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Predicting the effects of area closures and fishing effort restrictions on the production, biomass, and species richness of benthic invertebrate communities

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To effectively implement an Ecosystem Approach to Fisheries (EAF), managers need to consider the effects of management actions on the fishery and the ecosystem. Methods for assessing the effects on target stocks are generally well developed, but methods for assessing the effects on other components and attributes of the ecosystem are not. Area closures and effort controls are widely used fishery management tools that affect the distribution of fishing effort and may therefore have consequences for a range of species and habitats. An approach is developed to predict the effects of area closures and effort control on the biomass, production, and species richness of benthic communities in the North Sea. The redistribution of beam trawling effort as a result of management action was modelled with a random utility model, assuming that fishers selected fishing grounds on the basis of their knowledge of past catch rates. The effects of trawling on benthic invertebrates were predicted using a size-based model that accounted for differences in habitat among fishing grounds. Our simulations demonstrated that closures of different sizes and in different locations could have positive or negative effects on benthic communities. These predicted effects resulted from the trade-off between recovery in the closed areas and additional trawling effects in the open areas that arose from displaced fishing activity. In the absence of effort controls, closure of lightly fished areas had the strongest positive effect on benthic communities. Effort reduction also had a positive effect. Therefore, area closures in lightly fished areas, coupled with effort reduction, are expected to minimize the effects of fishing on benthic communities. As it was not possible to access full international data for the North Sea beam trawl fleet, the results of the analyses are illustrative rather than complete. Nevertheless, what is demonstrated is an effective approach for assessing the environmental consequences of fishery management action that can be used to inform management decision-making as part of an EAF.

Keywords: beam trawl, disturbance, diversity, ecosystem approach, fisheries management, marine protected areas, marine reserves, production.

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Introduction

The growing commitment to an Ecosystem Approach to Fisheries (EAF) implies that managers should take account of the environmental effects of fishing when taking management decisions (FAO, 2003). To implement an EAF, managers need to decide upon management actions informed by knowledge of the consequences for the fishery and the ecosystem. Methods to assess the effects of management action on target stocks are well developed (Quinn and Deriso, 1999), but methods to assess the effects on other components and attributes of the ecosystem are not (Sainsbury *et al.*, 2000).

Bottom-trawl fisheries disturb benthic species and habitats and can reduce biomass, production, and diversity (Hall, 1999; Kaiser and De Groot, 2000). As benthic species contribute to the flow of organic material from the water column to the bottom (benthic–pelagic coupling; Choi *et al.*, 2004), form habitats (Auster and Langton, 1999), and provide an important food source for demersal fish (Greenstreet *et al.*, 1997), the assessment of the sustainability of trawling impacts on these species is an important

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component of an EAF (Barnes and Thomas, 2005). Currently, there exist no target levels for benthic production, biomass, or species richness, and policy is aimed at conserving ecosystem functioning. What state the benthos needs to be in for this is unknown. The impacts of trawling on benthic species are greater in previously unimpacted areas than in areas that have already been trawled, and the magnitude of the impact will depend upon the frequency and intensity of natural disturbance (Duplisea *et al.*, 2002; Hiddink *et al.*, 2006). Consequently, management measures that displace trawling effort from existing fishing grounds can have significant effects on benthic communities (Dinmore *et al.*, 2003), the magnitude of these effects being determined by trawling frequency, and the frequency and intensity of natural disturbance.

Area closures and effort controls may be used to control fishing mortality on target stocks (Murawski *et al.*, 2005), and may also provide conservation benefits for vulnerable habitat, vulnerable species with low rates of movement, and for other species in a closed area (Halpern, 2003; Willis *et al.*, 2003). However, the aggregate environmental effects of closing large areas of the seabed to fishing have rarely been investigated (Horwood *et al.*, 1998; Steele and Beet, 2003; Halpern *et al.*, 2004; Murawski *et al.*, 2005), and few studies have sought to balance the benefits that may result inside a closed area against the costs that result from the displacement of fishing effort (Horwood *et al.*, 1998; Dinmore *et al.*, 2003; Halpern *et al.*, 2004; Kaiser, 2005). Although discounted by some, this wider perspective is necessary when judging the overall success of management. Effort controls are widely used to support conventional fishery management, and it is also necessary to understand how these affect ecosystem components other than target stocks.

To assess the effects of area closures or effort controls on benthic invertebrate communities, it is necessary to predict the spatial and temporal redistribution of effort following each management action, and to use this information to predict the consequences for benthic communities (Jennings *et al.*, 2005). In conjunction with an assessment of the effects of area closures or effort controls on target species, this approach allows managers to take account of some of the environmental consequences of their management decisions, consistent with an EAF (FAO, 2003). Here, we assess the aggregate impacts of area closures and effort controls in the North Sea beam trawl fishery on the production, biomass, and species richness of benthic communities. We account for the response of fishers to management action, and for the response of the benthic community to trawling in different environments with different histories of trawling disturbance.

Methods

Management scenarios

The consequences of seven area closures and four types of effort reduction were assessed (Table 1). For comparative purposes, we also considered the impacts of trawling with no closures or additional effort control. Five of the area-closure scenarios focused on closing those ICES rectangles (0.5° latitude by 1° longitude, approximately 30 × 30 nautical miles) from which a large proportion of the international catch of cod (*Gadus morhua*), plaice (*Pleuronectes platessa*), or sole (*Solea solea*) was taken. Such closures might be considered for emergency protection of target stocks (Rijnsdorp *et al.*, 2001). The remaining two scenarios focused on closing areas that were rarely fished. These approaches would help to maintain existing patterns of fishing disturbance, and were expected to have a small effect on the beam trawling fleet. ICES rectangles were used as unit for closures because of the availability of the necessary data at this scale, but when real closures are implemented in the North Sea, they may not necessarily be at this scale. For all closed area scenarios, ICES rectangles were ranked by their percentage contribution to the total international catch, and the rectangles contributing to a cumulative catch of x% were identified (starting with the rectangle with the highest or lowest rank). The effort-reduction scenarios considered "days at sea" restrictions, where the time that vessels are allowed to spend at sea is reduced, and "decommissioning", where a proportion of the least or most efficient boats in the beam trawl fleet were removed. Vessel efficiency was estimated using catch per unit effort (cpue), a simple approach that does not take account of differences in vessel characteristics including size, horsepower, and differences in fishing gear and crew. However, most vessels in this beam trawl fishery are of a similar size. The ICES rectangles hypothetically closed or kept open in scenarios 1–7 are listed in the Appendix.

Table 1. Closed area and effort-reduction scenarios.

Scenario	Description
Closed areas	
1.	Closed rectangles that account for 40% of the cod catch by all fleets in the North Sea
2.	Closed rectangles that account for 60% of the cod catch by all fleets in the North Sea
3.	Closed rectangles that account for 80% of the cod catch by all fleets in the North Sea
4.	Closed rectangles that account for 40% of the plaice catch by all fleets in the North Sea
5.	Closed rectangles that account for 40% of the sole catch by all fleets in the North Sea
6.	Closed rectangles that account for <20% of the total catch of beam trawlers
7.	Closed rectangles that account for low catches by any fleet
Effort reduction	
8.	Days at sea restrictions such that each trip is reduced in effort by 20%
9.	Days at sea restrictions such that each trip is reduced in effort by 40%
10.	20% most efficient vessels are decommissioned
11.	20% least efficient vessels are decommissioned

Effort redistribution

We evaluated the effect of area closures on the distribution of UK registered beam trawlers. Data to conduct the evaluation for vessels from other member states were not available, although these data would be needed if our methods were used to provide management advice at the scale of a fishery. We used 2002 as the reference year for "normal" fishing without restrictions, because it was the most recent year without area closures for which complete fishing effort data from the satellite Vessel Monitoring System (VMS) were available. The effect of area closures on the distribution of fishing effort was calculated in a two-step process. First, effort distribution was predicted at the ICES statistical rectangle scale, using a Random Utility Model for the North Sea (Hutton *et al.*, 2004; see model description below). Second, effort was reallocated at a 3 × 3-km scale, based on fishing locations identified from VMS data.

In 2002, the English North Sea beam trawl fleet operated out of ports on the east coast of England and the Netherlands, generally in ICES Area IV. Each vessel spent an average of 250 days at sea (on typically 6-day trips). The main species targeted were plaice and sole, but cod and other whitefish also contributed to the fleet's earnings. The beam trawlers had an average length of some 37 m, an engine power of 1300 kW, and were operated by a crew of about six.

Large-scale redistribution of trawling effort

The response of beam trawlers to area closures was modelled using a Random Utility Model (RUM) and a simulation model of individual vessels that depends on the results of the RUM (Hutton *et al.*, 2004). A RUM models discrete decisions, so no assumption of homogeneity among individuals is required. As in most economics-based choice models, utility was defined as a (linear) combination of a set of explanatory variables that are surmised to form (for the most part) the non-random components of the utility, and a stochastic error (random). The model was fitted using vessel-specific logbook records of past fishing activity, catch, and catch rates. The results from the RUM indicated that the number of trips, the average trip length, and the average effort in each ICES rectangle were significant variables affecting location choice, in addition to catch rate for the previous year, weighted by monetary value. A simplified spatially structured simulation model was then developed to predict the effect of closed areas on the distribution of the fleet, using the results of the RUM to define the assumptions, i.e. fishers make decisions on the spatial location of operation based on past catch rates. Hutton *et al.* (2004) describe the parameterization and validation of the models in detail. The model was used to simulate the effect of closing areas, composed of ICES rectangles, on a vessel-by-vessel basis for each month, based on a five-step process. First, each vessel's effort distribution is computed from individual trip logbook data, to obtain the total effort (in h) per spatial unit per month per vessel. Second, each vessel's spatial distribution of catch rate is computed to obtain the average catch rate (kg h^{-1}) per spatial unit per month per vessel. Third, some spatial units are closed (assuming the closure occurs in the next year), and the total effort in all the closed areas for each vessel for each month is computed. This is the effort that is subsequently redistributed. Fourth, based on the assumption that vessels will obtain the largest net benefit per trip if they fish in the accessible 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. Finally, the redistributed effort is added to the total effort per spatial unit per month per vessel (only to spatial units that are not closed), 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

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

$$\text{given} \sum_{r=1}^{R} E'_{(r,t+1,v)} = \sum_{r=1}^{R} E_{(r,t,v)}$$

for a particular combination of rectangles (r, that are still open), time period (t), fishing unit (v), and closed area (a). The effort of the fleet can be obtained by summing effort over all vessels. Scenarios 8 and 9 reduce the days at sea, respectively by 20% or 40% for every vessel. We assumed that this resulted in an unaltered relative distribution of fishing effort. Scenarios 10 and 11 decommission the 20% most and least efficient vessels, respectively. Vessel efficiency was defined as the annual average cpue.

An important characteristic of the model is that it does not account for vessels that explore new areas following displacement. Therefore, if all rectangles of a vessel fished in 2002 were closed, the vessel would have nowhere to go. It is known that exploration of new areas occurs in the fishery under conditions of increasing levels of effort (Kaiser, 2005), so the model was modified to account for such vessel searching, allocating them proportionally to areas fished by other vessels. This procedure makes the assumption that information is exchanged between vessels, either because skippers communicate directly, and/or because they observe the activities of other vessels and follow them.

Small-scale distribution of trawling effort

Fishing effort is patchy within ICES rectangles, and this patchiness is important when evaluating trawling impact. Because the response of benthic community biomass to trawling is not linear, evaluating impacts at a large spatial scale can lead to overestimation of the impact (Dinmore *et al.*, 2003). The small-scale distribution of trawling effort was calculated from VMS data for 2002. From 1 January 2000 onwards, 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 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 transmits positional data, but speed can be calculated from two consecutive records of time and position. Accordingly, vessels travelling at speeds >8 knots and stationary vessels were eliminated, because these vessels were assumed not to be fishing (Dinmore *et al.*, 2003). The number of trawl passes per 9-km^2 cell per year was calculated from the number of records in a cell in 2002. For the calculation of trawling intensity (y^{-1}), it was assumed that trawlers fished at a speed of 5 knots, with a total fishing gear width of 24 m (two beam trawls each 12 m wide). Therefore, one record per year per cell represents a trawled area of 0.449 km^2. The lower limit to the scale at which trawling effort could be evaluated was defined by the resolution of the VMS records. The 9-km^2 scale as used is close to the 1 × 1 nautical mile scale at which the distribution of fishing effort becomes random (Rijnsdorp *et al.*, 1998). We assumed that the small-scale distribution of trawling effort within rectangles did not change with total effort in the rectangle. Therefore, the small-scale distribution of trawling effort was calculated by multiplying the ratio of modelled to normal trawling effort for each rectangle effort by the small-scale effort determined from VMS data.

We assessed the relationship between the fishing effort from the logbook fishing activity database and VMS records in 2002 at the scale of ICES rectangles. The relationship between the numbers of hours fished per ICES rectangle from logbook and VMS records was analysed using correlation and principal axis approaches (Sokal and Rohlf, 1981). These methods were used because the two variables were both measured with error, and therefore a regression analysis was not feasible.

Because the rectangle-scale effort redistribution model was run for the whole North Sea, redistribution of effort into and out of our study area in the southern and central North Sea was possible. This means that distribution of effort and total effort change at the same time in the southern and central North Sea. To separate the effects of effort redistribution from the effects of changes in total effort, scenarios 1–7 were also run with effort standardized to 100% of 2002 effort, while holding the spatial distribution of effort constant.

Benthos model

We used an ecological model validated with extensive field data (Duplisea *et al.*, 2002; Hiddink *et al.*, 2006) to examine the large-scale impact of effort redistribution on benthic biomass, production, and species richness. The size-based model consisted of 32 body size classes of animals. Sediment, shear stress, erosion, and chlorophyll content of the sediment were included as environmental variables that affected the growth and mortality of the animals. The model has been validated using benthic biomass and production estimates from 33 stations subject to a range of trawling intensities, in four areas of the North Sea. For a detailed description of the model, validation, and the environmental data sets that were used, see Hiddink *et al.* (2006). The model was run to equilibrium in 1500 time-steps of 30 days using the 2002 trawling intensity. Then the new modelled effort distribution was implemented and the development of biomass, production, and species richness followed for 25 years (300 time-steps). Therefore, it was assumed that the effort distribution remained stable after the implementation of closed areas or effort controls. The large-scale impact of effort redistribution on biomass and production was examined by summing estimates of biomass or production in the 9-km^2 cells over the whole study area. Species richness was reported in terms of the proportion of cells with the maximum possible richness (i.e. cells in which there was no discernible trawling effect). This proxy for species richness is easy to understand, and describes the large-scale changes in a compact way. Preliminary analyses showed that changes in the distribution of species richness correlated closely with the proportion of cells with the maximum possible richness.

Results

Effort distribution

At an ICES rectangle scale, logbook records of fishing effort (h) by English beam trawlers in the North Sea in 2002 and VMS effort were positively correlated (Figure 1; Pearson correlation = 0.912, $p < 0.001$, $n = 203$; principal axis: logbook (h) = 1.02 VMS (h) − 82.5). As the slope of the relationship was close to unity and the intercept small compared with the range of values (0–5000 h fishing), both effort measures recorded similar patterns of effort distribution.

In 2002, the effort of UK beam trawlers was concentrated on the eastern Dogger Bank, and in the area southwest of the Dogger Bank around the Silver Pit (Figure 2, no closures). Figure 2 scenarios 1–11 show how the distribution of this effort was predicted to change under the 11 management scenarios. Redistribution of fishing effort was most

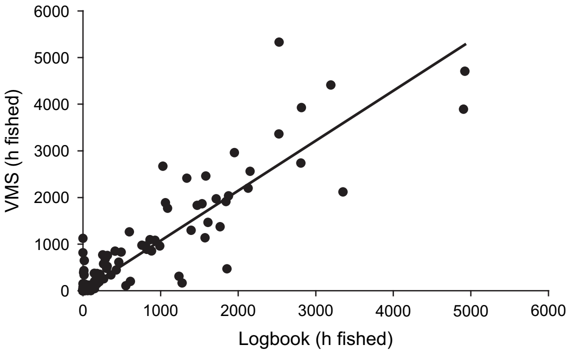

Figure 1. Correlation between logbook and VMS records of beam trawling effort in ICES rectangles in the North Sea in 2002.

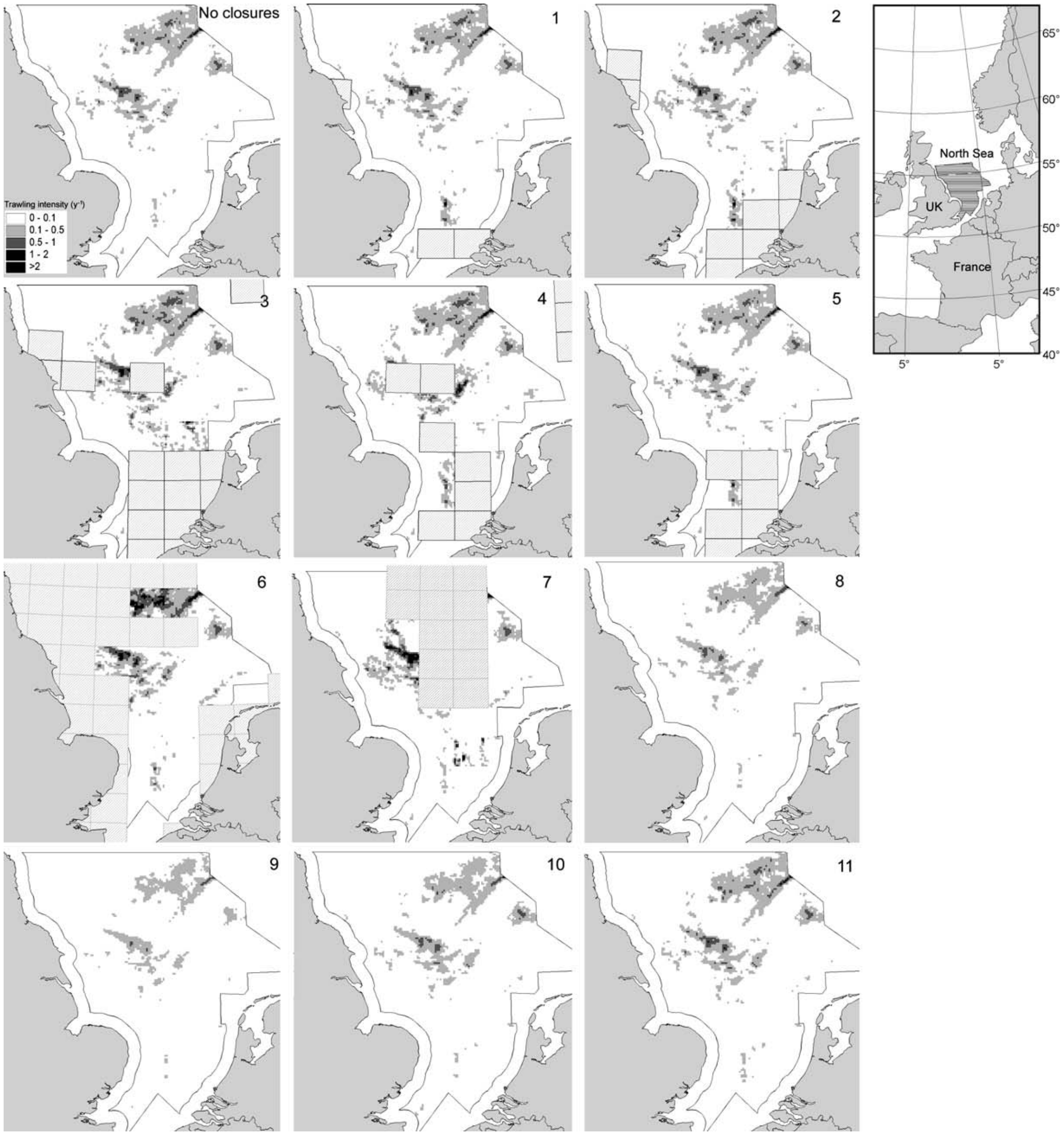

Figure 2. The study area − Dutch and UK North Sea south of 56°N, indicated by the solid line. The map in the top right-hand corner shows the position of the studied area in northwestern Europe. Trawling effort (y^{-1}) of UK beam trawlers in the study area was calculated from VMS records and is indicated by grey shading (see key). Numbers in the top right-hand corner of each map indicate the scenario number, and cross-hatched rectangles were those closed to trawling in the different scenarios.

apparent when previously important fishing grounds were closed, such as scenarios 3 and 6. If effort was not standardized within the southern and central North Sea study area, effort in the area increased for scenarios 1−6, and decreased for scenario 7 (Table 2). For the effort-reduction scenario 10, a few very efficient vessels only undertook a few trips, but significant effort was still removed. In scenario 11 (removal of the 20% least efficient vessels), the amount of effort removed was very small, because some of those vessels would have only made a few trips.

Effect of management scenarios on benthic communities

For the pristine situation without trawling, the average modelled production was 10.6 g WW m^{-2} y^{-1}, the average

Table 2. Comparison of the effects of 11 management scenarios on biomass, production and species richness of benthic communities in the North Sea. Biomass and production are given as a percentage of biomass and production without trawling. For scenarios 1−7s, trawling effort in southern and central North Sea study area was standardized to 100% of pre-management levels.

Scenario		Trawling effort relative to 2002 (%)	Biomass (B) (%)			Production (P) (%)			% cells with maximum species richness (%)
			Time (years)			Time (years)			
			5	10	25	5	10	25	$t = 25$
	No trawling	0.0	100.0	100.0	100.0	100.0	100.0	100.0	75.3
	Current trawling	100.0	81.7	81.6	81.6	95.4	95.4	95.4	62.9
	Stop trawling	0.0	85.3	87.5	90.4	97.4	98.5	99.3	64.5
1	Close 40% cod catch	107.0	81.5	81.4	81.3	95.3	95.3	95.3	62.9
2	Close 60% cod catch	113.9	81.2	81.0	80.8	95.2	95.1	95.0	62.9
3	Close 80% cod catch	113.0	80.7	80.3	79.9	94.9	94.7	94.6	62.4
4	Close 40% plaice catch	107.0	81.2	81.1	81.0	95.3	95.3	95.3	62.7
5	Close 40% sole catch	102.5	81.5	81.4	81.3	95.3	95.3	95.3	62.9
6	Close <20% plaice catch	115.0	81.9	82.1	82.6	95.3	95.4	95.4	62.8
7	Low catches by any fleet	74.3	82.5	83.3	84.6	95.8	96.2	96.5	63.0
8	Days at sea 20% reduction	80.0	82.3	82.7	83.1	95.8	96.0	96.1	63.2
9	Days at sea 40% reduction	60.0	83.0	83.8	84.7	96.2	96.6	96.9	63.6
10	Decommission 20% most efficient boats	82.9	82.1	82.4	82.6	95.7	95.8	95.9	63.1
11	Decommission 20% least efficient boats	99.3	81.7	81.7	81.6	95.4	95.4	95.4	62.9
1s	Close 40% cod catch	100.0	81.7	81.8	81.8	95.5	95.5	95.5	63.0
2s	Close 60% cod catch	100.0	81.7	81.7	81.7	95.4	95.5	95.5	63.0
3s	Close 80% cod catch	100.0	81.2	81.0	80.8	95.2	95.1	95.1	62.7
4s	Close 40% plaice catch	100.0	81.5	81.4	81.5	95.4	95.5	95.5	62.8
5s	Close 40% sole catch	100.0	81.6	81.5	81.5	95.4	95.4	95.4	62.9
6s	Close <20% plaice catch	100.0	82.2	82.7	83.3	95.6	95.7	95.8	63.1
7s	Low catches by any fleet	100.0	81.8	82.3	83.3	95.3	95.5	95.8	63.3

biomass was 10.1 g WW m^{-2}, and the average species richness was 87% of the maximum value. If part of the North Sea was closed to fishing, biomass and production in the closed area began to recover, while biomass and production in the area that remained open to fishing decreased. The net effect of area closures is the sum of these two effects. The fishery in 2002 and all the scenarios considered had relatively similar effects on the production, biomass, and species richness of the benthic community, leading to reductions of around 18% (relative to the unimpacted condition) in benthic biomass, 4.5% in benthic production, and some 12% in the number of cells where no species were lost through trawling (Table 2). In general, the management scenarios had a stronger impact on biomass than on production. Over the period of 25 years, some area closures had a positive effect, while others, through displacement of effort, had a negative effect on the overall biomass, production, and species richness of benthic communities (Table 2). If effort in the evaluated area was not standardized to 100%, scenarios 1−6 had a negative impact on biomass, production, and species richness. Only scenario 7 (closure of the area that represents low catches by any fleet) had a positive effect on benthic communities. Scenarios 8−11, which reduced total fishing effort, all had a positive effect on the benthic community, and the effect on biomass, production, and species richness was strongly correlated with the reduction in total effort ($r > 0.995$).

If effort in the evaluated area was standardized to 100% of pre-management levels, scenarios 3−5 had a negative impact on biomass, scenarios 3 and 5 on production, and scenarios 3 and 4 on species richness. Scenarios 6 and 7 had a relatively large positive effect on the benthic community. This shows that effort redistribution within the study area can affect benthic communities, although comparison with the non-standardized results shows that changes in total effort attributable to vessels moving into and out of the study area are equally important. In general, closing large areas that contributed a large fraction to catches (scenarios 1−5) had a negative effect, while closing areas that contributed little to catches had a positive effect (scenarios 6 and 7). The positive effects of management developed more slowly than negative effects.

Discussion

While the full international data needed to parameterize the effort redistribution model and to assess the small-scale distribution of fishing effort using VMS were not available, we have shown how it is possible to assess the environmental consequences of area closures and effort reductions in the context of an EAF. Notwithstanding the progress that has been made with methodological development, the constraints on compiling and accessing basic fishery data are an ongoing impediment to operationalizing an EAF in the North Sea and other EU waters. Because we measured the effects of only a small proportion of the international beam trawl fleet, the estimated *status quo* impacts of trawling in 2002 (18.4% reduction in biomass, 4.6% reduction in production, and 12.4% reduction in cells with no species loss relative to no trawling) were smaller than those that have been estimated when the effects of the international beam trawl fleet were considered in the same area (56% reduction in biomass and 21% reduction in production, Hiddink *et al.*, 2006), and the relative effects of the different scenarios on benthic communities will be less than if these scenarios were applied to the international beam trawl fleet. Nevertheless, the predicted responses of the benthic community to the different management scenarios clearly illustrate that managers acting in accordance with an EAF have to understand how management actions such as area closures affect effort distributions and, consequently, non-target species and habitats. The key results from this analysis are (i) that area closures in areas where existing fishing effort is low will lead to less effort displacement and are more likely to benefit benthic communities than closures in areas where fishing effort was high, and (ii) that effort reductions resulting from days at sea restrictions and decommissioning schemes are likely to reduce the spatial footprint of fishing activity and to provide benefits for benthic communities. These results apply when habitat types are relatively homogeneous, but they may not apply among habitats when there is significant variability in habitat type. Within habitat types, the results imply that a simple and effective goal of an EAF would be to minimize the area physically impacted by trawls for any given level of trawling effort. Long-term progress towards this goal would be supported by closing areas of habitat where there was no track record of trawling.

The observation that some area-closure scenarios had positive effects on benthic communities, while others had negative effects, was a consequence of the relationships between effort displacement and spatial patterns in recovery time. If the areas closed to fishing have low levels of production because of high natural disturbance, and/or recover quickly after disturbance, then closure tends to have a negative effect, because trawling effort may redistribute to more productive habitats with longer recovery times (e.g. scenario 3). If the closed areas have high production in the absence of disturbance, and effort is displaced to areas where production is low, then closure is more beneficial (e.g. scenarios 6 and 7). As our approach takes account of trawling history and the existing state of the benthic community, the long- and short-term effects of area closures can be different. For example, with scenario 4s, the short-term effect of the area closure is negative, with minimum benthic biomass after about 15 years, but after 55 years the closure starts to have a net positive effect. Although the estimated time needed for recovery may be overestimated because the model does not include variable recruitment or migration (Hiddink *et al.*, 2006), this pattern suggests that previous trawling history should not be ignored when choosing closed areas. The pattern is also relevant because it implies that temporary or rotating area closures, which are unlikely to allow time for recovery and effectively lead to greater homogeneity of trawling disturbance (Dinmore *et al.*, 2003) are likely to have a more negative effect on benthic communities than no closure. If temporary or rotating closures were required by managers, then our model would allow the effects of different closure cycles to be investigated.

Central to discussions of EAF are the ecological implications of management actions. Previous studies show that it is unclear whether closed areas have fishery benefits (Willis *et al.*, 2003). The results of our study show that creating areas that are closed to fishing without reducing overall trawling effort may or may not have conservation benefits, depending on the areas closed. To identify management solutions that are optimal/least costly for both the fishery and the ecosystem, areas that are most and least sensitive to trawling have to be identified (Hiddink *et al.*, in press) and fishing effort distributed accordingly, for example using individual habitat quota (Holland and Schnier, 2006).

Both the model of effort reallocation and the model of the effects of trawling disturbance on benthic production, biomass, and species richness rely on a number of assumptions, as described in detail during their development (Duplisea *et al.*, 2002; Hutton *et al.*, 2004; Hiddink *et al.*, 2006). While the effort reallocation model has been validated with data describing the effects of a temporary large-scale area closure in the North Sea during 2001 (that was designed to protect cod, the so-called "cod box"), and the benthic model was validated with extensive data describing trends in biomass, production, and species richness on gradients of trawling effort in different North Sea habitats (Hiddink *et al.*, 2006), the outputs will not reflect the complexities of response to management action that might be observed in real fisheries. In particular, our approach did not account for those fishers that deliberately seek out new fishing grounds when their usual fishing grounds are closed − a type of behaviour that was observed using VMS data during the 2001 cod box closure (Rijnsdorp *et al.*, 2001; Dinmore *et al.*, 2003) and which would have disproportionately large impacts on benthic communities that had not been previously fished (Hiddink *et al.*, 2006). This means that the real effect of introducing closures in intensively trawled areas is likely to be more negative than reported herein, further supporting the hypothesis that closures in rarely trawled and untrawled areas will minimize aggregate trawling impacts on benthic biomass, production, and species richness. Distance to fishing grounds was not considered in the effort-allocation model, but may be a key factor that could be included in future developments, and it may add significantly to the prediction capability of the model. A limitation of our approach is that it does not account for interactions between the benthos and the exploited fish. Large-scale closures such as scenarios 3 or 6 may result in a significant recovery of fish that feed on benthic invertebrates. Therefore, there may be significant effects on the benthos (Frank *et al.*, 2005; Heath, 2005). The size of this effect depends on the recovery rate of the predators in the absence of fishing mortality, and the strength of their effects on prey species. This means that we may have overestimated any positive effects of area closures on the benthic communities.

Our results emphasize the importance of assessing the ways in which management regulations alter the spatial distribution of fishing effort. For well-informed planning of area closures that are intended to support management of target stocks or broader “nature conservation” objectives, knowledge of the distribution of benthic habitats, their vulnerability to trawling, the current trawling regime, and the expected future trawling regime are necessary. Within an EAF, assessment of the implications of area closure should reasonably be extended to account for the effects of effort displacement on vulnerable non-target fish species as well (Walker and Hislop, 1998). In political decision-making, the direct effects of closed areas on the fished species are likely to carry more weight than ancillary effects such as mitigation of trawling disturbance, because in economic terms, mitigating losses in production of benthos is of little weight if the closures are not protecting the fishery. Our results emphasize that it cannot automatically be assumed that area closures have conservation benefits, as is assumed in some studies (e.g. Roberts *et al.*, 2001).

We demonstrate an effective approach for assessing the environmental consequences of fishery management action that can be used to inform management decision-making as part of an EAF. A concerted international effort would be needed to operationalize our approach at the scale of the North Sea. This would require compiled international data for bottom-trawl fleets to parameterize the effort redistribution model, knowledge of rates of benthic mortality imposed by gears other than beam trawls, compiled data on the benthic habitats of the North Sea, and knowledge of the interaction between fleets. This would need to be accompanied by consideration of appropriate targets for trawling impacts on benthic biomass, production, or species richness, based on the role of benthic communities in the ecosystem, as well as political commitment to the conservation of biodiversity.

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Appendix

ICES rectangles that were closed or left open in scenarios 1−7. Columns 1−5 and 7 indicate the rectangles that were closed in those scenarios. Column 6 indicates the rectangles that were left open in scenario 6.

1	2	3	4	5	6	7
Closed	Closed	Closed	Closed	Closed	All closed except	Closed
32F2	31F2	31F2	32F2	31F2	31F2	36F2
32F3	32F2	31F3	32F3	32F2	32F2	36F3
37E9	32F3	32F2	33F3	32F3	32F3	37F2
41F7	33F3	32F3	34F3	33F3	33F2	37F3
42F6	33F4	33F2	35F2	34F2	33F3	38F2
42F7	34F4	33F3	37F1	34F3	34F2	38F3
43F6	37E9	33F4	37F2		34F3	39F1
43F7	38E9	34F2	38F6		35F2	39F2
43F8	41F6	34F3	39F6		35F3	39F3
44F5	41F7	34F4	40F6		36F2	40F1
44F8	42F6	37E9	41F6		36F3	40F2
44F9	42F7	37F0	41F7		36F4	40F3
44G0	43F5	37F2	43F8		36F5	41F1
48E6	43F6	38E9	44F9		37F1	41F2
49F0	43F7	40F5			37F2	41F3
49F2	43F8	41F6			37F3	42F1
50E8	44F5	41F7			37F4	42F2
50F0	44F8	42F5			37F5	42F3
	44F9	42F6			37F6	43F1
	45F3	42F7			38F4	43F2
	45F4	43F5			38F5	44F1
	46F3	43F6			38F6	44F2
	47E6	43F7			39F2	45F1
	47F2	43F8			39F3	45F2
	48E6	43F9			39F4	46F1
	48E9	44F4			39F5	46F2
	49E6	44F5			39F6	47F1
	49E7	44F8			39F7	47F2
	49F0	44F9			40F4	48F1
	49F1	44G0			40F5	48F2
	49F2	45F0			40F6	49F1
	50E7	45F3			40F7	49F2
	50E8	45F4			41F5	
	50E9	45G0			41F6	
	50F0	46E6			41F7	
	50F2	46F3			42F6	
	50G0	47E6			42F7	
	51E9	47E9			43F7	
		47F0			43F8	
		47F2			44F9	
		47F3			44G0	
		48E6				
		48E7				
		48F0				
		48F2				
		49E6				
		49E7				
		49E8				
		49F0				
		49F1				
		49F2				
		50E7				
		50E8				
		50E9				
		50F0				
		50F1				
		50F2				
		51E8				
		51E9				
		51F0				
		51F1				