ICES Journal of
Marine Science

ICES Journal of Marine Science (2013), 70(6), 1085–1096. doi:10.1093/icesjms/fst066

Original articles

A proposed method for assessing the extent of the seabed significantly affected by demersal fishing in the Greater North Sea

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Diesing, M., Stephens, D., and Aldridge, J. 2013. A proposed method for assessing the extent of the seabed significantly affected by demersal fishing in the Greater North Sea. – ICES Journal of Marine Science, 70: 1085–1096.

Received 29 January 2013; accepted 4 April 2013; advance access publication 19 June 2013.

The widespread impact of bottom towed fishing gear on benthic species and communities has long been recognized. The responses to a given intensity of fishing disturbance can be influenced by the extent to which these species and communities are preconditioned to disturbance by natural processes, in particular waves and currents. The advent of vessel monitoring system (VMS) and models of natural disturbance enable high-resolution and large-scale comparisons of fishing and natural disturbance. VMS data were employed to estimate the trawled area per 12 km by 12 km grid cell. We then quantified natural disturbance by estimating the number of days in a year the seabed was disturbed by tides and waves. As natural disturbance acts on large spatial scales, we assumed that each natural disturbance event affects whole grid cells. Frequencies could thus be translated into an area of impact, allowing us to compare fishing with natural disturbance. We show how such comparisons can be used to estimate the extent of different seabed substrate types significantly affected by demersal fishing. A measure of the probability that fishing disturbance exceeds natural disturbance provides one metric for identifying areas of significant trawling impact on seabed habitats and might be used to measure progress towards achieving good environmental status for sea-floor integrity within the context of the European Union's Marine Strategy Framework Directive. For more than half the seabed in the English sector of the Greater North Sea, the results suggest that disturbance attributable to demersal fishing exceeds natural disturbance based on data from the years 2006 to 2008. The imbalance between natural and fishing disturbance is greatest in muddy substrates and deep circalittoral habitats.

Keywords: disturbance, English Channel, fishing, good environmental status, North Sea, sea-floor integrity.

Introduction

Seabed disturbance by demersal fishing gear (beam trawls, bottom otter trawls, and dredges) is recognized as a significant source of anthropogenic disturbance to continental shelf habitats worldwide (e.g. Kaiser *et al.*, 2002; Thrush and Dayton, 2002). Eastwood *et al.* (2007) assessed direct, physical anthropogenic pressures on the seabed in United Kingdom (UK) waters. They found that demersal trawling had a greater footprint than all other physical pressures, such as oil and gas, cables, wind farms, aggregate extraction, waste disposal, and fishing, combined. In a cumulative impact assessment of human pressures on seabed habitats of the UK shelf area, Foden *et al.* (2011) concluded that benthic fishing accounted for 99.6% of the spatial footprint. Consequently, information on the extent and significance of seabed disturbance caused by demersal fishing gear is basic to the assessment of anthropogenic impacts on seabed habitats, including an assessment of the "Extent of the seabed significantly affected by human activities for the different substrate types" proposed in the Marine Strategy Framework Directive (MSFD indicator 6.1.2; European Commission, 2010; Rice *et al.*, 2012).

In any given habitat, the associated communities will have adaptations and life styles that increase their resistance or resilience to an envelope of naturally occurring disturbance conditions (Kaiser *et al.*, 2002), such as hydrodynamics (waves and currents) and bioturbation (Hall, 1994). The relative impact of fishing on habitats and benthic community structure is therefore partly dependent on the balance between fishing and natural disturbance (Jennings and Kaiser, 1998; Kaiser, 1998). Fishing disturbance is likely to have a more significant impact if it exceeds the background levels of intensity and frequency of natural disturbance (Kaiser *et al.*, 2002). Shallow tide-swept and wave-impacted sandy habitats exhibit faunal communities that are well adapted to high rates of mortality

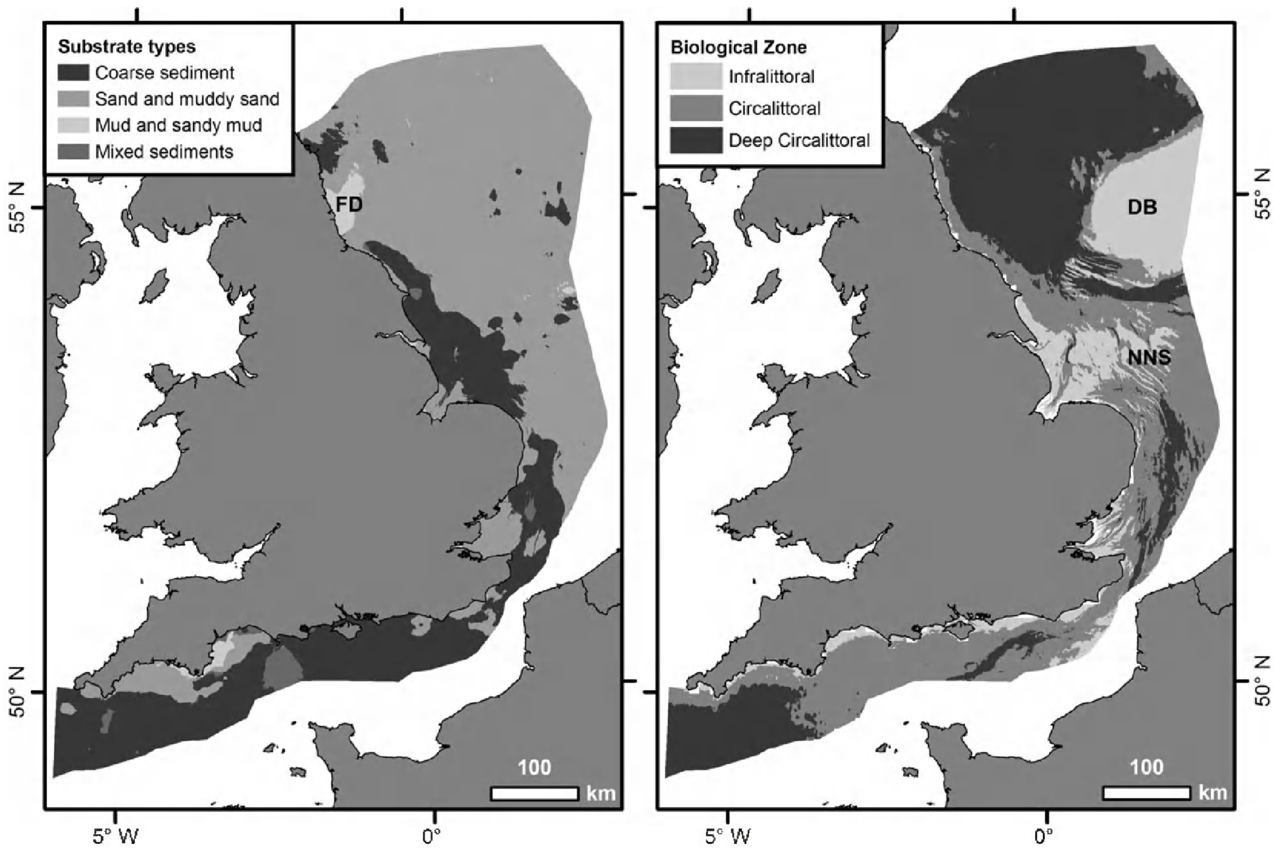

Figure 1. (Left) Substrate types in the English part of the GNS based on predictions from Stephens *et al.* (2011). (Right) Predicted biological zones in the same region (Cameron and Askew, 2011). FD, Farnes Deep; DB, Dogger Bank; NNS, North Norfolk Sandbanks.

and natural disturbance. These communities show greater resilience to fishing disturbance as well (e.g. Kaiser *et al.*, 1998). Conversely, deep and stable seabed habitats are often characterised by slow-growing, habitat-modifying species for which demersal fishing can have major and long-term impacts on biomass and diversity (Jennings and Kaiser, 1998; Watling and Norse, 1998). For example, Collie *et al.* (2000) showed that the impact of bottom fishing on emergent colonial epifauna is marked in deep (80–90 m) water, but insignificant in shallow (42–49 m) water on Georges Bank (east coast of North America). Hiddink *et al.* (2006b) employed a size-based model in an assessment of bottom trawl fishing of benthic fauna in different habitats. They found that the impacts of trawling were greatest in areas with low levels of natural disturbance, whereas trawling impacts were limited in areas with high rates of natural disturbance.

Recognizing that the response of benthic communities to fishing pressure will be linked to the balance between fishing and natural disturbance, we developed an approach that may help to support the monitoring, assessment, and reporting needs of the MSFD. Because demersal fishing disturbance is by far the most widespread human pressure affecting the seabed, the present methodology considers this pressure only. We assumed that relative impact of fishing disturbance was dependent on the frequency and intensity of natural disturbance. Fishing disturbance to the seabed caused by demersal fishing gear was estimated with vessel monitoring system (VMS) data from UK and foreign vessels deploying demersal fishing gear. Natural disturbance was estimated with hydrodynamic models by predicting the number of days in a year wave and/or current stress exceeded a grain size-dependent threshold. Using this information, we mapped the probability that natural disturbance exceeded fishing disturbance. We also assessed fishing disturbance on different substrate types (coarse sediment, sand and muddy sand, mud and sandy mud, and mixed sediments) and biological zones (infralittoral, circalittoral, and deep circalittoral).

Methods

Study site

The methods were applied in the English sector of the Greater North Sea (GNS) subregion (North Sea and English Channel, Figure 1). The seabed sediment composition (Stephens *et al.*, 2011), mapped according to the classification of Long (2006), is dominated by sandy substrates in the North Sea and coarse sediments in the English Channel (Figure 1, left). Muddy and mixed sediment substrates are locally restricted. Bedrock outcrops are present within the study site (e.g. Diesing *et al.*, 2009; Coggan and Diesing, 2011, 2012) but we did not include rock in the assessment because rock is spatially limited and accounts for just over 1% of area of seabed and is not subject to natural disturbance in the way we have defined it (see below). The spatial distribution of biological zones (Cameron and Askew, 2011) is shown in Figure 1 (right panel). The infralittoral zone, i.e. euphotic seabed, is limited to a narrow zone along the coasts down to ca. 10–20 m water depth, with a few notable exceptions. These include Dogger Bank and the North Norfolk Sandbanks in the North Sea as well as sandbanks in the eastern English Channel. The circalittoral zone (disphotic/aphotic seabed above the wave base) is situated in intermediate water depths down to ca. 50–60 m water depths. Deep circalittoral seabed (below the wave base and typically aphotic) is mainly limited to the western English Channel and the northern North Sea.

Disturbance

In the context of this study, physical disturbance was defined as the movement of surface layers of the seabed substrate. Physical disturbance can be caused by hydrodynamics, bioturbation, and human activities (Hall, 1994). Here, we restrict our analysis to waves and currents ("natural disturbance") and demersal fishing ("fishing disturbance"). We carried out our analysis on a common spatial grid with a resolution of ~12 km (determined by the grid resolution of the hydrodynamic model) encompassing the years 2006–2008. Data sources and analysis methods will be described in the following.

Fishing disturbance

VMS data for UK and non-UK registered vessels employing demersal fishing gear were obtained from the Marine Fisheries Agency (MFA) of the Department of Environment, Food and Rural Affairs (Defra). Preprocessing of the data was carried out in the manner defined by Lee *et al.* (2010). The basic steps included: (i) removal of duplicate records, (ii) removal of observations in ports, (iii) calculation of the time interval between pings, (iv) establishing the fishing gear used by each vessel, (v) filtering fishing from non-fishing observations based on speed rules, and (vi) estimation of the spatial distribution of fishing effort by aggregating observations to grid cells.

Although Lee *et al.* (2010) described fishing effort based on time spent fishing per unit area by making assumptions about gear dimensions, we convert this to the area of seabed impacted (detailed below). Gears affecting the seabed, such as dredges, beam trawls, and bottom otter trawls, were included in the analysis. The gear classification for UK vessels could be carried out with a high confidence as the gear type being used was taken from the vessels logbook. For non-UK vessels, this information was not available so the gear type was taken from the EU vessel register. Consequently, there was a lower confidence in the gear type used by non-UK registered vessels.

It is important to consider the spatial resolution of the analysis when calculating trawling intensities, as the representation of fishing intensity will depend on the scale at which the analysis is carried out. This can be especially important when considering the impact on the benthic system (Dinmore *et al.*, 2003; Mills *et al.*, 2007; Piet and Quirijns, 2009). In fact, the maximum fishing intensity measured and the total area where no fishing is recorded will both be related to the spatial resolution of the analysis. Mills *et al.* (2007) investigated how well the total spatial extent of trawling in the North Sea was represented at different spatial resolutions. They suggested that a grid cell size of around 10 km should be used to capture the patchiness of trawling effort which is very close to the 12-km cell size used in this study.

Some authors (Eastwood *et al.*, 2007; Fock, 2008; Hintzen *et al.*, 2010; Russo *et al.*, 2011) have proposed methods for the interpolation of vessel tracks between VMS observations, which potentially allow for higher spatial and temporal resolution of analysis to be carried out. Such methods include linear interpolations which involve drawing a straight line between consecutive observations (Eastwood *et al.*, 2007). As straight line interpolations underestimate the real distance travelled and therefore the fishing impact, more advanced interpolation using splines have also been proposed (Hintzen *et al.*, 2010; Russo *et al.*, 2011). The latest method takes into account vessel speed and heading of the observations in an attempt to create a more realistic representation of the vessel track between observations. Splines have been shown to be more accurate than linear interpolations. Although these methods attempt to refine the process of calculating trawl impacts from VMS data, it is still not clear what the implications are of choosing to interpolate vessel tracks vs. discrete observations at different spatial scales. Because of the relatively coarse grid cell being used as well as aggregating observations over a year, we assume that the discrete VMS observations will sufficiently capture the patterns of fishing effort and vessel track interpolation was not attempted.

To obtain estimates of fishing disturbance to compare with natural disturbance, we assumed that each VMS observation represents an area of impacted seabed. The following gear widths are imposed to represent the area of seabed affected: beam trawls, 2 × 12 m beams; otter trawls, 2 × 2 m otter boards; and shellfish dredgers, 24 × 0.85 m dredges (Eastwood *et al.*, 2007 and references therein). The area trawled (A_T) per grid cell for n observations (VMS pings) was calculated using Equation (1):

$$A_T = \sum_{i=1}^{n} S_i I_i w_i, \tag{1}$$

where S is the vessel speed, I the VMS ping interval, w gear width, and i refers to a given VMS observation.

The derived values of A_T were then converted to the trawled proportion (T) of the grid cell [Equation (2)], which is the metric used for comparison with the natural disturbance model.

$$T = \frac{A_T}{A_g}, \tag{2}$$

where A_g is the sea area of the grid cell. $T = 1$ if an area equivalent to the area of the grid cell is fished once per year.

As well as the explicit assumptions made about the gear widths and using speed as a proxy for fishing/non-fishing activity, there are implicit assumptions made when estimating the area fished using this method: (i) the speed at the time of observation (ping) is maintained until the next ping and (ii) the vessel remains within the same grid cell between pings.

Natural disturbance

Natural disturbance was quantified by estimating the number of days in a year the seabed was disturbed by tides and waves. Full details will be given in a forthcoming publication and only a summary is given here. The seabed substrate was classified as gravel, sand, or mud based on the predominant sediment type. This avoided dealing with mixed sediments whose behaviour is relatively unknown but still limits the confidence of prediction in regions where highly heterogeneous sediments occur. For mud–sand mixtures, fully cohesive behaviour was assumed when mud content exceeded 15%. At the resolution of the model grid, none of the locations could be classified as pure mud and therefore unequivocally expected to show cohesive behaviour. Grain size data were available from the British Geological Survey (BGS) covering the North Sea and English Channel with a variable sampling density averaging to around 5 km between sample stations. Information on gravel substrates in the English Channel was obtained from Cefas' own data holdings (e.g. Coggan *et al.*, 2012). Additionally, sediment type and grain size were obtained from the North Sea Benthos Survey (NSBS) (Basford *et al.*, 1993). All datasets included a breakdown of the seabed sediments into percentage mud, sand, and gravel and median size for the sand grain fraction. Only the data collected by Cefas included the measurements of the grain size of the gravel fraction. To estimate the gravel size in regions where there were no measured values, the Cefas data were used to derive a relationship between the sand–gravel ratio (available from all the datasets) and the median diameter of the gravel fraction.

Hydrodynamic conditions at the seabed were obtained from modelled hourly wave and current conditions for the years 2006–2008 on a grid with resolution 1/6 degree longitude and 1/9 degree latitude (∼12 km) undertaken by the National Oceanography Centre Liverpool (Brown *et al.*, 2010). Model outputs used were depth mean current, seabed wave orbital velocity, and seabed wave zero crossing period. Where required, these were converted to an appropriate seabed stress using the grain size roughness and, where total wave–current stress is needed, a wave–current interaction model. The response of the seabed to the simulated wave and current conditions was calculated based on a synthesis of existing predictive relationships derived from laboratory and field observations as described below. To account for uncertainty, a probabilistic approach based on Monte Carlo simulations was used. Simulation parameters were drawn from a probability distribution representing the uncertainty associated with the relationships used to predict natural disturbance. The resulting output yields a cumulative distribution function giving the probability χ that the number of days of disturbance per year exceeded a given value.

For locations classed as gravel, disturbance was assumed to occur when the threshold for the initial movement of sediment was exceeded. This was calculated based on the non-dimensional stress (Shields number) using the total wave–current stress. Paphitis (2001) gives upper and lower Shields threshold curves based on a range of observational and laboratory data, and these were used to define a probability distribution of values. A probability of 1 was assigned if the wave current Shields number was at or above the upper threshold, and zero if it was at or below the lower threshold curve limit, with a log-uniform (reciprocal distribution) scaling in-between.

For locations classed as sand, disturbance was calculated based on predicting the occurrence of wave and current ripple height as a function of median grain size and the local instantaneous wave and current conditions. As a sensitivity test, two formulae were considered (Soulsby and Whitehouse, 2005; O'Donoghue *et al.*, 2006). A tentative prediction of the occurrence and height of "Large Wave Ripples" (Li and Amos, 1999) was also included. The bedform height formulae were assumed to give the mean of a log-uniform probability distribution of bedform heights based on the characteristics of the scatter in the observational data.

The disturbance of the cohesive muddy substrate was based on the probability of extreme events. A number of workers (e.g. Amos *et al.*, 1992) have identified distinct modes of erosion for cohesive muddy sediments. Structural (or "type II") erosion can occur when the applied hydrodynamic shear stress exceeds values in the range of 4–10 N m^{-2} and is associated with the breakdown of the bed structure and erosion to depths likely to be of biological significance. Thus, for mud beds, "disturbance" was deemed to have occurred if a type II erosion event was predicted due to the occurrence of an extreme hydrodynamic bed stress. This requires an assumption about the probability distribution of wave velocity amplitude at the bed. Following You (2009), we assumed a modified Rayleigh distribution. Thresholds for the erosion of cohesive muddy beds are often site-specific and depend on the state of consolidation of the sediment. Monte Carlo simulations assumed the probability distribution of threshold stress for type II erosion was uniformly distributed in the range 4–10 N m^{-2}.

To make the definition of disturbance independent of the time resolution of the modelled waves and currents, a fixed "averaging" period was adopted and the probability of a natural disturbance "event" was calculated within each averaging period. Thus, multiple disturbances during the averaging interval were counted as a single event. Within the averaging period, predicted hydrodynamic conditions change at the resolution of the model output (in this case hourly). The averaging interval adopted was chosen to be 1 d on the grounds that this is a typical time-scale for a storm and thus a storm would count, as far as possible, as a single disturbance event. Clearly, a "storm" may extend over a day and a shorter wind event may straddle two successive days, so the number of days that disturbance is predicted may be sensitive to the particular choice of averaging period.

Comparing fishing and natural disturbance

The fishing disturbance was estimated as the area of grid cell fished, whereas the natural disturbance was estimated as the number of disturbance events for a grid cell. As natural disturbance acts on large spatial scales, we make the assumption that each natural disturbance event affects the whole grid cell. Frequencies can thus be translated into an area of impact, comparable with the description of fishing disturbance.

In areas where the substrate is classified as sand, the output of the natural disturbance model provides the cumulative probability distribution (χ) for the number of days in a year the bed is disturbed to a given depth. The aim is to obtain the probability that natural disturbance is greater than fishing disturbance ($\chi_{\mathrm{ND}>T}$). To do this, we need to select the probability value for natural disturbance that is greater than T. For example, if the area fished (in a year) in a grid cell is calculated to be twice the area of that cell ($T = 2$), then the probability that natural disturbance is greater ($\chi_{\mathrm{ND}>T}$) is the probability that there are >2 natural disturbance events in that year affecting the whole grid cell (assumption above), so in this case: $\chi_{\mathrm{ND}>T} = \chi_3$. For sandy substrates, weighted χ values are taken according to the assumed penetration depths of the different gears (described below).

Information on the penetration depths of the trawl gear is needed in the analysis, but such information is limited. For example, Linnane *et al.* (2000) compiled a table of penetration depths of otter boards and beam trawls over different substrates. The observed depth of penetration varied within and among the gear type and the substrate. Penetration depths on sandy sediments were up to 7 and 5 cm for beam trawls and otter boards, respectively. Another study by Gilkinson *et al.* (1998) highlights that scour from otter trawl doors was <3 cm in depth on the sandy substrate. Anon. (1995) reports that in the North Sea Beam trawl, shoes and chains penetrated to a depth of >6 cm, otter doors to a depth of 8 cm, and scallop dredges 3–4 cm.

To account for the uncertainty in penetration depth, we decided that the effort should be distributed across a range of depth values. The sum trawling effort within each grid cell was divided into three fractions each representing a penetration depth value. For the purposes of this study, the penetration depth distribution was fixed across gears and all grid cells. The values chosen for the distribution of penetration depths assigned to the proportion of trawling effort are: 3 cm, 0.4; 4 cm, 0.5; and 5 cm, 0.1.

The probability that natural disturbance is greater than fishing disturbance $\chi_{ND>T}$ was obtained by summing the weighted χ values for each gear type, as shown in Equation (3):

$$\chi_{ND>T} = f_{BT}\chi_{ND>BT} + f_{OT}\chi_{ND>OT} + f_{DR}\chi_{ND>DR}, \quad (3)$$

where f_g is the proportion of total effort associated with gear type g (BT, beam trawl; OT, otter trawl; DR, dredge). If the proportion of the area trawled for a given gear type is $T_g = \text{n.d}$, where n is the integer part and d the decimal, this is interpreted as meaning a proportion of the area (d) is trawled $n + 1$ times and the proportion $(1 - d)$ is trawled n times. Therefore, the probability that natural disturbance is greater than fishing disturbance for each gear type is obtained from Equation (4):

$$\chi_{ND>g} = d\hat{\chi}_{n+2} + (1 - d)\hat{\chi}_{n+1}, \quad (4)$$

where $\hat{\chi}_i$ is the natural disturbance χ_i value weighted by the assumed penetration depth distribution obtained using Equation (5):

$$\hat{\chi}_i = \sum_{d=3}^{5} \chi_{id} p_d, \quad (5)$$

where d is the depth and p the assumed probability of gear penetration.

The natural disturbance model is limited to predicting the depth of disturbance in sandy substrates. In substrates classified as gravel or mud, a χ value is given for disturbance but no indication of depth is associated with it (the substrate is either disturbed or not). For these areas, it is assumed that the depth of any natural disturbance would equal any trawling disturbance and depth of gear penetration is not considered.

The probability that fishing disturbance is greater than or equal to natural disturbance ($\chi_{ND<T}$) is $1 - \chi_{ND>T}$, as both probabilities sum to 1 ($\chi_{ND>T} + \chi_{ND<T} = 1$). We therefore assume that grid cells with a probability $\chi_{ND>T} > 0.5$ characterise areas where natural disturbance is greater than fishing disturbance. For the remaining grid cells, we assume that fishing disturbance is significant, i.e. larger than natural disturbance. For these cells, the fishing disturbance data were grouped into three classes (low T_{sig}, moderate T_{sig}, and high T_{sig}) using the Jenks natural breaks classification method to define the class boundaries. It should be noted that these classes do not indicate the extent to which fishing disturbance exceeds natural disturbance; rather, the data show the intensity of fishing disturbance in areas where fishing is greater than natural disturbance.

To derive the areas significantly affected by demersal fishing for different substrate types and habitats, we carried out an analysis in a GIS using the Union tool and calculated the areas in km^2.

Results

Fishing disturbance

The western and eastern English Channel are subject to the highest fishing activity in terms of hours fished per year by any bottom towed gear (beam trawl, otter trawl, and scallop dredge; Figure 2, left), but as different bottom gears have different footprints on the seabed, a focus on hours fished can be misleading when studying fishing disturbance. This is highlighted for the northern North Sea where the large number of hours per year is not always reflected in the mean trawled proportion T (Figure 2, compare left and right panels). This is because the dominant gear used in these locations is the otter trawl, which has a relatively small footprint. Lowest fishing disturbance tends to be in the deeper waters of the North Sea or where the ground is hard (e.g. central English Channel; Figure 2, right).

Natural disturbance

The modelled probabilities of disturbances at two sediment depths (1 and 4 cm) for frequencies of >1, >10, and >17 d per year are presented in Figure 3. It is likely that most of the seabed of the GNS is disturbed to a depth of 1 cm on more than 1 d per year ($\chi_{ND} = 0.8–1.0$; Figure 3, top left), although less so in muddy and gravelly areas off the northeast coast (Farnes Deep) and central English Channel, respectively. The overall picture does not change significantly with increasing disturbance frequencies apart from the northernmost corner of the North Sea (Figure 3, top centre and right). The probability of deeper disturbance, to 4-cm depth more than once per year, is nearly certain (χ_{ND} in range 0.8–1.0) primarily for the Dogger Bank and inshore regions of the western English Channel (Figure 3, bottom left). The occurrence of deep disturbance events is increasingly unlikely with increasing frequencies for most parts of the GNS (Figure 3, bottom centre and right).

Comparing fishing and natural disturbance

The probability of natural disturbance being greater than that of fishing disturbance is spatially variable across the GNS (Figure 4, left). Assuming that $\chi_{ND>T} > 0.5$ characterises areas where natural disturbance is greater than fishing disturbance allows us to identify and map those areas (Figure 4, right). Fishing disturbance stays below natural disturbance levels in areas close to the coast and in shallow areas such as Dogger Bank and the North Norfolk Sandbanks (Figure 1). In the North Sea, areas of high natural disturbance tend to be located in water depths shallower than ~50 m. This is approximately equivalent to the wave base, the water depth down to which the influence of the largest surface waves is "felt" at the seabed. Natural disturbance in the North Sea is strongly governed by waves rather than tides because the substrate is primarily sandy here and current generated ripples affect only the top 1 cm of sediment. High levels of significant fishing disturbance occur in the eastern and western Channel and the southern North Sea.

Overall, almost half (45.1% or 70 552 km^2) of seabed is predicted to experience natural disturbance levels higher than fishing disturbance. Approximately 39.8% (62 241 km^2) of the total seabed is subject to low levels of significant fishing disturbance, 10.1% (15 831 km^2) to medium levels, and 4.9% (7698 km^2) to high levels (Figure 5).

The distribution of fishing disturbance also varies among substrate types (Figure 6). A significant proportion of the area of the coarse sediment is subject to high levels of natural disturbance. This finding might be surprising; however, note that "coarse sediment" comprises sand–gravel mixtures ranging from pure gravel to almost pure sands with gravel contents as low as 5%. "Sands and muddy sands" are the most abundant substrate (two-thirds of the total seabed area) in the GNS (Figure 1, left) and hence the distribution of fishing disturbance for this substrate most closely resembles that of the GNS as a whole (Figure 5). The remaining substrates ("mud and sandy mud" and "mixed sediments") are predominantly subject to low levels of significant fishing disturbance but are spatially restricted.

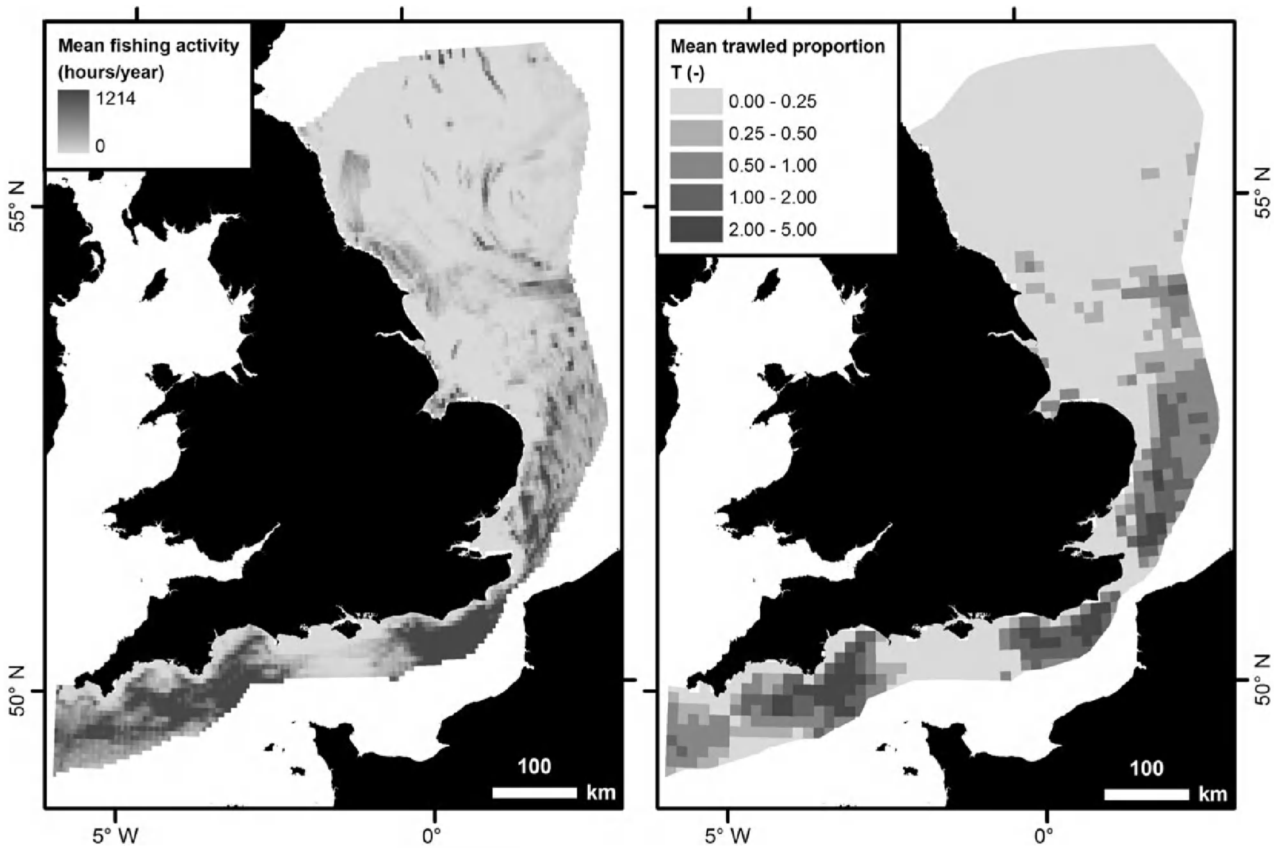

Figure 2. (Left) Fishing activity expressed as hours fished per year for demersal fishing gear (beam trawls, otter trawls, and dredges). A 2-s.d. stretch has been applied to these data. (Right) Trawled proportion of the seabed. Both panels show the mean values based on data covering the years 2006–2008.

Finally, we investigated the variation of fishing disturbance with biological zones as defined and mapped by Cameron and Askew (2011). The analysis reveals a characteristic progression across the biological zones (Figure 7). The shallow infralittoral habitats predominantly experience fishing disturbance at levels lower than natural disturbance. However, these habitats account for relatively small seabed areas (~18.6% of the whole). The relative importance of fishing disturbance increases with depth (expressed as biological zone) and is most pronounced in the deep circalittoral. This overall pattern indicates that the significance of fishing disturbance is likely to increase with increasing water depths as natural disturbance tends to decrease along the same depth gradient.

Discussion

Assumptions and limitations

Our aim was to develop a methodology that allows a direct comparison of physical seabed disturbance caused by the demersal fishing gear with natural disturbance due to waves and tides by further developing an approach by Stelzenmüller *et al.* (2008a). The rationale behind this is that areas experiencing high levels of natural disturbance typically harbour species that are capable of withstanding such environmental conditions. It could be argued that natural disturbance increases the resilience of benthic communities to fishing disturbance in at least two ways: first, resilience might be increased by selecting for fast-growing opportunistic species which quickly recolonise disturbed areas and are able to reach sexual maturity before the next disturbance event (Pianka, 1970). These species typically display small-size, short longevity and planktonic larval production traits. Second, naturally disturbed habitats may favour species which display traits that pre-adapt them to withstand the disturbance such as hard shells, deep-burrowing, and high mobility. The outlined methodology quantifies natural and anthropogenic disturbance on a common scale. We would, however, caution that there might be a qualitative difference between the two types of disturbance as the direct impact of the trawled fishing gear may not directly equate to the impact caused by sediment remobilisation. In that respect, our methodology might be better suited to account for resilience to fishing disturbance caused by selection for animals with a greater capacity to withstand a given mortality rate (the first case above).

Several assumptions had to be made when developing the methodology. These were highlighted in the "Methods" section and are summarised in Table 1. We think that all the assumptions we made are reasonable given the current knowledge. However, it appears that especially those assumptions relating to the impact of the different fishing gears on the seabed (assumptions 3, 14, and 15 in Table 1) are associated with the largest uncertainties. We will therefore briefly discuss these assumptions in the following.

Assumption 3 implies that only the doors of an otter trawl disturb the seabed. We used gear dimensions, including for otter trawls, that have been applied previously (Eastwood *et al.*, 2007). Hall (1999) states that for otter trawls, disturbance is largely restricted to the

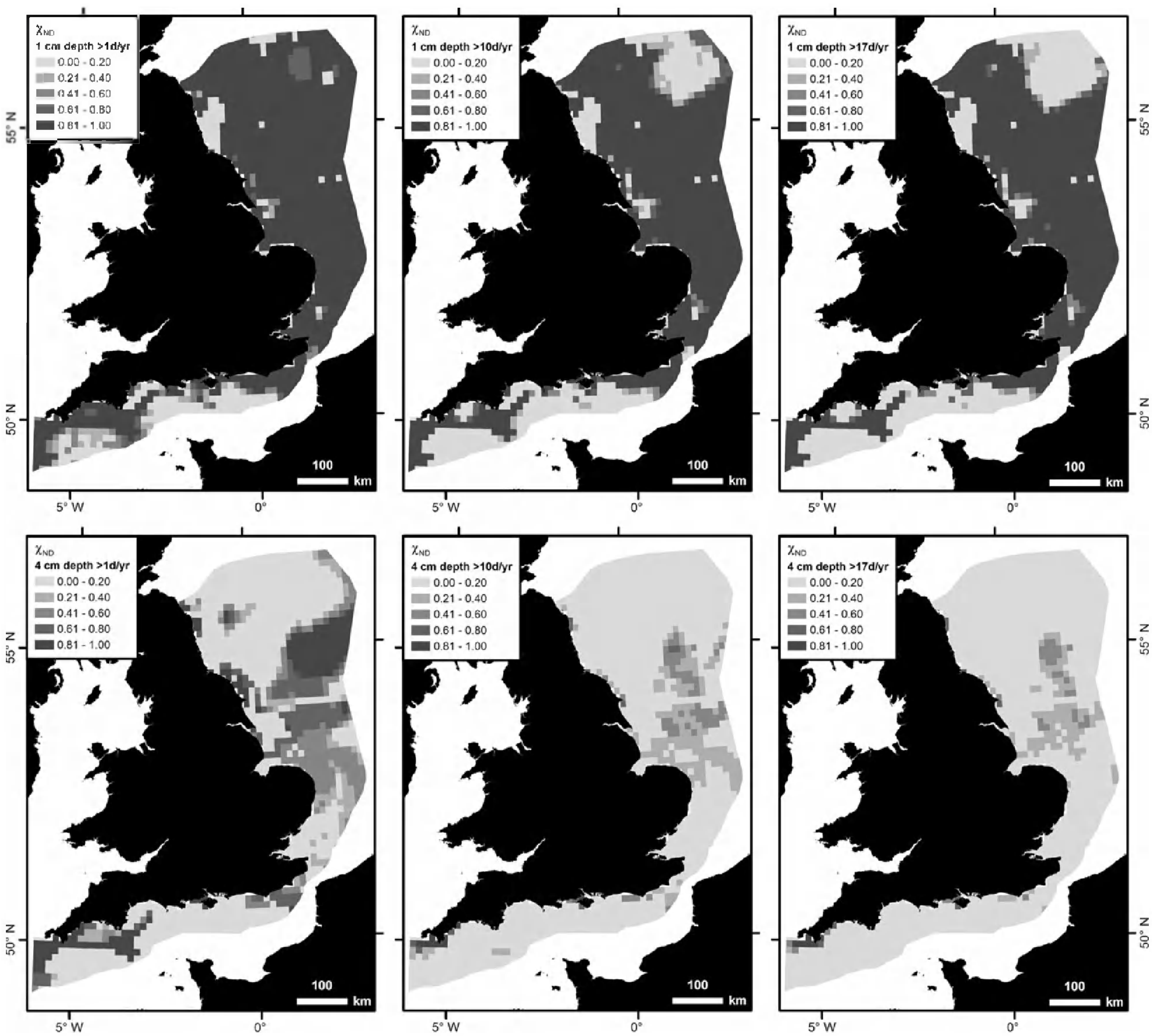

Figure 3. Probabilities of natural disturbance (χ_{ND}) of the seabed for different combinations of sediment depth (1 and 4 cm) and frequency ($>$1, $>$10, and $>$17 d year^{-1}) based on model results covering the years 2006–2008.

trawl doors. Sidescan sonar imagery of seabed affected by otter trawling typically shows tracks of otter doors that might be discernible for several months after trawling (Schwinghamer *et al.*, 1998). Other parts of the fishing gear touching the ground did leave no discernible marks in a study in Kiel Bay, Baltic Sea (Krost *et al.*, 1990). Although the authors caution that there might nevertheless be an impact on the seabed, this indicates that the impact by the otter trawl doors is dominant. The chosen gear dimensions might nevertheless underestimate the footprint for otter trawls, as the warps and footrope might detach certain epifauna (e.g. sea pens) from the seabed. Employing the full width of an otter trawl instead of the doors only would increase the gear width by an order of magnitude or more. A judgement had to be made and we felt that, on balance, the assumptions made by Eastwood *et al.* (2007) are defendable.

Assumptions 14 and 15 relate to gear penetration depths. As stated previously, reliable values of penetration depths for different gear types on different seabed substrates are relatively sparse. The problem is further confounded by the fact that the reported values exhibit significant scatter. Clearly, this indicates that more research is needed to address this knowledge gap. An interesting study in this respect was conducted by Ivanović *et al.* (2011). These authors modelled the physical impact of trawl components on the seabed employing a finite element model and compared results with laser line measurements carried out by scuba divers during sea trials. Although results are encouraging, the study was limited to the impact of otter doors and roller clumps and more research of this kind is needed for a better quantification of penetration depths of various fishing gears on different substrates.

Beyond that, there are shortcomings of the model that need to be discussed: general knowledge on the physics of seabed disturbance, although investigated for several decades, is still incomplete and consequently the predictions of natural disturbance are associated with some uncertainty. To account for this, we have adopted a probabilistic approach. In this way, we were able to associate a probability

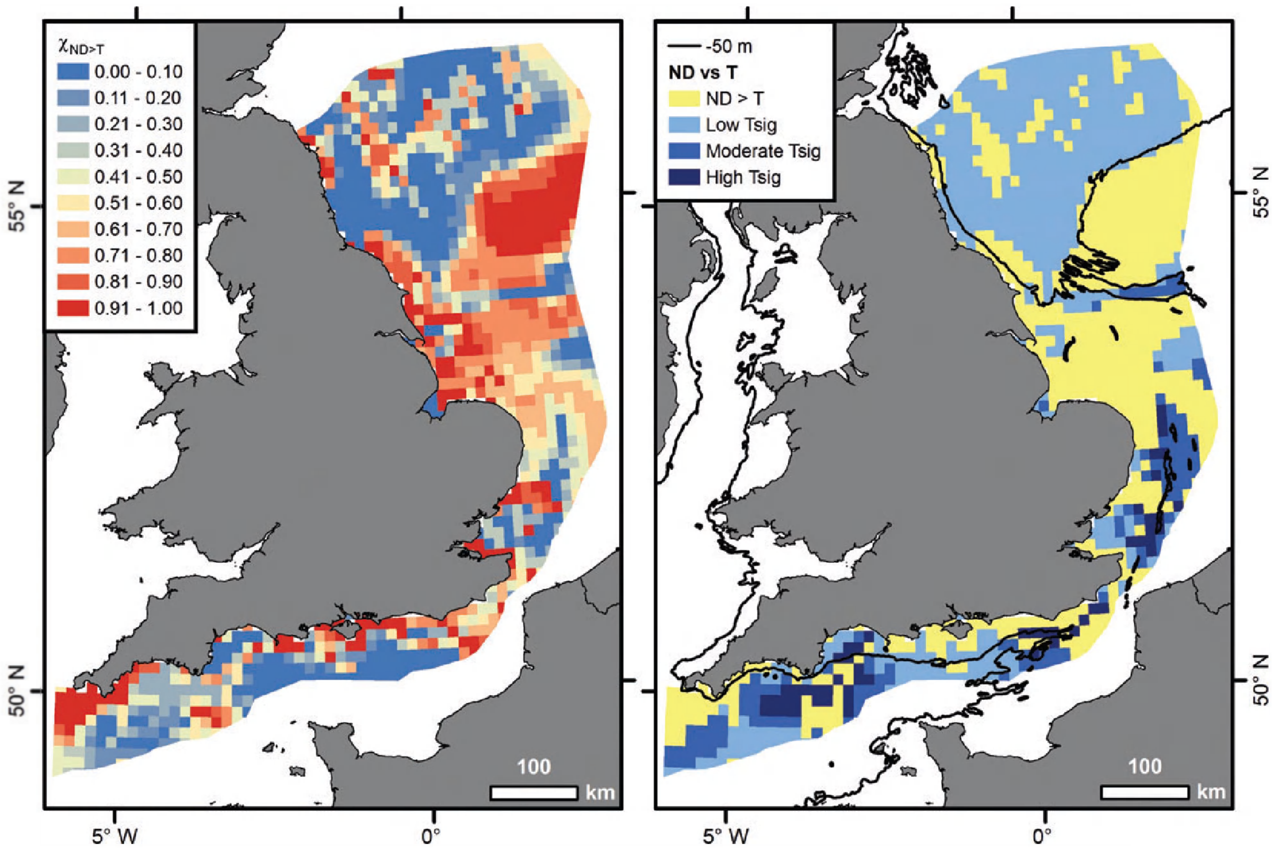

Figure 4. (Left) Estimated probability of natural disturbance ($\chi_{\rm ND}$) exceeding fishing disturbance (T). (Right) Comparison of fishing disturbance against natural disturbance: yellow indicates areas where natural disturbance is greater than fishing disturbance, assuming $\chi_{{\rm ND}>T} > 0.5$. Areas in blue indicate significant fishing disturbance ($T_{\rm sig}$), i.e. higher than natural disturbance levels. Areas of significant fishing disturbance were subdivided into three classes applying Jenks natural breaks. Low $T_{\rm sig}$, $T = 0-0.46$; moderate $T_{\rm sig}$, $T = 0.47-1.48$; high $T_{\rm sig}$, $T > 1.48$.

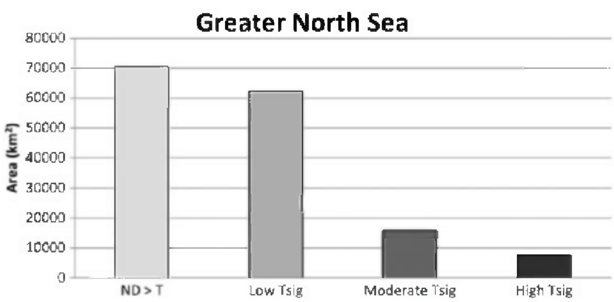

Figure 5. Distribution of fishing disturbance in the GNS.

with the predicted number of disturbance events. Ultimately, this allowed us to map the likelihood that natural disturbance is greater than fishing disturbance.

Additionally, it should be mentioned that VMS data are limited to vessels $\geq$15 m in length, which means that smaller inshore fishing vessels are not accounted for. These vessels tend to fish close to the coast. As a consequence, this might push actual fishing disturbance in coastal areas beyond the value of natural disturbance in some places. This shortcoming needs to be kept in mind when interpreting maps of relative fishing disturbance.

Our model considers the physical disturbance of the seabed caused by hydrodynamics and bottom fishing. It does not consider biological processes such as bioturbation or binding of the sediment. Such processes might directly (e.g. bioturbation leading to physical disturbance; Hall, 1994) or indirectly (e.g. binding of sediment increasing critical shear stress required for sediment remobilization) influence the physical disturbance of the seabed. Bioturbation might also result in the alteration of small-scale seabed surface topography with implications for the interaction with near-bed wave and current flow. To keep the methodology manageable, we had to limit it to important, widespread, and quantifiable processes. There is considerable uncertainty regarding the quantification of bioturbation processes (Teal *et al.*, 2008); thus, these are not included in the current methodology.

The limitation to certain agents of natural and anthropogenic disturbance, while necessary to reduce the complexity of the methodology, might be prone to underestimating impacts as cumulative effects are ignored. However, Foden *et al.* (2011) found that only a small fraction (<0.1%) of the seabed of the UK (England and Wales) continental shelf was occupied by multiple human activities based on data from the year 2007. Thus, while cumulative effects might be important in spatially restricted areas, they appear negligible at the scale of the whole study site.

We also acknowledge that the resolution of our model (ca. 12 km) is relatively low, especially compared with the level of detail of the substrate maps. Model improvements should focus on higher resolution adequate for resolving necessary detail.

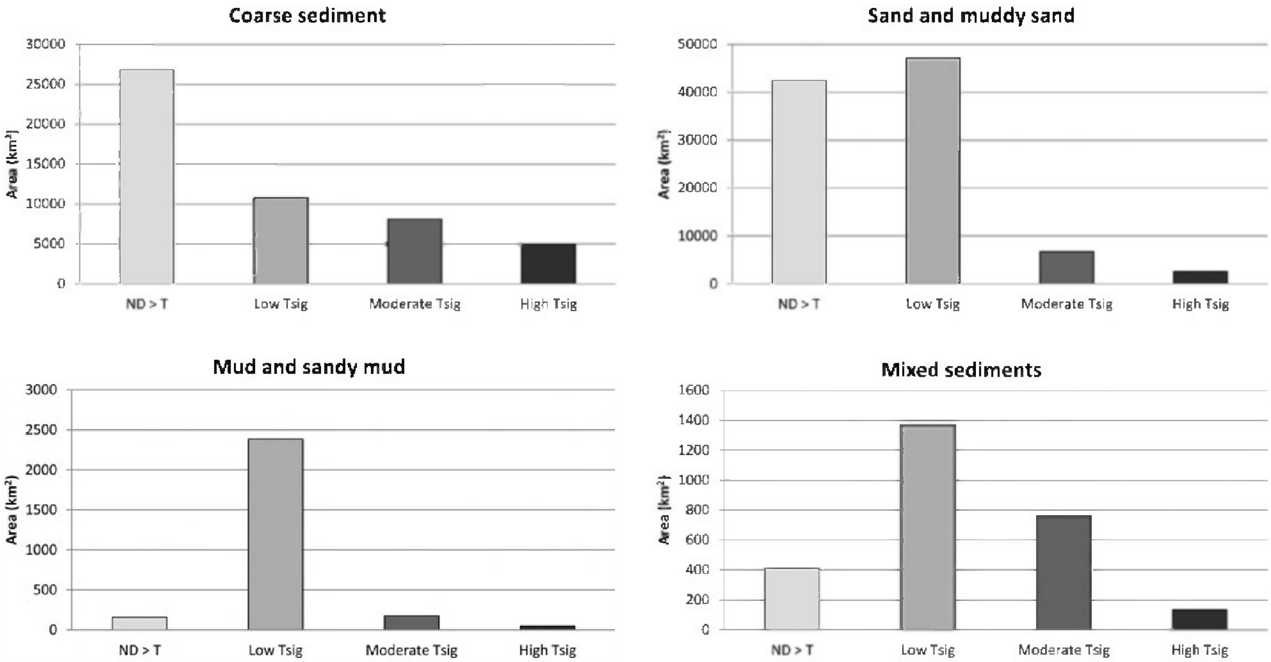

Figure 6. Distribution of fishing disturbance across different substrate types.

Further progress could also be achieved by prolonging the length of the period of model and VMS data, quantifying the uncertainty in the modelled wave and current inputs, assessing the sensitivity of the choice of the ripple height predictors (Soulsby and Whitehouse, 2005; O'Donoghue *et al.*, 2006), and testing the newly developed methods of track reconstruction (e.g. Hintzen *et al.*, 2010; Russo *et al.*, 2011). Although these research questions are worthwhile addressing, they were beyond the scope of the presented study.

It might also be feasible to test our predictions with independent empirical data gathered with acoustic sounders (multibeam echo-sounder and sidescan sonar). Diesing *et al.* (2006) showed that the time it takes to smooth out aggregate dredge furrows depends on the hydrodynamic regime. The same could be expected for furrows caused by demersal trawling. Therefore, given a certain fishing intensity, one would expect significantly less trawl marks in the areas of high natural disturbance when compared with that of low natural disturbance.

Physical disturbance of the seabed

We have described a quantitative and repeatable methodology that allows us to estimate the probability that natural disturbance is exceeding fishing disturbance (and vice versa) based on VMS data and hydrodynamic model outputs for the years 2006–2008. The described methodology might help identifying the areas of seabed where benthic communities are likely to be substantially modified by fishing and could contribute towards an assessment of MSFD indicator 6.1.2. While the methodology might help assessing the extent of the seabed significantly affected by human activities for the different substrate types, it was not our goal to define targets for this indicator. However, once such targets are defined, the methodology could help tracking progress towards good environmental status for sea-floor integrity.

Although we used data from the English part of the GNS to demonstrate the methodology, it could easily be applied to other marine subregions and regions as long as comparable information on hydrodynamics and fishing activity is available. The impact of other human activities could also be assessed. This is especially true for marine aggregate extraction, for which in UK waters vessel positions are currently recorded every 30 s during dredging. Nevertheless, we do not expect this to have significant effects at the scale of subregions or even regions, as the spatial footprint of human activities is dominated by demersal fishing (Eastwood *et al.*, 2007; Foden *et al.*, 2011).

Input data for the presented methodology were limited to the years 2006–2008. These were the most recent years for which consistent data on both fishing activity and hydrodynamics were available. Results were presented in a summarised form as multiyear averages for the sake of simplicity. Nevertheless, it is possible to provide results for individual years. In this way, the methodology could be used for monitoring change and tracking progress towards set targets for indicator 6.1.2 (extent of the seabed significantly affected by human activities for the different substrate types).

Our results demonstrate a high degree of spatial variability in both natural and fishing disturbance, consistent with similar results reported by Stelzenmüller *et al.* (2008a, b). As a consequence, the significance of fishing disturbance also varies spatially across the whole GNS area. Variation in the importance of fishing disturbance is also evident for different substrate types. Cohesive muddy sediments are almost exclusively characterised by significant fishing disturbance larger than natural disturbance levels (Figure 6). We assumed that the biologically significant natural disturbance of muddy substrates occurs under extreme conditions with associated high shear stresses and structural "type II" erosion (Amos *et al.*, 1992). Consequently, even low levels of fishing disturbance will likely be above the levels of natural disturbance. This is especially evident for Farnes Deep, where fishing disturbance is relatively low due to the predominance of otter trawling (Figure 2, right). However, the probability for

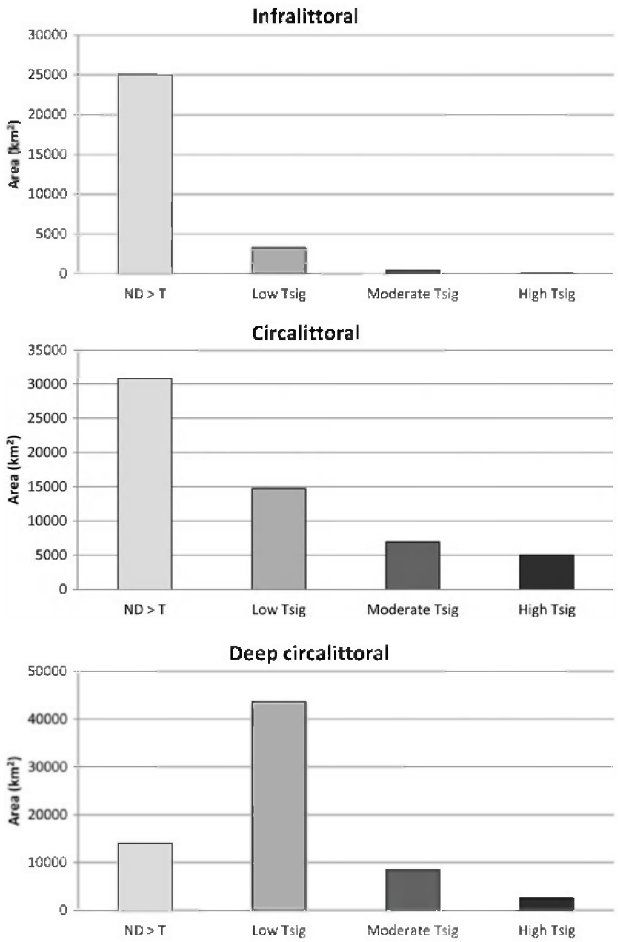

Figure 7. Distribution of fishing disturbance across different biological zones. The importance of significant fishing disturbance is increasing with increasing water depths (expressed as biological zones).

natural disturbance occurring here even only once a year to a depth of 1 cm is also low (Figure 3, top left), and our model predicts significant fishing disturbance above background levels of natural disturbance for Farnes Deep.

Natural disturbance is greater than fishing disturbance in about half the area characterised by coarse sediments (Figure 6). This holds especially true for coarse sediments in the North Sea, which are subjected to relatively high shear stresses but still fine enough to be frequently disturbed. Shear stresses are generally highest in the central English Channel (e.g. Pingree and Griffiths, 1979); however, substrates are too coarse to be frequently disturbed, and in places, bedrock is exposed at the seabed (Diesing *et al.*, 2009; Coggan and Diesing, 2012). Sand and muddy sand are the most widespread substrates in the GNS, occurring close to the coast and on shallow, exposed banks, as well as in relatively deep waters of the northern North Sea (Figure 1). Therefore, there is a relatively even split between the fraction of the area dominated by natural disturbance as opposed to fishing disturbance (Figure 6).

We also found a strong relationship between biological zone and fishing disturbance (Figure 7): deep circalittoral habitats appear to be subjected to a greater extent to fishing disturbance beyond background levels of natural disturbance than shallower circalittoral and especially infralittoral habitats. This is not surprising, as by definition, deep circalittoral habitats are relatively stable with low natural disturbance levels. As such, these deep circalittoral habitats are more adversely affected by demersal fishing than shallow coastal habitats (Kaiser *et al.*, 2002). As they account for large parts of the continental shelf (44.3% or 68 612 km^2), fishing disturbance is expected to exceed natural disturbance in a large proportion of the GNS, even if absolute levels of fishing disturbance are relatively low.

From physical disturbance to habitat sensitivity?

Our results show that muddy substrates and deep circalittoral habitats are more likely to experience significant fishing impact due to low probabilities of natural disturbance. These habitats

Table 1. A summary of assumptions made when developing the presented methodology

Fishing disturbance	1. Discrete VMS observations sufficiently capture the patterns of fishing effort
	2. Each VMS observation represents an area of impacted seabed
	3. Gear width dimensions: beam trawls, 2 × 12 m beams; otter trawls, 2 × 2 m otter boards; and shellfish dredgers, 24 × 0.85 m dredges
	4. The speed at the time of observation (ping) is maintained until the next ping
	5. The vessel remains within the same grid cell between pings
Natural disturbance	6. Averaging period of 1 d is the typical time-scale of a storm
	7. For sand, the disturbance depth equates to the height of small-scale ripples
	8. The bedform height formulae were assumed to give the mean of a distribution of possible bedform heights
	9. A log-uniform type distribution was assumed for the probability of disturbance to a given depth in sand
	10. For gravel, disturbance was assumed to occur when the threshold for the initial movement of the sediment was exceeded
	11. For mud, the probability distribution of wave velocity amplitude at the bed was assumed to be a modified Rayleigh distribution
	12. The probability distribution of threshold stress for type II erosion was assumed to be uniformly distributed in the range of 4 – 10 N m^{-2}
Comparing fishing and natural disturbance	13. Each natural disturbance event affects the whole grid cell
	14. Assumptions on the distribution of trawling effort with penetration depth
	15. For mud and gravel, it is assumed that the depth of any natural disturbance would equal any trawling disturbance (depth of gear penetration not considered)
	16. Grid cells with a probability $\chi_{ND>T} > 0.5$ characterise areas where natural disturbance is greater than fishing disturbance

might therefore be more sensitive to demersal fishing. This inference is supported by results from Bolam *et al.* (in press), who investigated the sensitivity of macrobenthic secondary production to trawling in the English sector of the GNS based on biological traits. They concluded that production is more trawling sensitive in deep, poorly sorted, gravel- or mud-dominated habitats, which experience little or no natural disturbance. Our analysis did not point to increased sensitivities of coarse (gravel-dominated) sediments. However, this might be masked by the broad definition of coarse sediments (Long, 2006), which include a range of sediment types from pure gravels to sand-dominated sediments with gravel contents as low as 5%. Therefore, the definitions of EUNIS substrate types might not be best suited for investigating the sensitivity to fishing disturbance.

Hiddink *et al.* (2006a) estimated recovery times for biomass and production following trawling disturbance using a validated size-based model of the benthic communities in parts of the southern and central North Sea. Sensitivity can be expressed as the inverse of recovery time (Hiddink *et al.*, 2007). Therefore, predicted recovery times can be interpreted as (habitat) sensitivity to trawling. Their map of habitat sensitivity for production (Figure 2 in Hiddink *et al.*, 2007) shows some resemblance with the results presented in this study (Figure 4): the least sensitive areas are Dogger Bank and an ~120 km wide strip off the English coast south of 55° N. These areas were typically associated with the shallowest water depths and the highest shear stress values and erosion rates (Appendix S1 in Hiddink *et al.*, 2007). Conversely, the most sensitive areas are Oyster Ground (in the Dutch Exclusive Economic Zone) and the deep circalittoral parts of the North Sea in the north of our study site, characterised by the greatest water depths and low values for shear stress and the erosion rate (Appendix S1 in Hiddink *et al.*, 2007). Differences between our results and those of Hiddink *et al.* (2006a, 2007) might partly be explained by the fact that the model intervals differed.

The overall agreement of our results with those of Bolam *et al.* (in press) and Hiddink *et al.* (2006a, 2007) gives us confidence that our purely physical model, which predicts the relative importance of fishing vs. natural disturbance, is ecologically relevant in that it aids in identifying areas of the seabed where production might be sensitive to demersal fishing. A final note of caution is, however, in order: although it is important to put fishing disturbance into context, this does not warrant that additional disturbance imposed by fishing is inconsequential, as fishing impacts might be added sources of mortality. Hall (1999) calls this the "fallacy of natural variation". Thus, while it is likely that fishing disturbance will have negative impacts on habitats and communities in the areas of low natural disturbance, it would be wrong to preclude negative impacts due to fishing disturbance in the areas of high natural disturbance.

Acknowledgements

This work was funded by the UK Department for Environment, Food and Rural Affairs (Defra) under project ME5301 "Mapping the structure, function and sensitivity of seabed habitats to support assessment of the sea-floor status and the broadscale monitoring and management of the benthic environment". VMS data were provided by Defra in a raw, uninterpreted form. The Secretary of State for the Environment, Food and Rural Affairs does not accept any liability whatsoever for the interpretation of the data or any reliance placed thereon. Grain size data from the BGS legacy particle size analysis database were received as uncontrolled data export (2011, BGS, www.bgs.ac.uk). NSBS grain size data were obtained from http://www.vliz.be/vmdcdata/nsbs/. Information on biological zones has been derived from EUSeaMap Consortium webGIS data (www.jncc.gov.uk/page-5040) which is made available under the pilot project for the European Marine Observation Data Network (EMODnet), funded by the European Commission's Directorate-General for Maritime Affairs and Fisheries (DG MARE). The Data Owner and EUSeaMap consortium accept no liability for the use of these data or for any further analysis or interpretation of the data. We thank two anonymous reviewers as well as Roger Coggan, Simon Jennings, and Stefan Bolam (all Cefas) for constructive comments on earlier drafts of the manuscript.

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Handling editor: Michel Kaiser