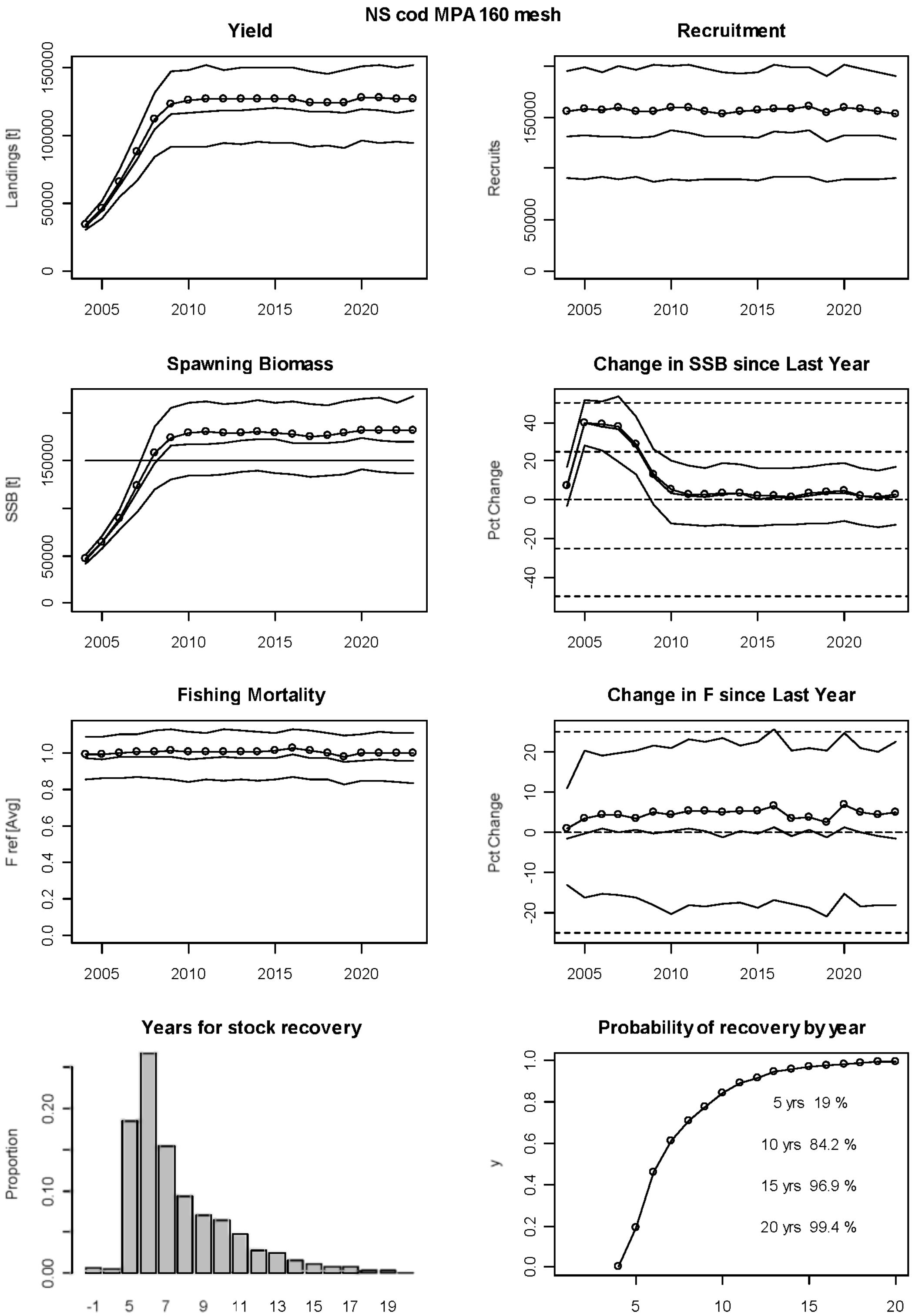


Figure 3.1.12 North Sea cod CS4 stock projection based on the reduction in fishing mortality at the youngest ages resulting from the selection pattern implied by a change to 160 mm trawl mesh for all cod-directed effort. Refer to Section 3.1.6 for a description of the panels.

3.2 A northeast coast mixed fishery simulation model

The scenario of a closed area located on the northeast coast of England (ICES rectangles 37E9 and 38E9) was examined, in detail, in the context of the locally important mixed gadoid and *Nephrops* fisheries. The results are presented in terms of the potential effects on the English fleets' partial fishing mortalities for each species. The UK (England and Wales) fleets landed approximately 10% of the total reported landings of North Sea cod in 2003. Changes in partial fishing mortality will constitute a relatively minor component of the total international fishing mortality.

3.2.1 Data

Data collected from the northeast coast fishery were available in greater detail than data from international commercial fleets operating in the North Sea. This enabled the model for effort redistribution to be fitted by quarter, in order to examine the impact of seasonal variations in spatial distribution.

The total England and Wales North Sea beam trawl effort directed into the two rectangles is relatively small (Section 2.1, Figure 2.1.2). Closing them has very little impact on beam trawlers, so the analysis examined the impact on otter trawlers only.

North Sea monthly average trip data (recorded landings by species and effort) for otter trawlers (excluding *Nephrops*-directed gears) landing into England and Wales in 2003 were extracted from the Fishing Activities Database, disaggregated by quarter, rectangle and species (cod, haddock, whiting and *Nephrops*). The data could not be subdivided into age or size categories, so the effect of changes in the effort distribution on adults and juveniles could not be evaluated independently. Effort distributions for each ICES rectangle were calculated by quarter and are presented in Figures 3.2.1–3.2.4.

3.2.2 Effort relocation

Displaced effort was reallocated to adjacent rectangles according to the three assumptions listed below.

1) Effort within the closed rectangles was removed from the fishery.
2) Effort was redistributed in proportion to the effort directed into each open rectangle by all vessels prior to closure. This assumption for effort redistribution is simplistic to some extent, because smaller vessels displaced by the closure are unlikely to relocate throughout the North Sea to fish; it is more likely that they would redistribute their effort locally. Larger vessels would, however, be able to move to more distant areas.
3) Effort was redistributed in proportion to the cpue of all species for individual vessels prior to closure (Section 2.2). This assumption allows for the vessel effects discussed under (2) above. Effort data were only available on an annual basis, so can only be compared at that time scale. The comparison is used to examine the sensitivity of the scenario results to the assumption used in effort redistribution.

3.2.3 Results

Quarterly landings distributions were calculated for each of the main gadoid species and *Nephrops* using spatial distributions of effort and recorded cpue, before and after closure, with and without relocation of effort. Tables 3.2.1–3.2.8 present the results from the analysis of the effect of the northeast box closure on the 2003 otter trawl landings from the gadoid otter trawl fishery. All calculations assume that there are no changes in fishing practice attributable to quota restrictions.

Table 3.2.1 presents the total recorded North Sea, England and Wales, otter trawl effort for 2003, and the quantity directed into the two rectangles. There is a distinct seasonal pattern, with significantly higher levels in the first and last quarters of the year. The seasonal distribution of effort is consistent with locally known cod seasonal movement patterns, moving into the area during winter.

The total England and Wales recorded landings in tonnes of each species, by quarter, are presented in Table 3.2.2, and the percentages taken from ICES statistical rectangles 37E9 and 38E9 are presented in Table 3.2.3. The seasonal pattern in the proportion of landings from the two rectangles reflects the distribution of effort through the year; the greatest proportions of the total England and Wales recorded landings of cod being taken inside the two rectangles during the first and last quarters. For haddock and whiting, the greatest proportion of landings is taken during the first quarter, with a more even distribution throughout the rest of the year.

The results of calculations for the impact, on the England and Wales otter trawl landings and hence fishing mortality, of closing ICES statistical rectangles 37E9 and 38E9, are presented in Tables 3.2.4–3.2.7. Table 3.2.4 presents the estimated 2003 England and Wales otter trawl landings of each species that would have been taken after closure and removal of the effort from the fishery. Table 3.2.5 presents the estimated of otter trawl landings for each species resulting from redistribution of effort according to the spatial pattern of effort located in the rectangles that remain open. Tables 3.2.6 and 3.2.7 present the percentage reductions in otter trawl landings by species and quarter with the annual reduction in landings, for the two effort-redistribution scenarios. Negative values indicate reductions in landings (mortality); positive values indicate increases. It is assumed that an increase in the estimated fleet catches is linked directly to an increase in landings; i.e. that quota is available to the fleets, preventing an increase in discarding.

Closing the two rectangles reduces the landings of cod in all quarters for both scenarios. Removal of effort results in the greatest reduction in landings, with highest reductions in quarters 1, 2 and 4. Similar seasonal patterns in the reduction in landings are estimated for whiting, haddock and *Nephrops*, but to a lesser extent. Relocating effort to the open rectangles in proportion to the historical effort reduces the reduction in the landings of cod by around 50% and changes the seasonal pattern of the reductions; quarters 2 and 4 have the largest reductions.

For whiting, haddock and *Nephrops*, the pattern of reductions is strongly influenced by the redistribution of effort. There are negligible reductions in landings of whiting and haddock during the third quarter, reductions of around 10% in the second quarter, and increases in landings averaging 10% in the first and fourth quarters. For *Nephrops*, diversion of effort away from cod increases the landings by an average of 15% in all quarters. The effort is displaced into areas of better cpue of *Nephrops*, and increased landings result.

If the calculations by quarter are combined into an annual index, there is no change in the landings of whiting and haddock, a 19% reduction in the landings of cod and a 15% increase in the landings of *Nephrops*. Annual calculations mask the significant seasonal variation in the impact of the closed area, so must be taken into consideration during the provision of advice.

Table 3.2.8 presents a comparison between the results of calculating otter trawl landings based on the assumption of quarterly and annual effort re-distribution on the basis of historical effort (Effort) by rectangle and historic catch rate of all species by rectangle (cpue). The results in the table illustrate that there is strong sensitivity in the output from the calculations to the way in which effort is redistributed. If cpue of all species is used as the basis for the decision as to where to fish, the resulting landings are relatively unchanged for cod, haddock and whiting, but increased by 12% for *Nephrops*. This result is similar to that found for international effort simulations, so targeting of areas with high catch rates of mixed species outside a closed area could result in no benefit from that closed area.

Table 3.2.1 England and Wales 2003 otter trawl effort (kw hours) recorded inside and outside ICES statistical rectangles 37E9 and 38E9, located on the northeast coast of England.

	Total	Inside	Percentage
Q1	15619	8440	54%
Q2	25682	7156	28%
Q3	17042	3458	20%
Q4	9425	4074	43%
Total	67768	23128	34%

Table 3.2.2 England and Wales 2003 recorded otter trawl landings (t) of cod, whiting, haddock and *Nephrops* recorded from the North Sea.

	Cod	Whiting	Haddock	*Nephrops*
Q1	204	103	155	110
Q2	220	97	427	41
Q3	105	69	194	70
Q4	177	49	104	70
Total	706	319	880	292

Table 3.2.3 Percentage of England and Wales 2003 otter trawl catch by species recorded inside ICES statistical rectangles 37E9 and 38E9.

	Cod	Whiting	Haddock	*Nephrops*
Q1	62%	52%	47%	48%
Q2	43%	33%	36%	17%
Q3	25%	22%	21%	13%
Q4	57%	37%	35%	30%
Annual	49%	38%	34%	31%

Table 3.2.4 England and Wales 2003 otter trawl landings of cod calculated for the North Sea fishery after closure of ICES statistical rectangles 37E9 and 38E9 and removal from the fishery of the effort directed into the rectangles.

	Cod	Whiting	Haddock	*Nephrops*
Q1	78	49	83	57
Q2	125	65	275	34
Q3	78	54	153	61
Q4	76	31	68	49
Total	357	199	579	201

Table 3.2.5 England and Wales 2003 otter trawl landings of cod calculated for the North Sea fishery after closure of ICES statistical rectangles 37E9 and 38E9 and redistribution of effort according to the spatial pattern of effort located in rectangles that remain open.

	Cod	Whiting	Haddock	*Nephrops*
Q1	170	107	180	125
Q2	173	90	382	48
Q3	98	67	192	76
Q4	133	54	119	86
Total	575	319	873	335

Table 3.2.6 Percentage change in the England and Wales 2003 otter trawl landings calculated for the North Sea fishery after closure of ICES statistical rectangles 37E9 and 38E9 and removal of displaced effort.

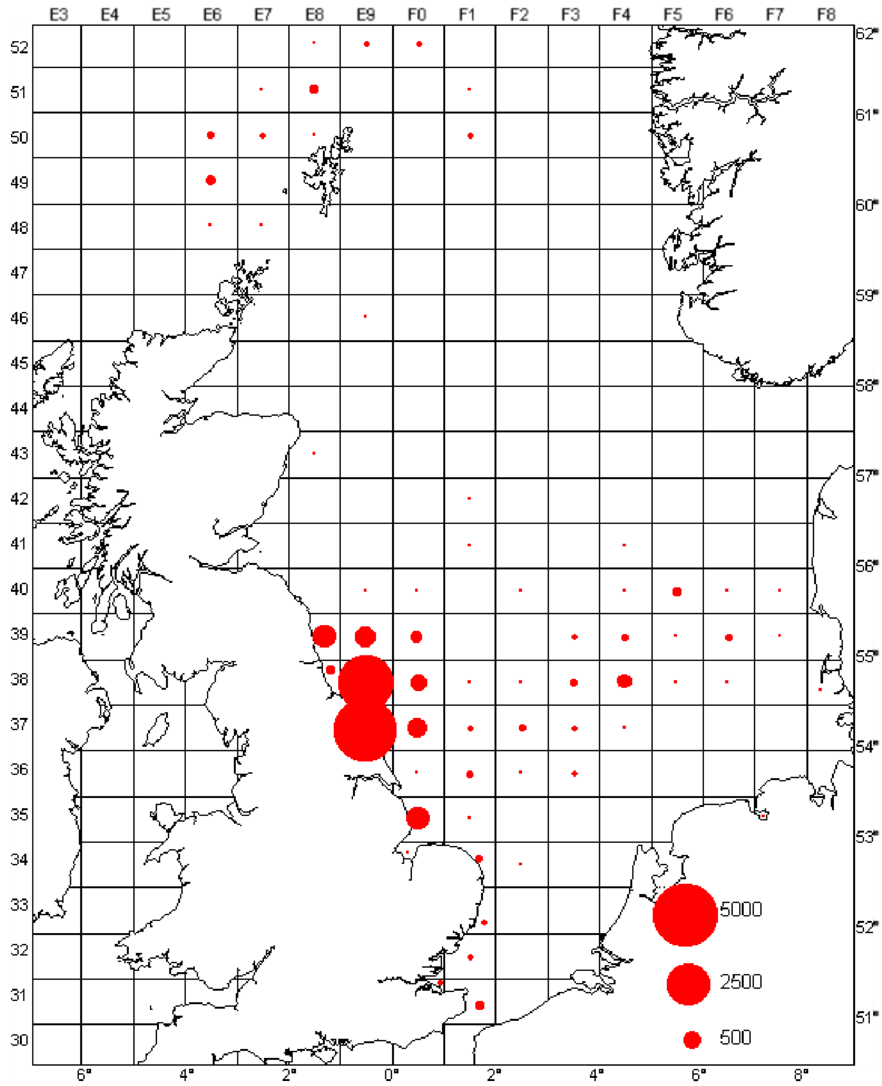
	Cod	Whiting	Haddock	*Nephrops*
Q1	-62%	-52%	-47%	-48%
Q2	-43%	-33%	-36%	-17%
Q3	-25%	-22%	-21%	-13%
Q4	-57%	-37%	-35%	-30%
Total	-49%	-38%	-34%	-31%

Table 3.2.7 Change in the England and Wales 2003 otter trawl landings calculated for the North Sea fishery after closure of ICES statistical rectangles 37E9 and 38E9, with redistribution of effort according to the spatial pattern of effort within rectangles that remain open.

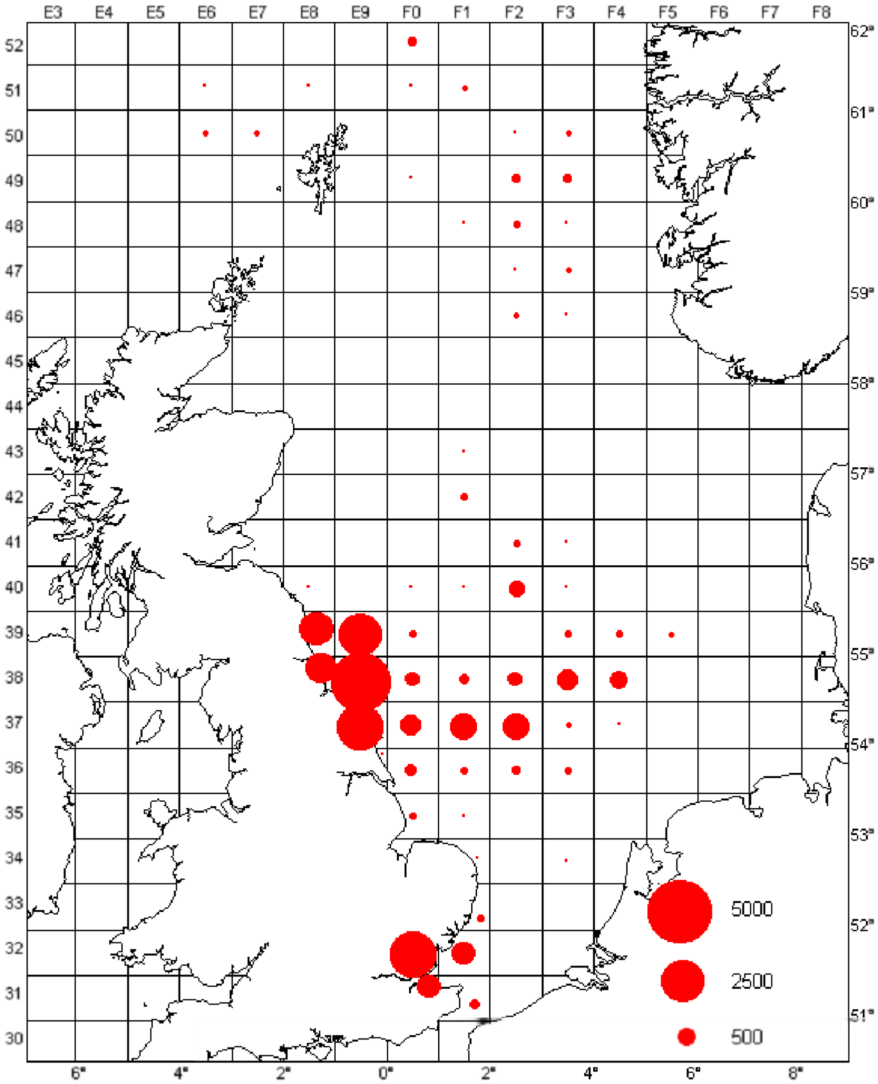
	Cod	Whiting	Haddock	*Nephrops*
Q1	-16%	4%	16%	14%
Q2	-21%	-7%	-11%	15%
Q3	-6%	-2%	-1%	9%
Q4	-25%	10%	14%	23%
Total	-19%	0%	-1%	15%

Table 3.2.8 Change in the annual England and Wales 2003 otter trawl landings of cod calculated for the North Sea fishery after closure of ICES statistical rectangles 37E9 and 38E9, with redistribution of effort according to three models, the spatial pattern of effort located in areas that remain open within and across quarters and the annual spatial pattern of the cpue of all species.

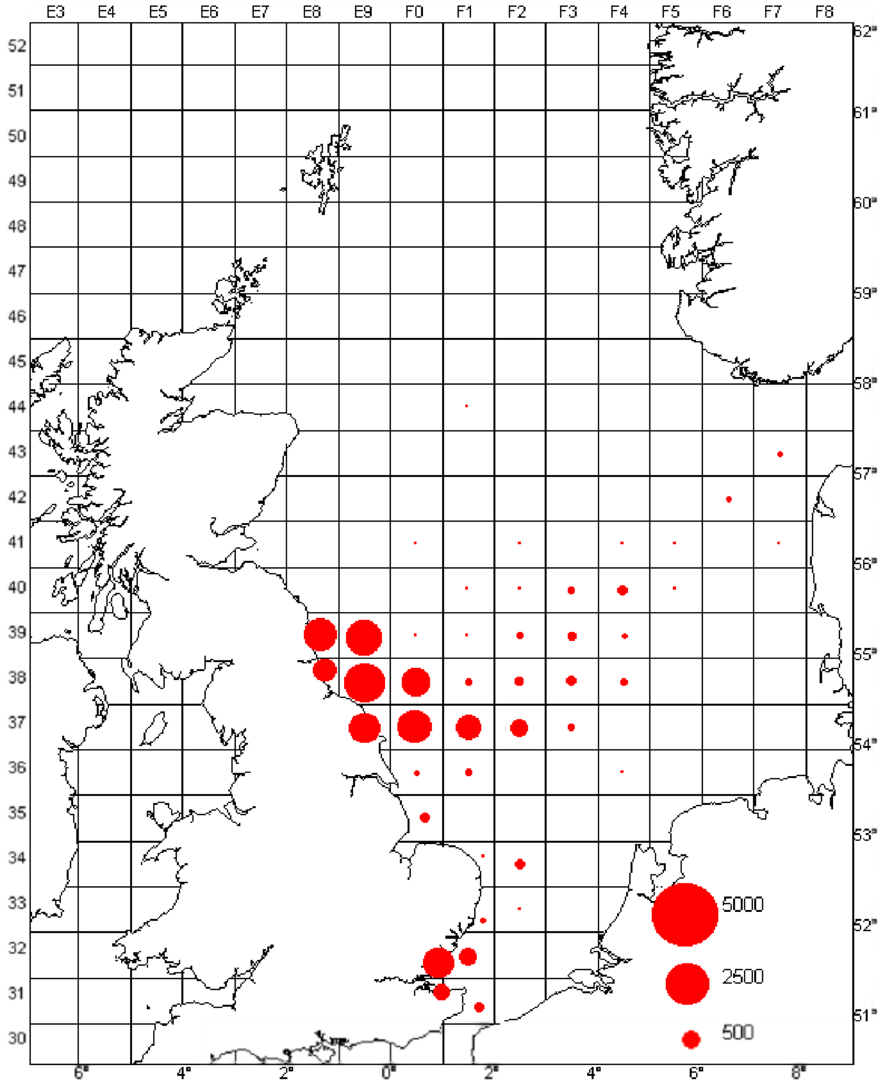
		Cod	Whiting	Haddock	*Nephrops*
Effort	Annual	-18%	0%	0%	12%
	Quarterly	-19%	0%	-1%	15%
Cpue	Annual	-3%	1%	4%	12%



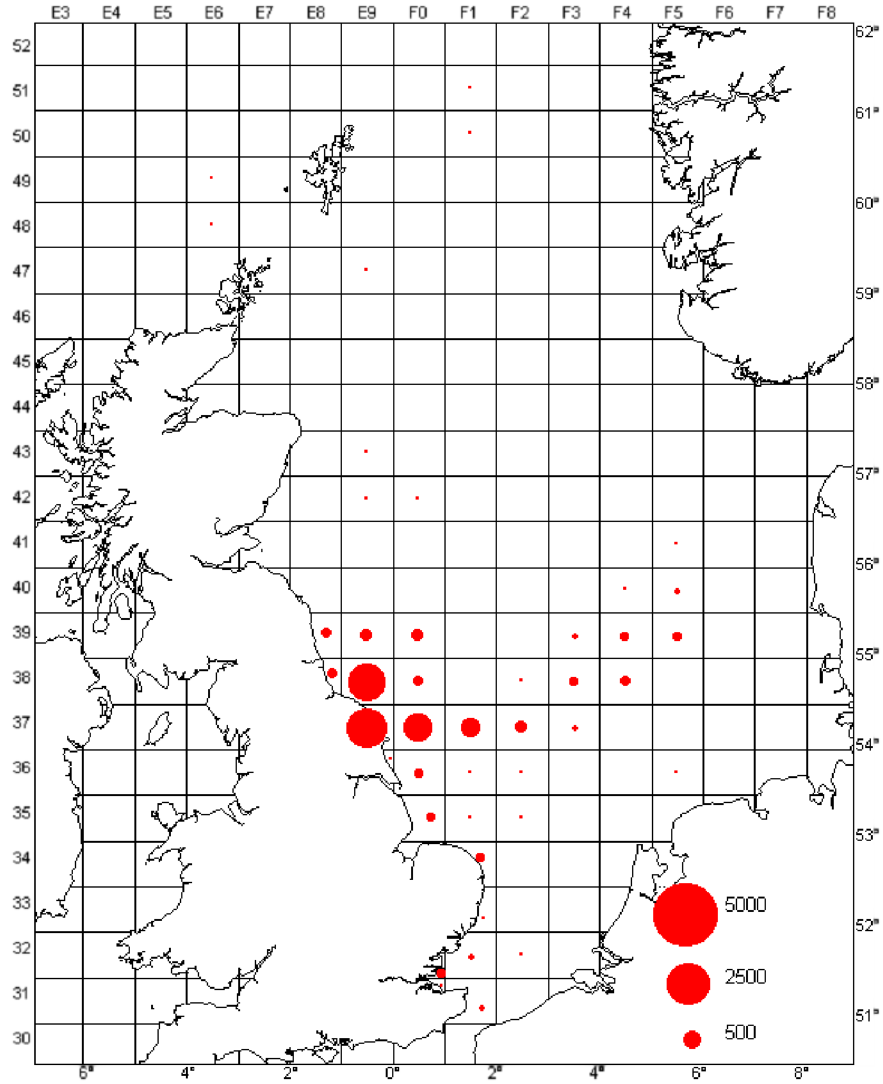
Figures 3.2.1 Recorded UK (England and Wales) otter trawl effort directed into the North Sea during quarter 1 of 2003.



Figures 3.2.2 Recorded UK (England and Wales) otter trawl effort directed into the North Sea during quarter 2 of 2003.



Figures 3.2.3 Recorded UK (England and Wales) otter trawl effort directed into the North Sea during quarter 3 of 2003.



Figures 3.2.4 Recorded UK (England and Wales) otter trawl effort directed into the North Sea during quarter 4 of 2003.

3.3 Discussion

3.3.1 Catch and effort data

The results of the model runs presented in Sections 3.1 and 3.2 are conditional on the quality of the data and assumptions used for the calculation of the catch (landings) per unit effort and effort reallocation regimes. The spatial distribution of the international landings data utilized in Section 3.1 is assumed to be representative and unbiased. An unbiased estimate of the absolute level of total landings is not essential to the model results, only the scale relative to other areas. Bias and therefore model error would be introduced by non-uniform spatial distributions of unrecorded removals resulting from discarding, under-reporting or the absence of a major fishing nation's data from the aggregated landings. If, for instance, records of discards are missing from an area, then the benefits of closing that area will be underestimated. An absence of catch data from an area attributable due to an absence of effort does not imply that there are no cod in the area and that closing it will have no beneficial effect.

The spatial distribution of survey cpue values has also been taken to be representative of the distribution of annual commercial catch rates. Survey data are subject to more noise than commercial catch rates and generally do not follow seasonal changes in stock distributions. The advantage gained by use of survey information is that the data are unbiased and provide a useful method for estimating a proxy for international effort, avoiding the significant difficulties involved in gear standardization.

Changes in stock distribution as a result of a reduction in biomass have been noted in survey results and in the distribution of catches. Therefore, the current spatial patterns of abundance are in some respects a product of overfishing. If effort reductions and closed areas allow a stock to rebuild, it would be expected that the spatial distribution would change as fish disperse away from the present concentrations. The spatial pattern of effort is also dynamic, changing with season and abundance, and would also evolve in time. The future dynamics of the North Sea cod stock after the imposition of a permanently closed area is very difficult to predict, so in order to examine and compare the effects of the closed area scenarios estimated by the simplified catch based models, the assumption was made that the current spatial patterns would hold until there was substantial recovery in stock abundance. Modelling of longer term temporal changes in the spatial distribution of cod in relation to abundance is carried out in Section 4.

3.3.2 Effort displacement

Closed area management of fish stocks is an effort relocation programme. In general, the types of closed areas that have been suggested are designed to make fishers less efficient at catching their target species. Therefore, if fishers increase either their effort expended or their efficiency to compensate for the reduced catch/revenue, the effectiveness of the closed area will be reduced.

A fisher's decision as to where to fish after being displaced from a closed area has a strong influence on the success or failure of a closed area designed to reduce fishing mortality. The models used in this analysis assume that when relocating effort from one area to another, the displaced vessels have equivalent efficiency and catch the same species in the same proportions as vessels that were fishing in targeted locations prior to the imposition of the new management regime. Vessels entering a rectangle for the first time use equivalent gear to those already fishing there, their catch rates are equivalent and do not degrade with the advent of the increased effort directed into the area, and they have sufficient quota to handle the new mixture of species that they catch.

Displacement of large amounts of effort into ICES rectangles producing high catch rates will invariably deplete the local aggregations of fish and would produce interactions (positive and negative) between vessels, potentially resulting in further unpredicted relocations. Therefore, the model assumptions will gradually break down as the size of the closed areas increases, effort becomes more concentrated, and more vessels are displaced from their home fishing grounds.

3.3.3 The design of closed areas

The closed area simulation study has used simplified models to examine the potential impact of closed areas on international and localized cod fisheries as well as the robustness of the estimated effects to the way in which effort redistributes within the areas that remain open.

The most significant impact of a closure on cod mortality rate is when the effort directed into the area is removed from the fishery completely. If the closed area boundaries are defined on the basis of areas from which high total catches are removed, the removed effort has a proportionally greater impact. Relocation of the effort into areas that remain open, derogations to fish inside it, and increases in effort or efficiency to compensate for lost revenue, all reduce the effectiveness of a closed area.

When displaced effort is relocated within the open areas in proportion to the historical distribution of effort, closed areas that are designed on the basis of total catch (such as the 2001 North Sea closed area) can reduce the fishing mortality of cod, if total effort is held constant and efficiency increases are restricted. However, if the effort is redistributed in proportion to historical cpue, fishing mortality could be increased substantially by closing the area, a consequence of the way in which the closed areas were originally defined on the basis of total catch and not catch rates. The spatial distribution of catch is a product of the distributions of effort and population abundance. Areas that do not attract high levels of effort because they provide less revenue owing to their less attractive mix of species, distance from port, etc. may have relatively high cod abundance. Vessels forced to relocate into the area by a closure will have an increased catch of cod, and mortality rates increase.

Note that, to date, the Commission of the European Union has identified the boundaries of its suggested closed areas on the level of total catches from an ICES rectangle. This design strategy could lead to increases in catches and higher mortality rates. For instance, annual closure of the 2001 closed area that was designed to prevent fishing on adult cod could, in reality, have doubled adult catches and fishing mortality. If closed areas are designed on the basis of total catch and catch rates, reductions in fishing mortality are more robust to the choices that fishers would have to make when redistributing effort.

3.3.4 The impact of closed areas in the North Sea

The model results indicate that annual closure of the area suggested by the STECF, based on the 2002 catches and that imposed in 2001, could result in increases in fishing mortality of North Sea cod. If redesigned to be robust to the variations in the resultant spatial distribution of relocated effort, then closed areas can reduce cod fishing mortality. However, the extent to which this takes place will always have a high degree of uncertainty. The most reliable approach to reducing mortality is to remove effort from the system.

The scale of mortality reductions resulting from closures of the magnitude of the 2001 and STECF area are such that the upper bound of the reduction in mortality rates is likely to be <25%. If current mortality rates of North Sea cod are as high as the values estimated by ICES (2004), closed areas of this scale would at best be estimated to halt the decline in stock size. Closed areas that deliver greater "guaranteed" reductions in cod mortality without reducing current levels of effort would require the closure of substantial areas of the North Sea. The impact of displacing significant proportions of a fleet's effort into areas remaining open would be considerable, and it could result in many traditional fishing grounds being closed and numerous conflicts of interest.

The results of the analysis of the closed area located on the northeast coast of England have established that there is a temporal effect in the impact of the closure. Catch rate of cod is greater within the area during the first and fourth quarters, and the impact of the closure would therefore be greater in winter. Cod are located in other areas during the second and third quarters, and could be targeted outside the closed area. If total effort is capped to prevent increases compensating for the loss of catch resulting from closure, moving effort between seasons could reduce the effectiveness of the closed area. Catches of, for instance, *Nephrops* will increase by closure of the rectangles. If quota is not available for the relocated vessels, there would be increased discarding and negative secondary impacts on other fisheries. As noted in Section 2, the area covers the total fishing grounds of a substantial proportion of the local fleet.

The closed areas examples simulated within this study have illustrated that if large permanent closed areas such as the 2001 Cod Box are established, analysis of international effort redistribution should be carried out at an individual fleet/métier level, and the consequences for the catches of juvenile, adult and concurrent species should be evaluated in detail.

4 Modelling the effects of closed areas on the North Sea cod fishery using a spatially explicit model

Jessica Andrews, Bill (W.) S. C. Gurney, Mike R. Heath, Alejandro Gallego, and Carl M. O'Brien

4.1 Introduction

A spatial model from Andrews *et al*. (2005), developed for the entire UK shelf (Figure 4.1.1) was used. In order to provide a baseline for scenario testing, this model was extended by the addition of spatially heterogeneous fishing mortality within the North Sea assessment region, then fitted to a data set comprising smoothed spawning stock biomass (SSB) trend data from 1985 to 2001 and the spatial distribution of SSB for 1991–1998 data determined from the ICES-coordinated IBTS survey.

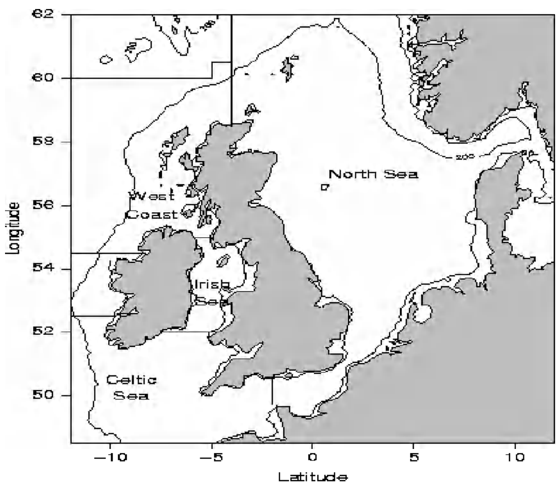


Figure 4.1.1 The model domain.

The model was run from 2001–2020, for each of the closed area scenarios defined in Section 1.3 and the effort relocation regimes described in Section 2.4. The permutations were:

1) fishing effort remains constant;
2) the 2001 cod box closures are permanent, with effort redistributed from closed areas;
3) the 2001 closures are permanent, with effort from closed areas removed from the fishery;
4) the 2002 STECF area closures are permanent, with effort redistributed from closed areas;
5) the 2002 STECF area closures are permanent, with effort from closed areas removed from the fishery;
6) UK northeast coast fishery closures, with effort redistributed from closed areas;
7) UK northeast coast fishery closures, with effort from closed areas removed from the fishery.

Model behaviour is critically dependent upon the physical and biotic environment, which consists of flow, temperature and fishing effort distribution. The future fishing effort distribution was specified as described in Section 2.4. The flow fields for the prior fitting effort were determined from a statistical characterization of HAMSOM (Hamburg shelf ocean model) output relating flows to air-pressure distribution (SNAC; Logemann *et al.*, 2004). As air-pressure data are not available for years beyond 2005, a flow-field sequence consisting of repetitions of the years 1994–2004 inclusive was constructed. Because future temperature movements are equally important and undefined, two alternative possibilities are explored. In the model runs labelled 1(a) –7(a) it is assumed that the annual spatio-temporal temperature distribution continued at the level observed in 1999. In model runs 1(b) –7(b) we assume that the form of the spatio-temporal temperature distribution continued to have the form observed in 1999, but that the annual spatial mean sea-surface temperature increased by 1° over the extrapolation period.

4.2 Model description

The key to our modelling methodology is selecting a single measure of development, namely length, to which all aspects of life history can be related. Length is chosen because there are strong direct relationships between it and maturity and mortality. To calculate fecundity and biomass, we assume a constant length-weight relationship.

The model region is broken down into spatial cells matching ICES statistical squares. Each of these cells has a specific growth rate for all non-egg stages, which is updated independently between movement updates. In each cell the biological system is updated in a series of time steps; individuals in a given developmental class before the update are obligate members of the next class immediately after it. Physical and facultative transport is represented by regular application of transfer matrices specifying relocation of individuals between cells, determined by an off-line particle tracking process described in detail by Andrews *et al.* (2005).

The model representation of the cod life cycle is shown in Figure 4.2.1. Eggs progress to pelagic larvae and juveniles, at which point they settle if possible or otherwise remain unsettled until they find a suitable region in which to settle. Settled fish eventually mature into adults, at which point they begin to spawn.

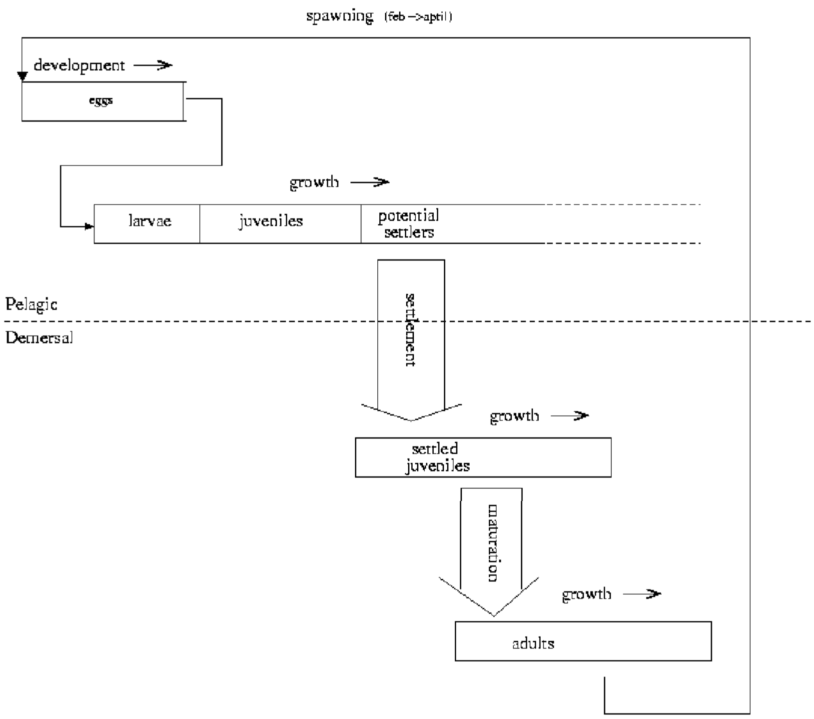


Fig 4.2.1 The biological model.

4.3 Model inputs

4.3.1 Physical environment

The physical environment for the model was determined using the temperature fields from Heath *et al.* (2003), flow fields established by SNAC (Logemann *et al.*, 2004), and bottom depths from NOAA data. SNAC is an ocean circulation model fitted to HAMSOM (Hamburg shelf ocean model) output, and uses air pressure measurements from eight weather stations to predict ocean currents.

Movement of cod was determined using transfer matrices which define redistribution and mixing at bi-weekly intervals following the methodology in Gurney *et al.* (2001), using SNAC flow-field output (Logemann *et al.*, 2004). Particle tracking was executed for each movement period by starting a number of points in each cell and allowing them to redistribute according to a time-dependent flow direction and a random component. At the end of the movement phase, the number of particles that have relocated to each cell are used to assess the probability of moving into each model cell from the starting cell. Depth of movement was estimated from depth functions in Heath *et al.* (2003), such that eggs are tracked at 6.3 m, pelagic juveniles at 25 m, fish attempting to settle at 70% of bottom depth and settled fish at 1 m above the seabed. The derived transfer matrices are used at the appropriate time in the model to capture the spatial movement of the different life stages.

Bathymetry data are used in the tracking program to ensure that the cod do not travel onto land, and for settled fish are used to prevent cod from travelling into deep water (depths >200 m). They are also used to reset tracking depth to 1 m above the seabed when the water is too shallow for the normal egg and juvenile tracking depth.

Temperature data are used to determine the length of time spent in the egg stage, and as a fitting parameter for carrying capacity and pelagic mortality. The temperature data only cover as far south as 50°, so the temperatures between 48.5° and 50° were estimated using the three southernmost data points for each longitude.

4.3.2 Cod development

Cod are tracked by length rather than age because it was felt to be more realistic to base mortality, reproduction and settlement on size. The model requires length classes that are consistent across spatial cells and have identical update times for any single cell. This can be achieved with von Bertalanffy growth curves if a consistent maximum size is chosen for the whole domain.

To fit cell-specific von Bertalanffy growth curves, data were acquired from the Cefas and FRS databases; a single maximum length and variable growth rates were estimated across cells. The estimated growth rates for all rectangles with sufficient data are shown in the first graph in Figure 4.3.1. Growth rates for cells with insufficient data for independent fitting were estimated using a correlation between fitted growth rate, latitude, longitude and annual bottom temperature.

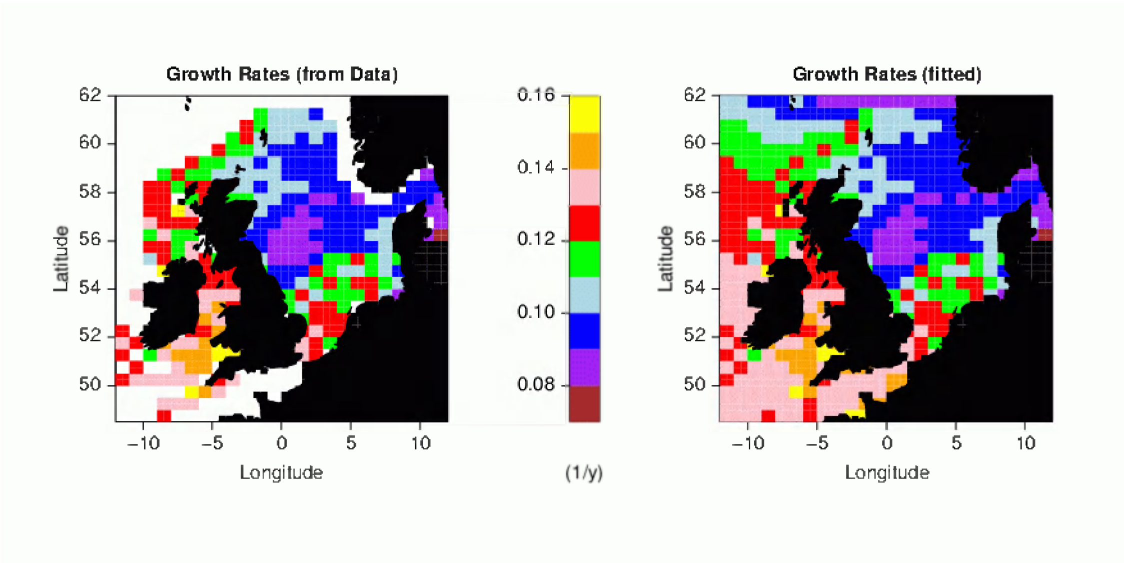


Figure 4.3.1 The left graph shows the growth rates fitted using SMALK data. The right graph shows the growth rates for the entire region, with missing data filled in using the correlation between growth and temperature and location.

The number of days spent as an egg in each spatial cell was calculated with the formula of Page and Frank (1989), using temperature data from Heath *et al*. (2003; for more detail, see Andrews *et al*., 2005).

4.3.3 Cod fecundity

Spawning is assumed to take place from February to April. The number of eggs produced during the spawning season in a cell is calculated using the number of mature fish in the cell, a one-to-one sex ratio and a weight-dependent fecundity relationship for Icelandic cod from Marteinsdottir and Begg (2002; for more detail, see Andrews *et al.*, 2005).

4.3.4 Natural mortality

ICES estimates of North Sea cod natural mortality are used to calculate natural mortality in this model. We have followed Appendix 3.2.2. of Heath *et al.* (2003) and model natural mortality as a decreasing function of age. We then used our age-length key for the North Sea to turn this into a function of length. This estimate was used for all stages in all regions once cod have settled.

For non-settled fish the natural mortality was increased by multiplying the natural mortality rate of settled fish by an assumed exponential term (see Andrews *et al.*, 2005). Non-settled fish are easy prey targets for larger settled fish, increasingly so as they grow, and will be removed from the population quickly. We represent this in the model by a rapid increase in the mortality experienced by oversized pelagic fish, and further assume that mortality of settled fish increases if the population of a cell exceeds carrying capacity (see Andrews *et al.*, 2005).

For eggs, a daily mortality rate of $Z = 0.232$, calculated using egg diameter from the relationship in Rijnsdorp and Jaworski (1990), was used. Pelagic mortality for non-egg stages is assumed correlated with environment, using a statistical relation whose parameters are determined in the fitting process (Andrews *et al.*, 2005).

4.3.5 Fishing mortality

Fishing mortality was modelled in each region (Figure 4.3.2) as

$$F_{yrlx} = f_{yr} s_l f_x$$

where f_{yr} is a correction factor calculated for each year in each assessment region, s_l a dimensionless selectivity for length, and f_x is a dimensionless multiplier for location. Selectivity at length and year multipliers for each region were calculated over all regions using the methods described in Andrews *et al.* (2005).

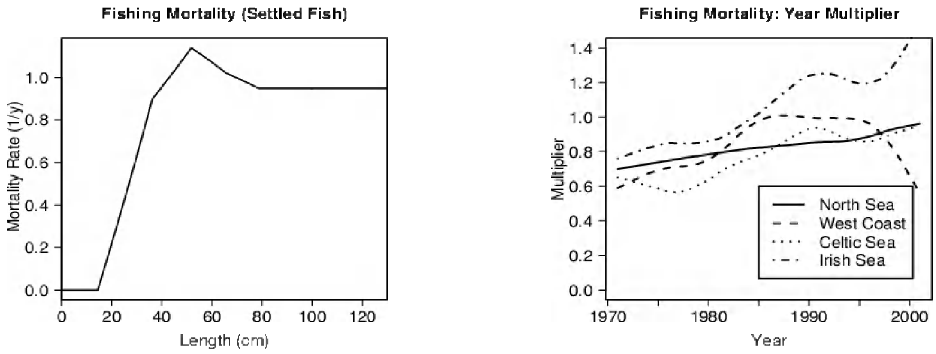


Figure 4.3.2 Components of fishing mortality.

Proxies for international fishing effort distributions were taken from the models fitted in Section 2.2 and used as fishing mortality rate multipliers for the North Sea. As there are no such data for the other regions covered by this model, it is assumed that fishing mortality is constant over those regions.

4.3.6 Movement models

There are two essentially different types of movement considered in this model: movement of settled individuals that are large and able to swim against currents, and movement of eggs and pelagic fish that are very small and therefore unable to make much headway against ocean currents and have little long-term individually directed movement. Therefore, unsettled stages in the model are assumed to drift with ocean currents at specified water depths. Cod in those stages are assumed to advect with currents with a small diffusion constant, to ensure that movement between cells will be included in the case of very slow flows.

Settled fish are assumed to have more control over their movement, so although their movement includes advection with currents, there is also a large diffusive component in their movement. Adults have further directed movement when they are assumed to move to the closest (fitted) spawning region just before the beginning of each spawning season. During the spawning season, density-dependent mortality is removed for the first two months, because during model-fitting exercises, it was found to improve fits to spatial distributions significantly.

4.4 Results

4.4.1 Model fitting

The trend fits achieved by the model for the calibration period before the scenario runs are shown in Figures 4.4.1 and 4.4.2. The model results are consistent with trends in regional spawning-stock biomass (SSB) estimated by ICES, but tend to overestimate biomass throughout the time-series.

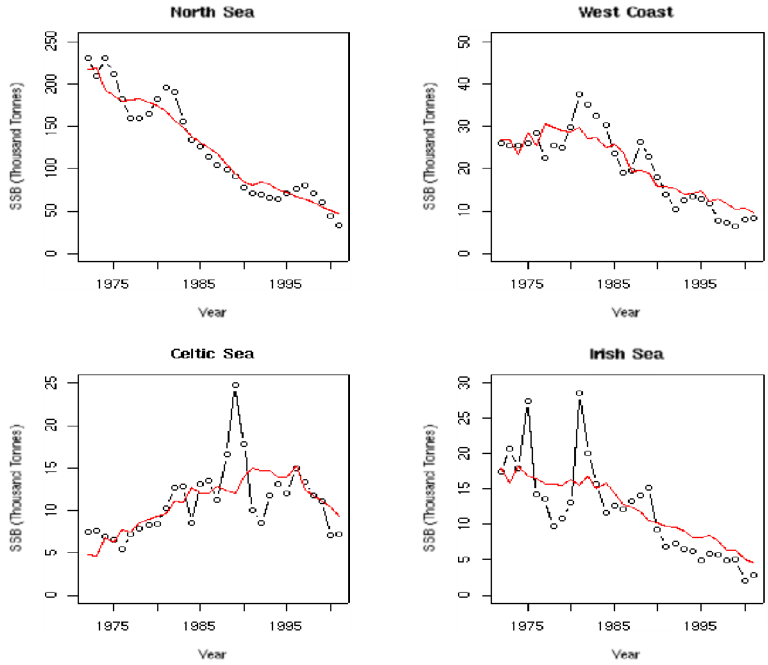


Figure 4.4.1 Fits to SSB trends. Model values are in red while ICES estimates are in black.

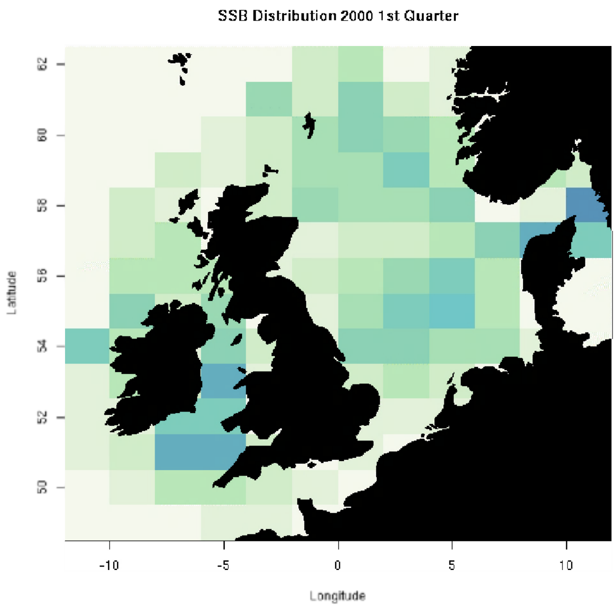


Figure 4.4.2 Fitted SSB distribution for the first quarter of 2000.

4.4.2 Future environmental conditions remain constant

Scenarios 1(a) –7(a) assume that the annual spatial temperature distribution is constant at the level observed in 2001. Table 4.4.1 presents the projected time-series of SSB for each scenario; Figure 4.4.3 illustrates the projected time-series of SSB and Figure 4.4.4 the spatial distribution of spawning stock biomass in 2015 from scenarios 1, 3, 5 and 7.

Table 4.4.1 Time-series of projected SSB ('000 t) for the North Sea resulting from the 7 closed area management scenarios assuming constant sea temperature throughout the forecast time period. (1) Fishing effort remains constant; (2) the 2001 cod box closures with effort redistributed; (3) the 2001 closures with effort removed from the fishery; (4) the 2002 STEFC area closures with effort redistributed; (5) the 2002 STEFC area with effort removed from the fishery; (6) UK northeast coast fishery closures with effort redistributed; (7) UK northeast coast fishery closures with effort removed from the fishery.

Year\Scenario	1a	2[a]	3a	4a	5a	6a	7a
2001	47	47	47	47	47	47	47
2002	37	47	50	42	45	38	38
2003	35	50	57	42	48	36	36
2004	37	61	72	47	56	40	40
2005	39	75	91	53	67	43	43
2006	42	80	100	57	73	45	46
2007	39	72	94	52	68	41	42
2008	36	74	102	51	71	39	39
2009	34	73	101	50	69	36	37
2010	31	66	94	46	64	33	34
2011	28	60	87	41	59	30	30
2012	25	55	80	37	54	27	27
2013	21	50	77	32	49	22	23
2014	20	51	81	32	49	22	22
2015	22	63	102	38	59	25	25
2016	23	79	127	44	71	28	28
2017	24	77	121	44	70	28	28
2018	23	68	107	40	64	26	27
2019	22	69	114	40	66	25	26
2020	22	68	112	39	64	25	25

4.4.3 Changing environment

Scenarios 1(b)–7(b) assume that the form of the environmental spatial distributions continued to have the structure observed in 2001, but that the annual spatial mean sea-surface temperature increased by 1° over the extrapolation period. Table 4.4.2 presents the projected time-series of SSB for each scenario. Figure 4.4.5 illustrates the projected time-series of SSB and Figure 4.4.6 the spatial distribution of SSB in 2015 from scenarios 1, 3, 5 and 7.

Table 4.4.2 Time-series of projected SSB ('000 t) for the North Sea resulting from the seven closed area management scenarios, assuming a 1° rise in sea temperature throughout the forecast time period. (1) Fishing effort remains constant; (2) the 2001 cod box closures with effort redistributed; (3) the 2001 closures with effort removed from the fishery; (4) the 2002 STEFC area closures with effort redistributed; (5) the 2002 STEFC area with effort removed from the fishery; (6) UK northeast coast fishery closures with effort redistributed; (7) UK northeast coast fishery closures with effort removed from the fishery.

Year\Scenario	**1b**	**2b**	**3b**	**4b**	**5b**	**6b**	**7b**
2001	47	47	47	47	47	47	47
2002	37	47	50	42	45	38	38
2003	35	50	56	42	48	36	36
2004	37	61	71	47	56	39	40
2005	39	74	91	53	66	43	43
2006	40	78	98	55	71	44	44
2007	36	69	90	49	65	38	39
2008	31	68	95	45	64	34	34
2009	27	65	92	42	60	30	30
2010	24	58	84	37	55	26	26
2011	20	50	77	32	49	22	23
2012	17	44	70	27	43	18	19
2013	14	41	67	24	39	16	16
2014	14	43	72	25	41	16	16
2015	16	55	94	30	51	19	19
2016	17	71	119	37	63	22	22
2017	16	68	113	35	61	20	21
2018	14	58	98	30	54	18	18
2019	12	58	104	28	54	16	16
2020	11	57	102	27	52	15	15

4.5 Discussion

The scenario tests have involved assumptions as to future variations in sea surface temperature (SST). However, within the limitation of the assumption that the spatial pattern of SST remains constant, our results show reasonable consistency between the extrapolations that assume that SST remains constant over time and those which assume that mean SST rises by 1° over the extrapolation period.

With no change in fisheries management policy (Scenarios 1a and 1b) the North Sea cod stock decreases by approximately 60% over the projection period, with the spatial distribution of the stock remaining relatively unchanged. However, in other assessment areas we predict a significant rearrangement of stock distribution, with stocks in the West Coast area rising relative to those in the Celtic and Irish Sea areas, and the Celtic Sea stock falling in relation to the North Sea stock. These latter effects are clearly dependent on our temperature assumption, with much more pronounced changes being observed under the assumption that mean SST increases by 1° over the period.

Tables 4.4.1 and 4.4.2 clearly show the considerable difference in the overall effect of the various closure policies, with the most effective policy, the removal of effort from the 2001 closed area (scenario 3), resulting in an increase in SSB of 230%, compared with 148% for the next most favourable, removal of effort from the STECF area (scenario 5), and a decrease of 60% for no closures. The distribution maps demonstrate that although closure of a given region produces some increase in local spawning stock, the major change of the more effective closure policies is to strengthen the stock in the southeastern part of the North Sea – both by increasing peak densities in the area and by increasing the spatial extent of the region of high abundance.

The most effective closure policies are those that are accompanied by an equivalent reduction in total fishing effort.

The northeast coast closure produces no increase in the whole North Sea SSB even if effort is relocated, but rather stems the tide of decrease a little.

The predictive capability of the model used here could be significantly improved by

- Formulating and calibrating a sub-model describing the relationship between individual development and the physical and biotic environment to which the individual has been exposed. A preliminary view would envisage development rate as a unique function of temperature, but it seems likely that a model that is fully fit for this purpose would need to include elements of individual energetics.

- Formulating and calibrating a dynamic sub-model describing the spatial distribution of fishing effort, and more particularly the manner in which this effort is redistributed in response to economic and regulatory cues.

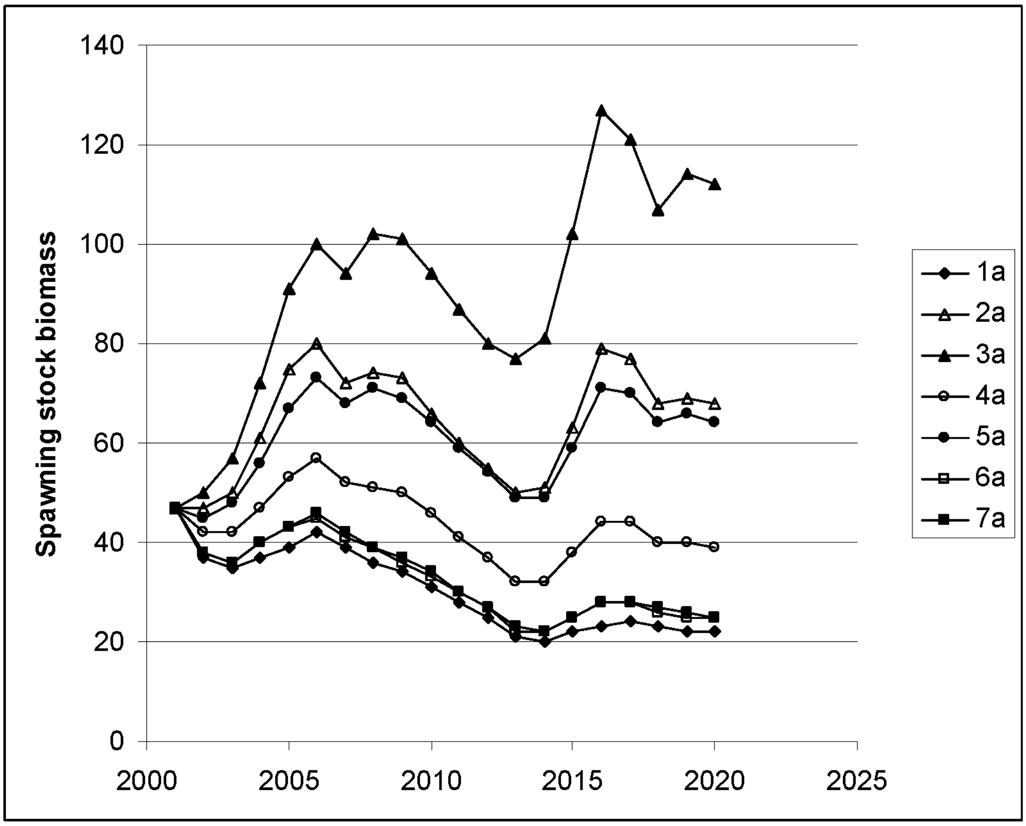


Figure 4.4.3 Time-series of projected SSB ('000 t) for the North Sea resulting from the seven closed area management scenarios assuming constant sea temperature throughout the forecast time period. (1) Fishing effort remains constant; (2) the 2001 cod box closures with effort redistributed (3); the 2001 closures with effort removed from the fishery; (4) the 2002 STEFC area closures with effort redistributed; (5) the 2002 STEFC area with effort removed from the fishery; (6) UK northeast coast fishery closures with effort redistributed; (7) UK northeast coast fishery closures with effort removed from the fishery.

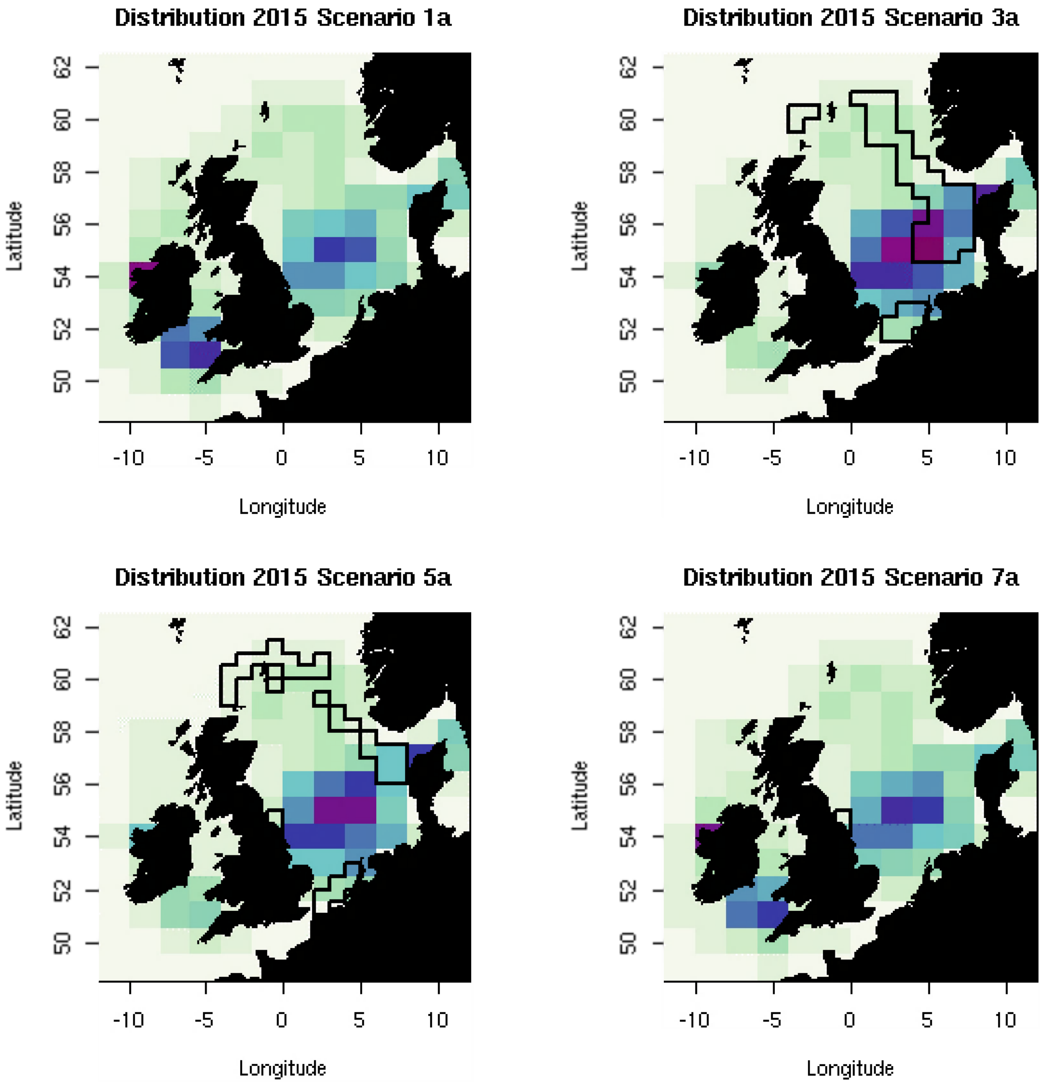


Figure 4.4.4 The 2015 spatial pattern of projected SSB ('000 t) for the North Sea resulting from the closed area management scenarios assuming constant sea temperature throughout the forecast time period. (1) Fishing effort remains constant; (3) the 2001 closures with effort removed from the fishery; (5) the 2002 STEFC area with effort removed from the fishery; (7) UK northeast coast fishery closures with effort removed from the fishery.

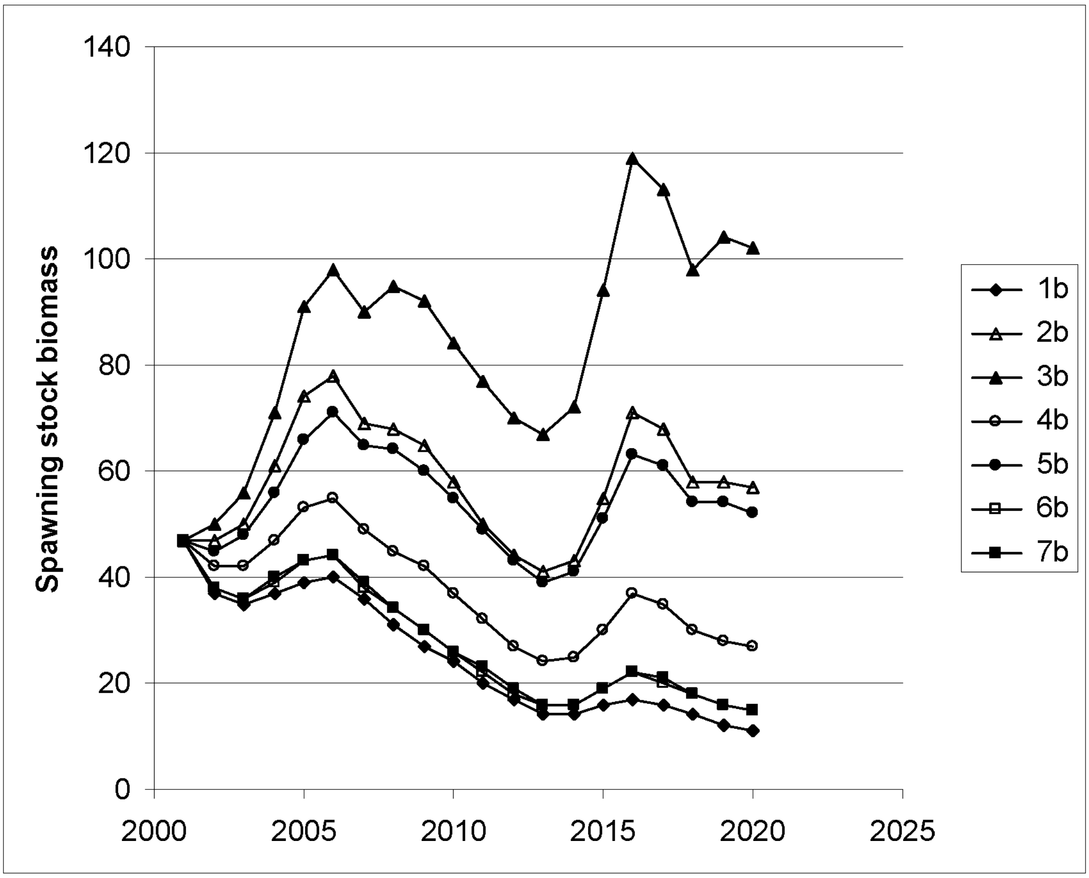


Figure 4.4.5 Time-series of projected SSB ('000 t) for the North Sea resulting from the seven closed area management scenarios, assuming a 1° rise in sea temperature throughout the forecast time period. (1) Fishing effort remains constant; (2) the 2001 cod box closures with effort redistributed (3); the 2001 closures with effort removed from the fishery; (4) the 2002 STEFC area closures with effort redistributed; (5) the 2002 STEFC area with effort removed from the fishery; (6) UK northeast coast fishery closures with effort redistributed; (7) UK northeast coast fishery closures with effort removed from the fishery.

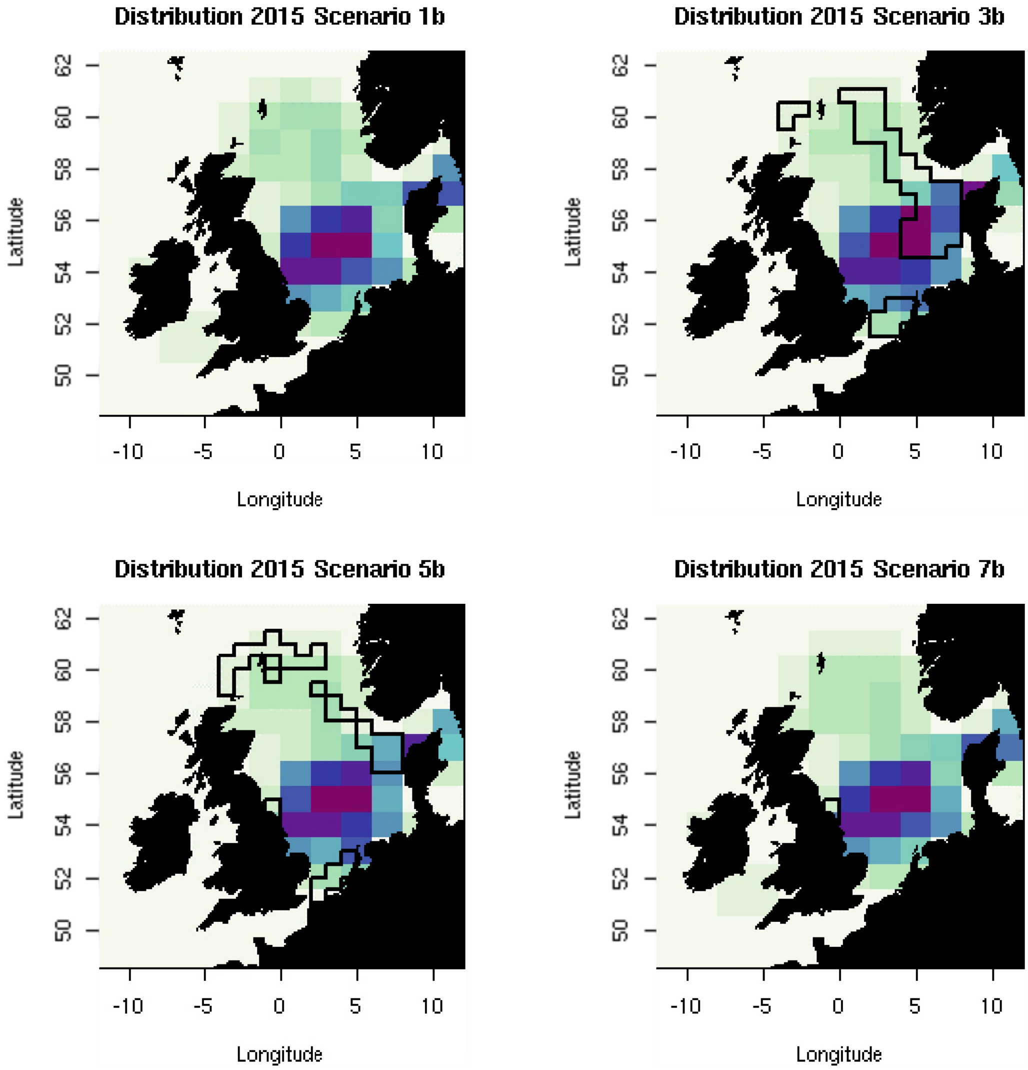


Figure 4.4.6 The 2015 spatial pattern of projected SSB ('000 t) for the North Sea resulting from the closed area management scenarios, assuming a 1° rise in sea temperature throughout the forecast time period. (1) Fishing effort remains constant; (3) the 2001 closures with effort removed from the fishery; (5) the 2002 STEFC area with effort removed from the fishery; (7) UK northeast coast fishery closures with effort removed from the fishery.

5. Modelling the effect of closed areas on the benthic invertebrate community of the North Sea

Jan G. Hiddink

A theoretical model is used to examine the large-scale impact of eight area closure scenarios in the North Sea on the biomass, production and species richness of benthic invertebrate communities. Four scenarios evaluated area closures where fishing effort was redistributed from closed to open areas, and another four scenarios considered the same closures but with the difference that fishing effort in the closed areas was completely removed from the fishery. Six of the analyses were done for the whole North Sea, extrapolating the model to areas where it has not been validated. Therefore, the results have to be interpreted with caution. The impact of area closure on benthic invertebrate communities was evaluated over a 25-year period. When fishing effort was redistributed from closed to open areas, benthic production was negatively impacted in three of four scenarios, and biomass was negatively affected in all scenarios. Removing fishing effort from the closed areas without redistribution had a positive effect on benthic invertebrate biomass and production. Large-scale distribution of species richness was hardly affected by area closures for any scenario. The results of the study show that the redistribution of fishing effort from area closures that are not accompanied by associated effort reduction can have a negative effect on the biomass and production of benthic invertebrate communities.

5.1 Introduction

Fisheries research has traditionally been driven by the requirement to manage stocks of harvested species. However, research in the last two decades has increasingly focused on the environmental effects of fishing on non-target fauna and marine habitats (Hall, 1999; Sinclair and Valdimarsson, 2003), and it has assumed increasing importance with the desire to invoke more ecosystem-based approaches to the sustainable use of marine resources (Murawski, 2000; Pikitch *et al.*, 2004). The impacts of bottom trawls on the seabed are a particular environmental concern, because they have the potential to modify seabed habitat, disrupt foodweb processes and extirpate vulnerable species (Hall 1999; Kaiser and De Groot 2000).

In coastal seas, the major sources of seabed disturbance are near-bed currents, wind-induced waves (Hall, 1994) and bottom trawling and dredging (Jennings and Kaiser, 1998). Fishing vessels that target flatfish, gadoids, scallops and other benthic animals use beam trawls, otter trawls and scallop dredges that can disturb the seafloor to varying depths (from 2 to 20 cm) and kill a significant fraction of the benthic fauna in the path of the fishing gear. In a global analysis of the effects of bottom fishing, Collie *et al*. (2000) found that one trawl reduced the mean abundance of animals by up to 55%. As benthic invertebrates constitute the major food source for many commercially exploited fish species, the effects of trawling on the production of benthic communities are of direct relevance for the management of commercial fish stocks in addition to other ecosystem functions the benthos may support (Widdicombe *et al.*, 2004).

In general, individuals and species of smaller body size are less severely affected by trawling than those that are larger, because smaller species are impacted less by a given rate of mortality because they have higher intrinsic rates of increase (Duplisea *et al.*, 2002). As these smaller animals have a higher production to biomass ratio (P/B; Brey, 1990), trawling reduces biomass more than production (Jennings *et al.*, 2001; Hermsen *et al.*, 2003). A size-based model developed by Duplisea *et al.* (2002) was used to assess trawling impacts on the benthos and indicated that smaller animals are unlikely to have the capacity to utilize all the resources that become available when the abundance of larger competitors is reduced. Therefore, trawling reduces secondary production by benthic communities and changes the distribution of production across body size classes, and may alter ecosystem processes such as the use of primary production by the benthos and the provision of food to higher trophic levels.

Here, a theoretical model validated with extensive field data (Duplisea *et al.*, 2002; Hiddink *et al.*, submitted-a, submitted-b) is used to examine the large-scale impact of different area closure scenarios in the North Sea on benthic biomass and production. The size-based model consisted of 37 body size classes of animals. Sediment, shear stress, erosion and chlorophyll content of the sediment were included as habitat features that affected the growth and mortality of the animals. The model was run to equilibrium in 1500 time steps of 30 days, using 2003 trawl intensity as a baseline level of physical disturbance by bottom trawling. The new effort distribution was then implemented and the development of biomass and production followed for 25 year (300 time steps). The large-scale impact on biomass and production was examined by summing these parameters over the whole evaluated area, and comparing values with the trawling impact in baseline year 2003.

5.2. Methods

5.2.1 Scenarios

Eight area closure scenarios are evaluated, four for area closures in which fishing effort was redistributed to areas outside the closed area, and four for the same area closures where fishing effort in these areas was removed entirely from the fleet. The modelled redistribution patterns of effort are described elsewhere in this report (section 2). The first six scenarios were evaluated at the ICES rectangle scale, across the whole North Sea, using international fleet effort. The last two scenarios were evaluated at a 25 km^2 scale using English fleet effort data.

The scenarios examined were:

a) (i) Relocation of the international effort from the 2001 area (2001 cod box closure)

(ii) Removal of the international effort from the 2001 area (2001 cod box closure)

b) (i) Relocation of the international effort from the 2002 area from which 60% of catches were taken (STECF closure)

(ii) Removal of the international effort from the 2002 area from which 60% of catches were taken (STECF closure)

c) (i) Relocation of the international effort from two squares on the northeast coast (NE closure)

(ii) Removal of the international effort from two squares on the northeast coast (NE closure)

(iii) Relocation of the English effort from two squares on the northeast coast (NE closure)

(iv) Removal of the English effort from two squares on the northeast coast (NE closure)

5.2.2 Model of trawling impacts on size-structure

Our model of soft-sediment benthic community responses to trawl disturbance was developed using the approach of Duplisea *et al.* (2002). The basic assumptions, additions and modifications are described. State variables in the model were defined on the basis of body size and three faunal groups: meiofauna (MEIO), soft-bodied macrofauna (SOFT) such as polychaetes, and hard-bodied macrofauna (HARD) such as bivalves and crustaceans. The model contained 37 state variables; 5 MEIO (0.001–0.2 mg wet weight), 16 SOFT (1.9–500 mg), and 16 HARD (50–60 000 mg). As the 37 state variables represented only three groups that differed in body size, there were only three sets of parameters and the model is relatively simple in both structure and parameter demand. Growth of the population biomass in each body size and organism type compartment was modelled by modifying the basic Lotka–Volterra competition equations to give the population biomass flux for a compartment:

$$\frac{dB_i}{dt} = B_i r_i \left(\frac{C_i - B_i - \alpha_{ij} B_j}{C_i} \right) - B_i Mort_i \qquad (1)$$

where *i* and *j* are competing groups of organisms, B_i the biomass of animals in compartment *i*, *r* the specific growth rate, C_i the carrying capacity of compartment *i*, B_j the biomass of competitor *j*, α_{ij} the competitive influence of a unit of the competitor *j* biomass on the carrying capacity of population *j* and $Mort_i$ the mortality rate of compartment *i*. SOFT and HARD were assumed to be in competition, but MEIO were assumed not to compete with either of the other groups. Table 2 of Duplisea *et al.* (2002) summarizes all parameter values for all size classes of the three faunal groups

The interaction between habitat type and trawling effects was modelled by including relationships between growth and mortality and the environment in the model. Included are the effect of sediment type on trawling mortality, bed shear stress on population growth rate, chlorophyll *a* content of the sediment on carrying capacity, and (4) sediment erosion on mortality.

5.2.2.1 Trawling mortality in different sediments

The Gaussian curve describing the relationship between body size and trawling mortality in Duplisea *et al.* (2002) was replaced by a function that described the effect of sediment type rather than body size on mortality rate. Mortality caused by a single trawl on different sediments was estimated from a meta-analysis of experimental studies by Collie *et al.* (2000). This is currently the most extensive quantitative database describing the direct effects of trawling on the population size of specific benthic organisms. Only those studies that examined the effects of otter trawling and beam trawling on gravel, mud, muddy sand and sand habitats in the subtidal zone were included in the analysis. Because the aim was to estimate the mortality caused by a single trawl pass, only studies that examined the effect of a single trawling event and that sampled the substratum within 10 days of that event were included in the analysis. As one trawling event could consist of one or more trawl passes, the effect size was corrected assuming that the passage of every trawl reduced the population size by a similar fraction. Each species in the database was assigned to the classes MEIO, SOFT or HARD. The impact of trawling on a species (% increase or reduction after trawling compared with the condition before trawling or a control area) was $\ln(x+101) - \ln(101)$ transformed to normalize the data (Collie *et al.*, 2000). The impact of one trawl pass was calculated from the coefficients of a two-way ANOVA, with sediment type and faunal group as factors.

After the analysis, figures were back-transformed to give percentage mortality caused by one trawl pass. In all, 381 records from 24 experimental manipulations from 10 studies were used. An attempt to fit a body-size-dependent mortality curve based on these data was not successful, so no size-dependence was assumed. For meiofauna, insufficient data (n = 2 studies) were available to give separate values for different sediments, so one common value was used. On average, MEIO density was reduced by 18.6% per trawl pass. Mortality rates were greater for HARD than for SOFT, and were greater for coarser sediments (gravel, sand) than for finer sediments (mud, muddy sand)). There was a significant effect of sediment ($F_{3,376} = 4.9$, $p = 0.0025$) and faunal group ($F_{1,376} = 5.4$, $p = 0.0205$) on trawling mortality. Contrary to the original model (Duplisea *et al.*, 2002), trawling mortality was implemented as a discrete, once yearly event, as opposed to an instantaneous rate. This is probably realistic, given that most trawling in the North Sea appears to be clustered in time on a small scale. There are, however, no strong seasonal trends in fishing effort in the southern North Sea at larger scales by vessels using beam trawls that are the main gear type (Jennings *et al.*, in press). It was assumed that there was no direct effect of sediment on benthic growth or mortality rate because I do not know of a mechanism to explain such a relationship. Instead I assumed that any correlations between sediment type and benthic community biomass could be explained through the correlation of sediment type with shear stress, chlorophyll *a* content and erosion rates.

5.2.2.2 Shear stress

Currents and the associated seabed shear stress can influence food availability for benthic communities (Jenness and Duineveld, 1985) and benthic secondary production (Warwick and Uncles, 1980; Wildish and Peer, 1983). High shear stress results in scouring and high current velocities inhibit feeding activity, whereas water movement at the seabed is necessary for the supply of food to the benthos. Below a certain current velocity threshold, food particles transported from other areas may begin to sink to the seabed, where they become available as food to the benthos (Creutzberg, 1984). Therefore, it was assumed that bottom shear stress affected the biomass of benthic communities through growth rate. A quantile regression showed that infaunal biomass at 209 stations (VLIZ 2003) is limited by M_2 bottom shear stress (generated by the M_2, semidiurnal, component of the tidal current) according to a second order polynomial optimum relationship (90^{th} quantile, p = 0.034, R_1 = 0.053; for more information on quantile regression see Cade *et al.*, 1999). There was no interaction between the effect of shear stress and chlorophyll *a* content of the sediment (see 2.1.3) on the on-benthos biomass. The relationship between growth rate and shear stress was modelled by multiplying the density-dependent growth rate as calculated by the Lotka-Volterra equation with a factor that describes the effect of shear stress on the growth rate. The relationship was modelled as a Gaussian curve according to:

$$G = G_{\min} + (G_{\max} - G_{\min})e^{\frac{(S-S_m)^2}{-V}} \quad (2)$$

where G is the shear-dependent growth-rate modifier, G_{min} the minimal growth rate (0.95), G_{max} the maximal growth rate (1.2), S the shear stress$^{0.5}$, S_m the shear stress$^{0.5}$ at which the maximum growth rate is reached (0.5), and V is the variance of the Gaussian curve (0.075).

5.2.2.3 Carrying capacity

The carrying capacity level in the model is simply a scaling factor, i.e. absolute levels do not affect the model outcomes, but the relative differences between size classes and stations are important. The biomass of benthic communities in a habitat can be limited by the input of food (Beukema and Cadee, 1997). The base of the benthic food chain is generally fuelled by microalgae. A Type II functional response was used to describe how benthic biomass (g ash free dry weight m^{-2}) in the North Sea was limited by the chlorophyll *a* content of the sediment, using data from the North Sea Benthos Survey in April/May 1986 (VLIZ, 2003), using upper boundary analysis (Blackburn *et al.*, 1992): *Infaunal biomass* = 54.6 *chlorophyll a* / (1 + 1.72 *chlorophyll a*), r^2 = 0.66, $F_{1,12}$ = 23.3, p = 0.0004).

5.2.2.4 Sediment erosion attributable to disturbance by waves and tides

Additional to the normal mortality rates, which relate to body size, sediment movement attributable to wave action caused by wind and tides can be a major cause of mortality among benthic animals, and has been shown to affect secondary production (Emerson, 1989). The relationship between sediment erosion and benthos mortality was parameterized using mortality and erosion data from Zuhlke and Reise (1994) and Yeo and Risk (1979), and can be described by the equation: *Benthos population reduction* (%) = 0.14 *erosion depth* (cm) (r^2 = 0.34, n = 67, p<0.0001). MEIO, SOFT and HARD were assumed to be affected in the same way because there were no data to justify discriminating among these groups. Annual mortality rate attributable to sediment erosion was modelled as:

$$\textit{Erosion mortality} = 1 - (1 - \textit{mortality per storm})^{\textit{number of storms}}.$$

5.2.3 Relationships between body mass and species richness

To relate the reduction in biomass of a body mass class to the loss of a number of species, it was necessary to describe the relationship between the number of species in each body mass class and body mass and to identify a threshold biomass reduction at which species loss would be anticpated.

The relationship between species richness and body mass was determined from the slope of a regression of the number of species in $\log_3$ body mass classes against log-body mass. All species of free-living infauna and epifauna recorded in the central North Sea were used to determine the relationship, and the heaviest body mass class to which species were assigned was based on their maximum historically recorded body mass (because maximum observed body mass in trawled areas will fall in response to elevated mortality). Epifauna were defined as those species that live on the seabed or burrow in it temporarily, and infauna were defined as those for which parts of the body remains more or less permanently in the substratum. This number included all species found in a body mass class, not just mature adults. Therefore, smaller body mass classes have more species than large classes, because they contain both juveniles of large species and adults of small species. As a species is found in its adult body mass class and in all smaller body mass classes as juveniles, the number of adult species in a body mass class can be described by the slope of the relationship describing species number against body mass. The number of adult species per body mass class in the model was described by the derivative of the relationship between number of species and body mass (*Number of adult species per* $\log_3$ *body mass* = 65 exp (–0.35 $\log_3$ *body mass*)) (Hiddink *et al.*, submitted-a).

Species were assumed to be lost if the adult biomass fell by 95% from non-impacted levels. Adults of each species were assumed to be present only in the heaviest $\log_3$-body mass class, because Charnov *et al.* (1990) predicted that the average ratio of length at maturity to maximum length is 2/3 for species for which growth is described by a Von Bertalanffy growth equation. Assuming that body mass increases linearly with the cube of length, the predicted body mass at maturity is 30% of maximum body mass, so almost all mature individuals of a species will be found in the top $\log_3$ body mass class of its size distribution

In the model, the loss of adult species did not affect the abundance of the smaller size classes. Despite local loss of a species, it was assumed that the biomass of the juveniles of species lost could be replaced by juveniles and adults of smaller species.

Loss of diversity was reported as a proportional loss from the total number of species present in body mass classes >0.2 g. This approach was adopted because the number of local species will be smaller than the number of regional species and the model needed to be applied consistently at different scales.

The average non-impacted biomass per $\log_3$ body mass class was obtained by running the model with trawling set to zero for the Dutch and British sectors of the North Sea, in the area south of 56 °N, because this was the area for which all environmental data were available. The areas inside the coastal 12 nautical mile zone and the plaice box were excluded from the analysis.

5.2.4 Habitat data for the North Sea

The scenarios were evaluated at the ICES rectangle scale for the whole North Sea (Figure 5.2.1) and at a scale of 25 km^2 for the UK North Sea south of 56ºN (Figure 5.2.2).

5.2.4.1 Small scale

Data on sediment, depth, shear stress and chlorophyll *a* content of the sediment were required to validate the model and to make large-scale predictions of the effects of trawling on biomass and production in the North Sea. Sediment data were obtained from digital British Geological Survey (BGS) sediment maps for the North Sea (BGS 2002). As the relationship between sediment and trawling mortality was parameterized for four sediment classes only (gravel, mud, muddy sand, sand), the BGS classification (Wentworth Folk classification in 15 classes) was simplified into these four only. All sediments with gravel content of >5% were classified as gravel. For those with <5% gravel, sediments with a sand:mud ratio of more than 9:1 were classified as sand, with a sand:mud ratio between 1:1 and 9:1 as muddy sand, and with a sand:mud ratio smaller than 1:1 as mud.

Depth was interpolated from a data set of 1 nautical mile resolution. A two-dimensional hydrodynamic model of the northwest European shelf, originally developed at the Proudman Oceanographic Laboratory, UK, was used to predict the depth-mean M_2 tidal current at a spatial resolution of 1/8° longitude by 1/12° latitude (approximately 8 km). Bed shear stresses attributable to the M_2 tide were then calculated using a quadratic expression, with bed stress dependent on the predicted maximum ellipse current and an appropriate bed friction coefficient, that is assumed to have a value of 0.0025 (J. N. Aldridge, Cefas, unpublished data).

Sediment erosion rates attributable to the combined effects of currents and wind-induced waves were modelled as the maximum erosion for a single event, i.e. the maximum erosion depth over a whole year. They do not take account of bedload transport or modifications to current associated with bedforms (Cefas, unpublished data). On average, there are 4.75 major storms of similar magnitude in a year (Cefas, 2004)

The chlorophyll *a* content of the sediment was interpolated from the data for 209 stations in the North Sea spaced at 0.5° of longitude and latitude (VLIZ 2003). Data were interpolated at a scale of 9 km^2 using a Universal Transverse Mercator Projection zone 31, prior to analysis.

5.2.4.2 Environmental data ICES rectangle scale

Environmental data at the ICES rectangle scale were extracted by taking environmental conditions in the centre of each rectangle from the small-scale data sets described above. Additional sediment data were obtained from AWI Mar-GIS (http://www.awi-remerhaven.de/GEO/Marine_GIS/MARGIS.htm). No erosion data were available north of 56°N, so these missing data were extrapolated using the relationship between erosion, shear stress and depth from the area south of 56°N (Erosion (cm) = –0.92 – 0.096 * shear stress (Pa) – 0.009 * depth (m) + 0.019 * shear stress * depth; r^2 = 0.71, $F_{3,51}$ = 42.5, p<0.001).

Average trawling intensity in each rectangle was calculated assuming that 1 h of fishing represented 0.22 km^2 trawled by both beam and otter trawlers (see below). Trawling intensity was therefore calculated as:

Trawling intensity = h fished * 0.22 / area rectangle (km^2)

The sea area of each ICES rectangle was calculated in the UTM-zone 31 projection. The model area used in the large-scale calculations is shown in Figure 5.2.1.

5.2.5 Small-scale distribution of trawling effort

Fishing effort is patchy within ICES rectangles, and this patchiness is important when evaluating trawling impacts. Because the response of benthic community biomass to trawling is not linear, evaluating impacts at a large spatial scale causes an overestimate of the impact of trawling (Dinmore *et al.*, 2003).

Only the impact of the UK otter trawl and beam trawl fleets on benthic communities was considered for scenarios c(iii) and c(iv). Small-scale effort distribution of beam trawlers was determined using VMS observations for 2003. From 1 January 2000 on, all EC fishing vessels >24 m were required to report their location, via satellite, to monitoring centres in their flag states, at 2-h intervals. The only exception is made for vessels that undertake trips of <24 h or that fish exclusively within 12 miles of the coast (Dann *et al.*, 2002). The VMS data do not indicate whether a vessel is fishing when it sends position data, but the speed of a vessel can be derived from two consecutive records. Accordingly, vessels travelling at speeds greater than 8 knots and stationary vessels were eliminated, because these vessels were assumed not to be fishing (for more detail, see Dinmore *et al.*, 2003). At the ICES rectangle scale, there is a positive relationship between the numbers of VMS observations and the hours fished according to logbooks (VMS record = $0.3934x + 13.4$; $r^2 = 0.76$; Figure 5.2.3). This relationship was used to calculate the hours trawled per 25 km^2 cell from the number of records in a cell in 2003.

Small-scale effort distribution of otter trawlers was determined using fishery protection overflight observations. As otter trawlers are often smaller than 24 m and fish extensively within the 12 mile zone, VMS observations did not correctly represent their effort distribution. At the ICES rectangle scale, there was a positive relationship between the numbers of observations from the air and the hours fished according to logbooks (overflight observation = 0.0151 h fished logbook – 1.0897; r^2= 0.72;Figure 5.2.3). This relationship was used to calculate the hours trawled per 25 km^2 cell from the number of records in a cell in 2003.

For the calculation of trawling intensity (y^{-1}) from the number of hours fished, it was assumed that all trawlers fished at a speed of 5 knots, with a total fishing gear width of 24 m (two beam trawls each 12 m wide or one otter trawl 24 m wide). Therefore, 1 h fishing per year represents a trawled area of 0.22 km^2.

Within rectangles, it was assumed that the relative small-scale distribution of trawling effort did not change with the large-scale changes in effort between rectangles. Therefore, the small-scale distribution of trawling effort during area closures was calculated by multiplying the small-scale effort by the relative ratio of modelled to 2003 trawling effort per rectangle. The resulting small-scale effort distribution in a situation without closures is presented in Figure 5.2.1.

5.2.6 Analysis

Trawling was implemented as a once yearly event in the model. Therefore, modelled biomass and production are presented as 12-month running averages. Species diversity at t = 1800 (25 years after closure) is presented as a cumulative plot of the area against relative species richness.

5.3. Results

5.3.1 Redistribution of effort: biomass and production

When fishing effort was redistributed from closed to open areas, the benthic community in the closed area recovered, whereas the community in the open area was more strongly impacted by trawling (Figure 5.3.1). The net effect of the area closure therefore depends both on the recovery rate in the closed area and the increased impact of trawling in the open area and the size of the closed area. When closing areas, the modelled impact of trawling on biomass and production ranged between a 1% increase and an 8% decrease relative to the non-impacted community, which corresponded to a 10–20% change in the impact of trawling.

Closing part of the northeast coast while relocating the effort (scenario c(i)) had a small positive effect on production and a small negative effect on biomass of benthic communities when evaluated for the whole North Sea at the ICES rectangle scale. All other scenarios had a negative effect on benthic biomass and production. For the scenario in which effort is redistributed from the 2001 closure (a(i)), benthic biomass started to recover after 10 years, although the benthic community had not fully recovered from the effects of the area closure after 25 years (Figure 5.3.2). Figure 5.3.3 presents the spatial distribution of the relative change in benthic production, comparing continued trawling at the 2003 level with closure of the northeast coast fishery and relocation of the English effort (scenario c(iv)), 25 years after closure. Production increased in the closed areas, whereas it decreased in adjacent areas that remained open.

5.3.2 Removing effort: biomass and production

Removing fishing effort from the closed area without redistributing it to open areas had a positive effect on biomass and production of benthic communities. When closing areas, the modelled impact of trawling on biomass and production increased by 1–6% relative to the non-impacted community, corresponding to a 10–20% decrease in the impact of trawling. The effect of closing the 2001 cod box was most positive (scenario a(ii)), wherease closing the northeast coast fishery (scenarios c(ii) and c(iv)) had a much smaller effect on benthic biomass and production.

5.3.3 Species diversity

The cumulative area-species curves were similar for the different closure scenarios (Figure 5.3.4), and there was no obvious effect of closing areas on modelled species richness.

5.3.4 Examined scale and area

There were clear differences in the predicted impact of area closures, depending on the evaluated area and the scale of evaluation. To allow proper comparison of the effect of area closures on benthic production and biomass at different scales, the same area in the southwestern North Sea was compared on both a 25 km^2 and ICES rectangle scale for the 2003 situation and the northeast coast closure for the English fleet (scenario c(iii); Table 5.1). When modelled at an ICES rectangle scale, the modelled impact of trawling was greater and so was the negative impact of area closures.

Because only fishing effort of the English fleet was considered at a 25 km^2 scale, the modelled impact of trawling at the 2003 level was smaller when evaluated at that scale for the southern North Sea than when evaluated at an ICES rectangle scale for the international fleet. However, as the northeast coast closure area (scenarios c(i)-c(iv)) made up a relatively larger fraction of the southern North Sea than it did of the whole North Sea, the impact of closing that area was greater when evaluated for the southern North Sea at a 25 km^2 scale than at an ICES rectangle scale for the whole North Sea.

Table 5.1. Production and biomass of benthic communities, relative to an untrawled situation (%), modelled at ICES rectangle and 25 km^2 scales for the North Sea south of 56°N, evaluated 25 years after closure.

	Production		Biomass	
	No closure	Northeast coast closure	No closure	Northeast coast closure
ICES rectangle	90.1	87.9	60 .3	57.4
5×5 km	91.5	90.2	64.2	62.1

5.4. Discussion

When interpreting the results of the benthic model, several limitations and assumptions have to be considered. The model predictions critically depend on the input of effort distribution and modelled redistribution. It is assumed that beam and otter trawls fished the same area of seabed per unit time and had the same impact on the benthic community. This assumption was made because it was necessary to accommodate the large variation in gears deployed in the North Sea. The model discerns between mortality rates on different sediment types, with lesser mortalities per trawl pass on muddier sediments than on sand and gravel. Because otter trawls concentrate on muddy sediments and beam trawls on sandier sediments, the lesser impact of otter trawls on the benthic community was incorporated in the model.

The model was validated using data for the southern (biomass) and western (diversity) North Sea (Hiddink *et al.*, submitted-a, submitted-b). This means that the analysis at an ICES rectangle scale for the whole North Sea extrapolates the model to areas where it was not validated. Therefore, the results have to be interpreted with caution.

Hiddink *et al.* (submitted-a, submitted-b) showed that the relationship between trawling intensity and the biomass, production and species richness of the benthic community is non-linear. The impact of trawling is strong at low trawling intensities, but an increasing trawling intensity over already high trawling intensities had hardly any impact on the benthos. In scenarios c(iii) and c(iv), only UK trawlers on the benthic community was evaluated, ignoring trawlers from other countries. This means that the total impact of trawling on the benthic community is underestimated for those scenarios. Comparing the scales of modelling also shows that the non-linearity in the relationship between ecological impact and trawling intensity means that the impact of trawling is overestimated when evaluated at the scale of ICES rectangles.

The model used in the present study does not include migration between areas (ICES rectangles or 25 km^2 cells in this study), nor does it include recruitment. Therefore, recovery from trawling can only take place through local growth of biomass. This means that recovery rates may be an underestimate of those in a real North Sea ecosystem. However, unfortunately very few empirical data describing recovery of benthic community biomass after cessation of trawling are available for comparison with modelled recovery rates.

Closing the northeast coast area with redistribution of fishing effort (scenario c(i)) had a small positive effect on modelled benthic production and a small negative effect on biomass in the whole North Sea. For all other scenarios, including the small-scale evaluation of the northeast coast area closure (scenario c(iii)), the modelling results indicate that on short time scales (<10 years), closing areas had a negative effect on benthic biomass and production when effort is redistributed to areas that remain open, and that only after more than 10 years did benthic community biomass start to recover in some scenarios. These effects were relatively small (<20%) compared with the overall effect of trawling on biomass and production in the North Sea. Removing effort from closed areas had a positive effect on benthic biomass and production for all area closures. The difference in biomass and production between the scenarios evaluating redistribution and removal of effort is equal to the size of the negative effect of the redistribution of effort from closed to open areas. This negative effect of displacing fishing effort to areas outside the protected areas is large in all evaluated scenarios, and is therefore an important process to consider when evaluating the ecological impact of area closures. Hardly any effect of area closures on species richness of benthic communities was found.

In general, closing the northeast coast area had the smallest negative and positive effects on benthic biomass and production (scenarios c(i) – c(iv)). Closing the 2001 cod box had a smaller negative (effort redistribution, scenario a(i)) and larger positive effect (effort removal, scenario a(ii)) than closing the STECF area (scenarios b(i) and b(ii)).

The results of the modelling study indicate that area closures where fishing effort is redistributed to open areas can have a negative impact on benthic communities. Only one of three closure scenarios had a small positive effect on the production of benthic invertebrate communities. Removing fishing effort from closed areas always had a positive effect on benthic community biomass and production.

Many closure scenarios are possible, but only three were examined here. An extensive comparison of different area closure scenarios may be capable of identifying what type of area closures yield the largest benefit to the benthic invertebrate community while causing the least disruption to bottom trawling. The current study only evaluated the effect of permanent closure of areas on benthic invertebrate communities. In the past, however, area closures have mainly been implemented as temporary measures, e.g. the 2001 cod box closure lasted just 75 days. It would therefore be instructive to compare the impact of permanent area closures on benthic invertebrate communities with temporary, seasonal and rotating area closures in future studies.

Here it has been shown that the scale of evaluation has an effect on the predicted impact of trawling; small-scale evaluations show a smaller (and probably more realistic) impact of trawling than large-scale evaluations. This means that future analyses ideally should be done at a small scale (e.g. 25 km^2). The practicality of this suggestion depends on the availability of small scale fishing effort data for all countries fishing in the North Sea, as well as of environmental data.

Bottom trawling influences both fish stocks and benthic invertebrate communities. Commercial fish stocks such as cod, haddock, plaice and sole depend on benthic invertebrates for a large part of their diet. This means that bottom trawling not only affects fish stocks directly by catching them, but potentially also indirectly through an effect on the benthic invertebrates. Combining models of the effect of fishing on fish population dynamics with models on the effect of fishing on benthic invertebrate biomass and production may help in understanding whether this indirect effect of fishing on fish stocks is important. That suggestion would, however, require information on the relationship between food availability (benthic production) and fish population dynamics, which currently seems to be lacking for most commercially important species.

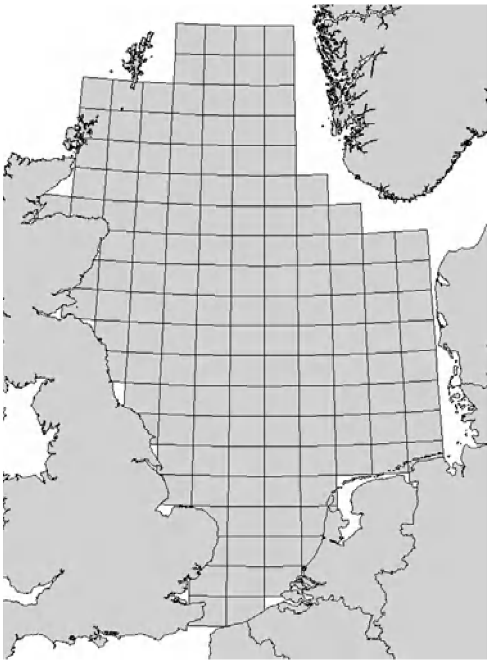


Figure 5.2.1 The area that modelled in the ICES rectangle scale evaluation of area closures.

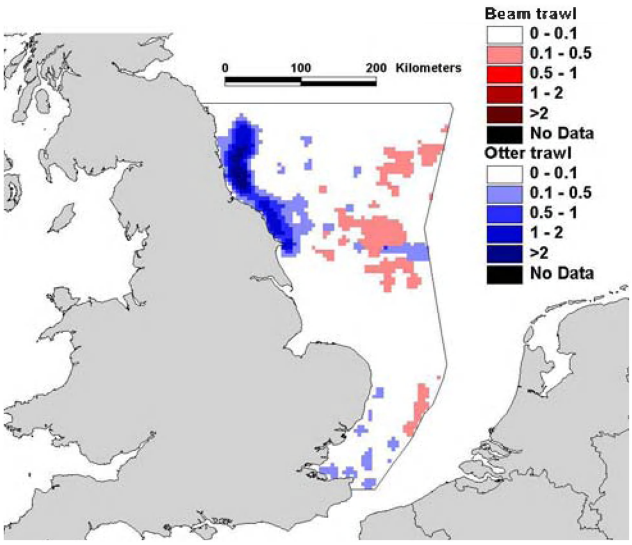
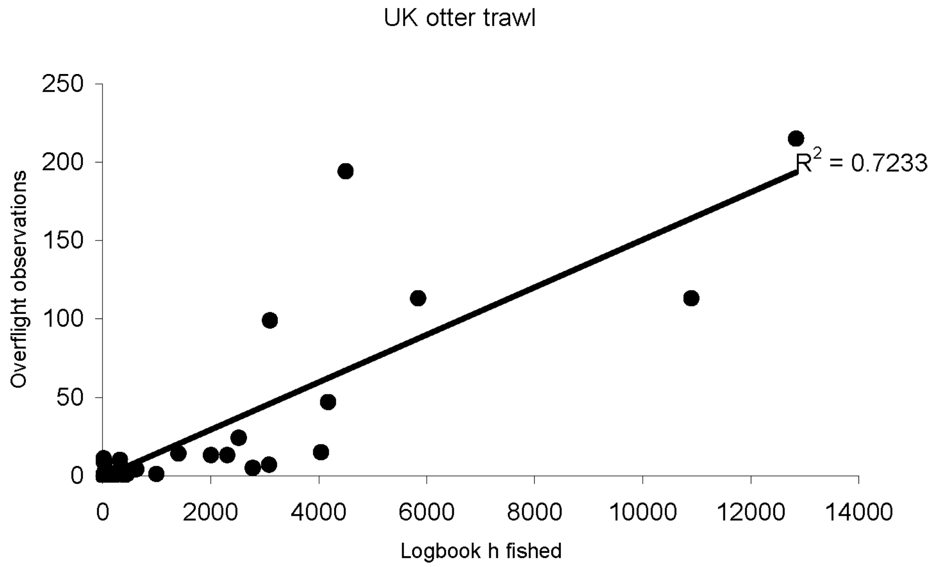


Figure 5.2.2 Small-scale trawling intensity (y^{-1}) of UK beam trawlers and otter trawlers, as calculated from VMS and overflight observations.

(a)



(b)

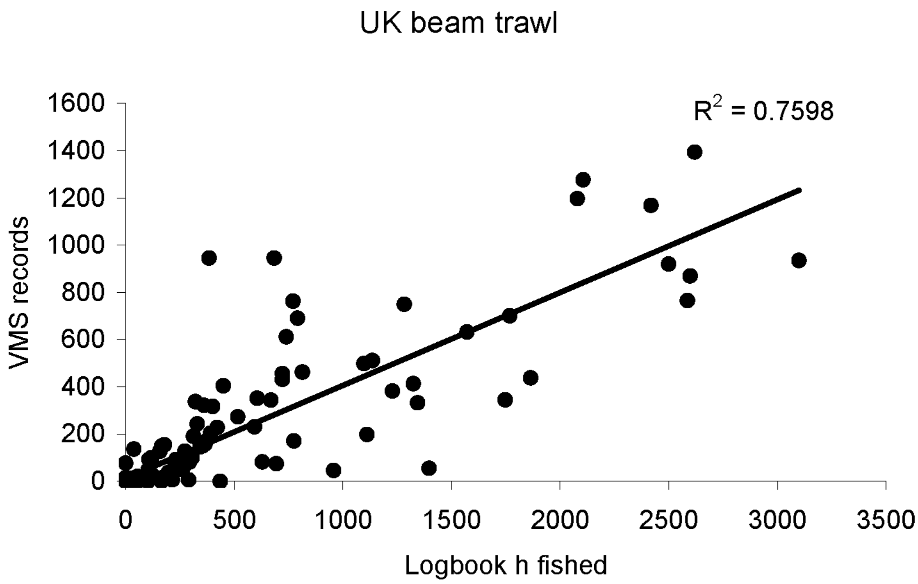


Figure 5.2.3 Relationship between fishing effort per ICES rectangle calculated from logbook data and more spatially detailed effort data. (a) Otter trawl logbook against overflight observations. (b) Beam trawl logbook against VMS observations.

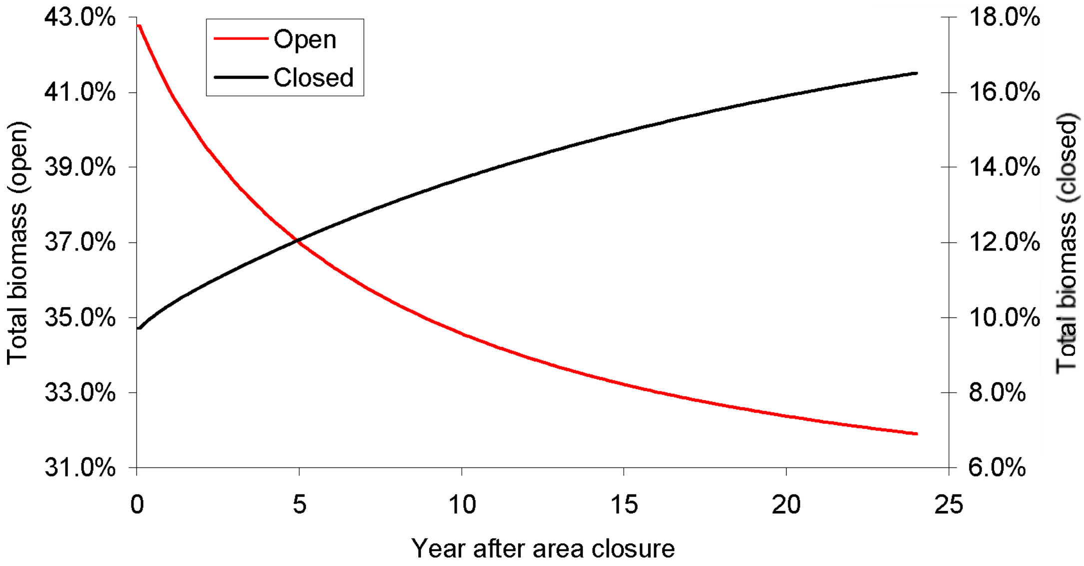


Figure 5.3.1 Example of biomass development in the open and closed area for the 2001 cod box closure (scenario a(i)), evaluated for the whole North Sea at an ICES rectangle scale, as a percentage of the biomass of an untrawled community. See Figure 5.3.2 for the summed biomass of the closed and open area combined.

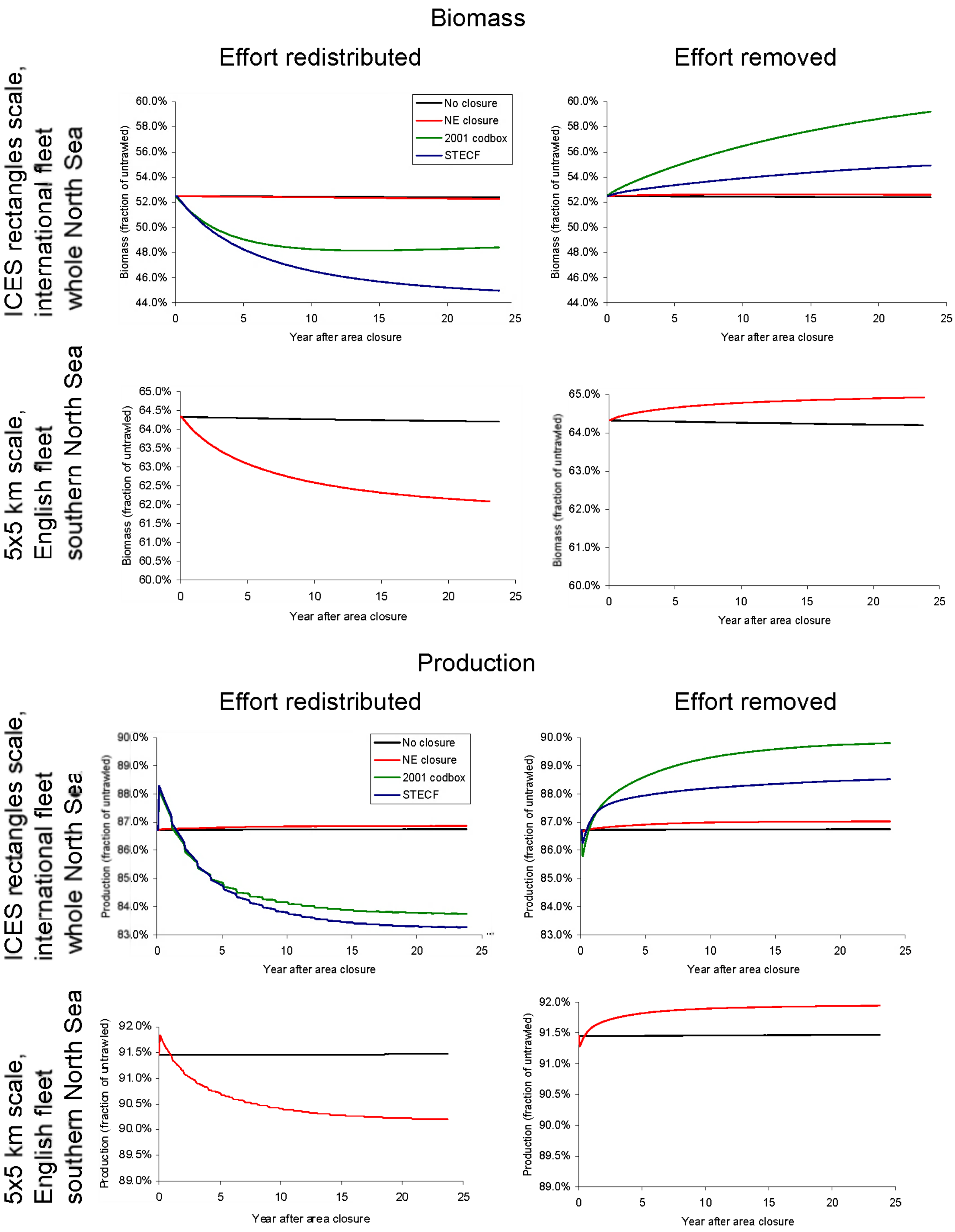


Figure 5.3.2 Biomass and production development after area closures, for ICES rectangle scale model runs for the international fleet (scenarios a(i), a(ii), b(i), b(ii)) and small-scale model runs for the English fleet (scenario c(iii), c(iv)).

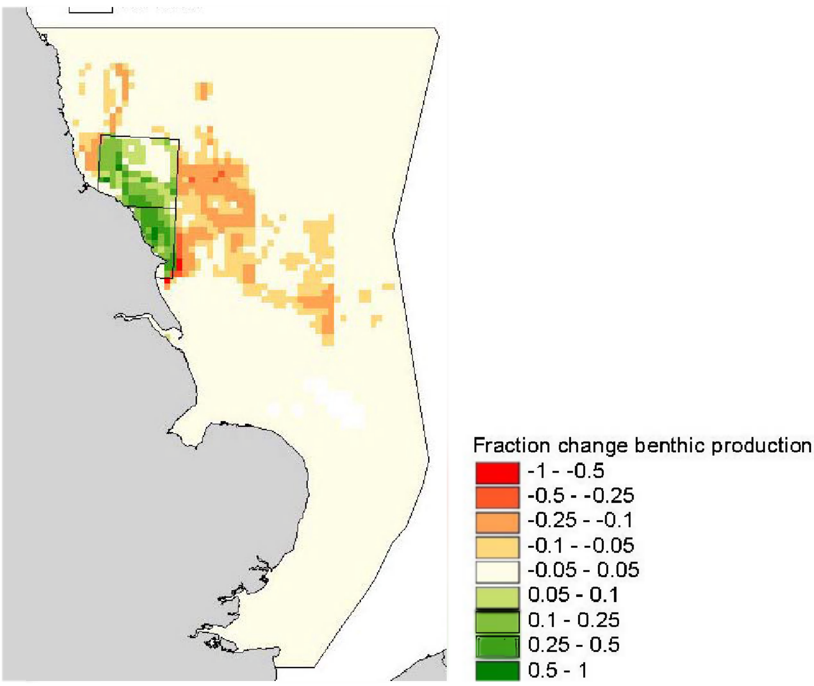


Figure 5.3.3. Spatial distribution of relative change in production of benthic communities in the southern North Sea at a scale of 25 km^2, 25 years after closure of the northeast coast fishery (scenario c(iii)). The closed area is indicated by the two squares. Green indicates an increase in production, red a decrease in production, and yellow a <5% change in production.

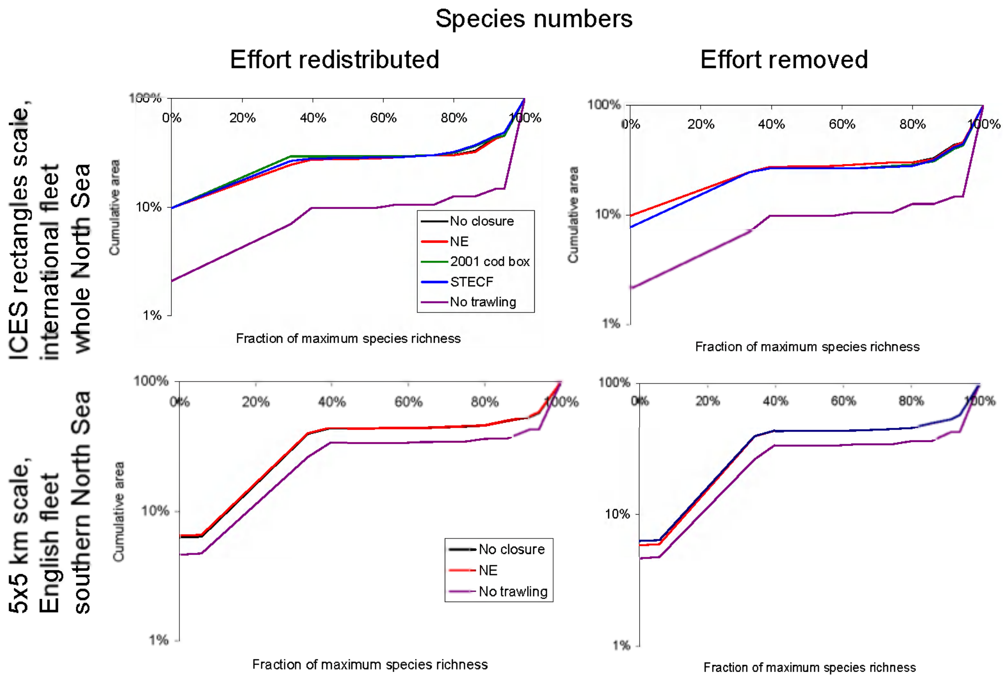


Figure 5.3.4. Cumulative distribution of species richness for three different area closures after 25 years, for ICES rectangle scale model runs for the international fleet and small-scale model runs for the English fleet.

6. Summary

Closed areas have been proposed as one of a range of potential management approaches that could be applied to control the exploitation rate of North Sea cod. However, while theoretical studies of the potential effects of closed areas are numerous, they are of limited use for providing practical management advice because they are not case-specific. The aim of this project was to bring together fishers' knowledge of current and potential future North Sea fleet fishing activity with research on the spatial movement of fleets, cod population biology and the impact of fishing on benthic biodiversity, in order to provide practical advice on the impact of closed area management in the North Sea. Research with this purpose is needed to help provide Defra and the fishing industry with practical advice on the potential impact of closed area management on cod population dynamics, habitat diversity and the economics of North Sea fleets.

Examples of closed area management regimes for North Sea cod have been simulated and the impact on the catches of cod, mixed gadoids and benthic productivity and diversity evaluated. Funding and the time available for the study was limited, so the work examined three example scenarios for cod: two evaluating the impact of large, broad-scale, North Sea closures, and the others at a more detailed scale the effect of local closures close to the northeast coast of England.

The outcome of the predicted changes in the dynamics of the North Sea fleet effort distributions on the benthos and the cod stock is described. Conclusions are drawn with respect to the potential impact of the closures, including comparisons with other management actions or technical measures that could be employed to manage the stock; the design of closed areas for restricting access to stocks; and the effectiveness of the modelling approaches.

The research has provided improved understanding of the potential impact closed areas could have on the English and international fleet yields and the population dynamics of the cod, especially recovery rates to biological reference points. The analyses have also highlighted areas where the science and knowledge base is limited, and where further industry input and additional data analysis are required to provide a rapid response to managers and stakeholders when closed areas are proposed.

The studies have been collated as a series of papers, each presented independently. Key points of each, by relevant subject area, are summarized in the following sections.

6.1 Effort management

- Removal from the fishery of effort directed in closed areas results in the most significant impact from a closure. If effort is allowed to relocate into areas remaining open, the impact of the closed area is reduced substantially and the effects on the stock could be detrimental. Similarly, any derogation to fish in a closed area will reduce its impact.

- The approach used by fishers to relocate effort displaced from a closed area is a critical determinant of the effectiveness of a closure.

- Case-specific dialogue with fishers during the study design phase in terms of potential changes in effort distribution resulting from a closure, is considered to be an important factor in reducing the uncertainty associated with expected returns.

- Closed area management cannot be used in isolation of quota and effort regulation. Closed areas are designed to make fishers less efficient at catching protected species. If either effort or efficiency increases after relocation to open areas in order to compensate for the reduced efficiency, benefits of the closure will be reduced.

- The movement of large numbers of new vessels into an area will result in conflicts between local and relocated fishers.

- Fishers prevented from accessing local stocks will move into areas that they may not have fished before. This will introduce inefficiency and reduce income. The incentive to provide biased landings and effort data will be greater. The quality of catch and effort data is likely to become even more uncertain, until the stock recovers and pressures are relieved.

- The evaluations are based on relative stability in the amount, location and the type of gear used; switching to alternative gears reduces the benefit of closed areas

6.2 The North Sea cod fishery

- At a time of increasing uncertainty in the resource status resulting from bias in catch data, closed areas will remove some of the cod stock from exploitation, protecting at least a portion of the resource.

- The effectiveness of a closed area is conditional on its design, with respect to the decisions that fishers must make when they are redistributing effort.

- If fishers target cod using effort displaced from closed areas, the current approach to designing closed areas adopted by the Commission of the European Union could increase cod fishing mortality rates substantially. This results from areas in which high catch rates occur being omitted from those closed on the basis of total annual catch.

- Designing closed areas with respect to the areas from which high proportions of catch are taken <u>and</u> the potential catch rates in other areas provides a management approach to reducing fishing mortality that is more robust to the way in which effort is relocated.

- If redesigned, closed areas of the magnitude suggested by the EU Commission can reduce cod fishing mortality. However, the estimated reductions in mortality rate are relatively small and, at best, will only stabilize the decline in stock size; they will not result in recovery of spawning stock biomass to safe biological levels.

- Closed areas that deliver “guaranteed” reductions in cod mortality, leading to stock recovery, without reducing current levels of effort would require the closure of substantial areas of the North Sea. The impact of displacing significant portions of the fleet’s effort into areas remaining open would be considerable and could result in many traditional fishing grounds being closed and numerous conflicts of interest.

- Under a regime using closed area management and within which effort was allowed to relocate, closure of up to 20% of the North Sea reduced fishing mortality on cod in the range 5–20%. This was only sufficient to stabilize the cod spawning stock biomass at just less than B_{lim} (70 000 t), and the expected effects of closing such large areas are associated with a high degree of uncertainty because of the redistribution of large numbers of vessels.

- In all cases, removal from the fishery of the effort directed into the example closed areas examined had by far the most significant effect on reducing the mortality of North Sea cod. If effort was allowed to relocate into areas remaining open, the reduction in mortality rate was reduced substantially and could actually increase. If total effort increases in the open areas, the beneficial effect may be negligible, implying that a restriction on total effort would then be needed.

- Simulation models using simplified assumptions with respect to the underlying population dynamics of cod gave results consistent with those of more complex models. However, the simple models omit density-dependent spatial variation in the stock structure. If adopted, the methodology would require frequent revision if and when the stock rebuilds and historical spatial patterns are revisited.

6.3 Alternative management strategies

- The North Sea fishery selection-at-age ogive (relative fishing mortality) estimated by the recent ICES Working Groups is congruent with that of a 90 mm mesh, well below the 120 mm suggested as optimal for directed cod fishing. Although vessels targeting gadoids in the North Sea are required to use 120 mm mesh, those using a wide range of gear types catch and discard or land cod; the combined effect is a much lower effective mesh.

- The use of 120 mm mesh throughout all fisheries catching cod would have the same impact as the reduction of discards to zero, and for an unchanged level of effort results in growth of the stock to B_{lim}; using 140 mm mesh increases biomass to between B_{lim} and B_{pa}, and 160 mm allows the stock to recover to above B_{pa}. The analysis assumes that effort does not increase to compensate for the loss of smaller species and the initial losses of small cod from the catch.

- Catches recorded from the North Sea cod fishery have spatial structure within them, indicating possible sub-stock structure. This study has not evaluated the impact that this might have for each sub-unit. Closure of an area containing one sub-unit may completely protect it from exploitation while forcing effort onto a second area, making that area more vulnerable to exploitation.

- Seasonal migration and movement can have a significant impact on the effectiveness of a closed area. Closed areas must be designed to be robust to temporal variability in stock distribution; boundaries may have to be moved during the year or, alternatively, permanent closures expanded in order to maintain their effectiveness.

6.4 Mixed fishery aspects

- Relocating fishing effort away from concentrations of cod will impact on the catches of other species. The small example area for which appropriate data were available, located on the northeast coast of England, resulted in increased catches of *Nephrops* throughout the year and of whiting and haddock in the first and fourth quarters.

- Seasonal migration and movement had a significant impact on available catch composition. Increasing catch rates of associated species will have a strong impact on discard rates if additional quota is not available for displaced vessels.

6.5 Impact on the benthos

- Closure of fishing grounds will move fishers away from traditional fishing areas, resulting in increased effort and seabed disturbance in areas that were previously relatively lightly fished. There is therefore a net reduction in diversity and biomass across the North Sea before any increases within the closed areas have had time to accrue.

- Redistribution of fishing effort from the example area closures that were not accompanied by associated effort reduction had negative effects on the biomass and production of benthic invertebrate communities. Removing fishing effort from the closed areas always had a beneficial effect on benthic community biomass and production.

- The large-scale closure scenario results indicate that at time scales of <10 years, closing areas had a negative effect on benthic biomass and production when effort was redistributed into areas that remained open, and that only after more than 10 years did benthic community biomass start to recover in some scenarios.

- The model was validated using data for the southern (biomass) and western (diversity) North Sea. The analysis at an ICES rectangle scale for the whole North Sea extrapolates the model to areas where it was not possible to validate it. Therefore, the results must be interpreted with caution.

6.6 Recommended work

- The effect of seasonal variation could not be examined for larger areas in the available time and because of a lack of international data. However, such an analysis should be given high priority (using national and international data, when available) because the results may illustrate the difficulties of applying closed area management at a large scale within the restrictions of relative stability in national quota allocations.

- The simulation models using simplified assumptions with respect to the underlying population dynamics of cod developed within this study have generated results consistent with those of more complex models. They can therefore be used to provide the basis for modelling other commercially important stocks and to evaluate the need for the degree of flexibility in quotas required to manage a mixed fishery if large closed areas are proposed to protect cod. They can therefore provide a rapid response to calls for advice. However, the format of the current models does not easily lend itself to a user-friendly interface, so creating this should be assigned a high priority.

- The benthic model was validated using data for the southern (biomass) and western (diversity) North Sea. The analysis at an ICES rectangle scale for the whole North Sea extrapolates the model to areas where it has not been validated. If detailed analysis of large-scale areas is required, fine-scale distributions from co-ordinated collation of North Sea wide data sets will be required.

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