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Assessing cumulative human activities, pressures, and impacts on North Sea benthic habitats using a biological traits approach

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The application of a biological traits analysis, in the present study, has allowed benthic habitat sensitivities and their risk of impact to be mapped at a spatial scale appropriate for the assessment of the North Sea ecoregion. This study considered habitat impacts associated with five important marine sectors; bottom fishing, marine aggregate dredging, sediment disposal, renewable energy devices (tidal, waves, and wind) and the oil and gas sectors, both individually and cumulatively. The significance of the "actual" footprint of impact arising from these human activities and their associated pressures (sediment abrasion, sediment removal, smothering, and placement of hard structures) is presented and discussed. Notable differences in sensitivity to activities are seen depending on habitat type. Some of the more substantial changes in benthic habitat function evaluated are potentially associated with the placement of hard structures in shallow mobile sedimentary habitats, which result in a shift in habitat dominated by small, short-living infaunal species, to a habitat dominated by larger, longer-lived, sessile epibenthic suspension feeders. In contrast, the impacts of bottom fishing, dredging and disposal activities are all assessed to be most severe when executed in deep, sedimentary habitats. Such assessments are important in supporting policies (e.g. spatial planning) directed towards ensuring sustainable "blue-growth," through a better understanding of the potential ecological impacts associated with human activities operating across different habitat types. The aim of this study is to provide a better understanding of the spatial extent of selected human activities and their impacts on seabed habitats using a biological trait-based sensitivity analysis.

Keywords: benthos, biological traits, cumulative impacts, disposal, dredging, extraction, fishing, habitat, human activities, North Sea, pressures, seabed, sensitivity, sustainable blue growth.

Introduction

Most marine ecosystems, at all spatial scales, have to some extent been altered by human activities (Halpern *et al.*, 2008, 2015). Indeed, some studies report that as much as 41% of the global ocean area has been subject to multiple anthropogenic perturbations in one form or another (Halpern *et al.*, 2008), with coastal and shelf seas being particularly susceptible, not least because they host most of the world's largest cities (>2.5 million inhabitants; Houde *et al.*, 2014). Furthermore, coastal and shelf seas provide important habitats and nurseries for sensitive biological communities that are critical for the delivery of vital ecosystem processes and functions, which in turn are responsible for maintaining the health and productivity of the marine environment (Lotze *et al.*, 2006). In the European Union, the growing "blue" economy is estimated to be worth almost €500 billion a year and employs roughly 5.4 million people (European Commision, 2012). However, the rapid development of marine resources, by multiple industrial sectors (fisheries, energy, minerals, transport, and recreation), further increases the risks of inducing long-term and possibly permanent changes in marine ecosystem functions by the combined and cumulative effects of human activities (Houde *et al*., 2014). To counter this, the European Commission (*inter alia*) has implemented a sustainable "Blue Growth" strategy which aims to ensure economic growth across marine sectors is sustainable by recognising the limits which naturally healthy, biodiverse, and biologically productive ecosystems have in sustaining human activities (European Commisision, 2012). However, the challenge for the scientific community lies in developing robust scientific methods to assess the cumulative ecosystem effects of human activities, especially in the analysis of the causes (sources of pressures and effects), pathways and consequences of these effects on receptors (Judd *et al*., 2015).

In a recent review of global marine cumulative pressure and impact assessments (Korpinen and Andersen, 2016), it was shown that current impact assessment methods tend to rely on three "core" steps; e.g. (i) analysing spatial data on the intensity of activity based pressures, (ii) spatial analysis of sensitive ecosystem components (e.g. habitats), and (iii) an analysis of the interactions between multiple pressures and ecosystem components (habitats) to determine impact. Whilst improvements in the monitoring of human activities and ecosystem components are continually being made, largely because of developments in, and the applications of, autonomous and remote sensing technologies (Kenny and Sotheran, 2013), there remains uncertainty in understanding the causal pathways linking human activities, pressures, and their actual impacts on ecosystem components (Korpinen and Andersen, 2016). This is especially the case when attempting to assess the significance of cumulative impacts on ecosystem process and functions which underpin the natural capital upon which society depends (Reid, 2005). Accordingly, most of the studies described by Korpinen and Andersen (2016) rely on expert judgement to estimate the sensitivity of the ecosystem components to the pressures or severity of the pressures on ecosystem components.

To better describe and assess the consequences of multiple human activities, an understanding of when and how ecosystem processes and functions might be impacted is inherently required. This includes understanding certain attributes that define the functional diversity of the ecosystem (e.g. species life history, behavioural characteristics, and morphology). These attributes of functional diversity can then be used as indicators of how species will behave and respond to the pressures exerted by human activities. Such attributes can be used to describe the functionality of a range of marine ecosystem components in the littoral, benthic, and pelagic zones. These ecosystem attributes provide a critical role in controlling the services that ecosystems provide. For example, if the attributes describe an ecosystem sensitive to disturbance, there is likely to be an associated change in value, or alternatively, if the attributes describe a resilient ecosystem, then a given disturbance may have a limited impact on value.

The present study utilises the outcome of recent research on the application of Biological Traits Analysis (BTA) to marine benthic data (Bolam *et al*., 2017). Compared to more commonly used structural or taxonomic approaches, BTA can provide an enhanced understanding of the changes in benthic functioning along environmental and pressure gradients by describing what species do rather than what they are (Dimitriadis *et al*., 2012; Van Son *et al*., 2013; Duarte *et al*., 2015; Bolam *et al*., 2016, 2017). Certain biological traits, such as size, longevity, sediment position, mobility and reproductive strategy, are closely associated with the characteristics of their environment (Bolam *et al*., 2016; Beauchard *et al*., 2017). For example, benthic organisms living in mud and sand sediments in deeper waters experience fewer natural disturbances, so they tend to be longer-lived and slower-growing (Kaiser and Spencer, 1996; Kaiser *et al*., 1998; Hiddink *et al*., 2006; Queirós *et al*., 2006). In contrast, organisms living in habitats with a relatively high degree of natural disturbance tend to have small body size and fast rates of growth, which are traits adapted to periodic sediment resuspension and smothering (Collie *et al*., 2000; Bremner *et al*., 2005; Atkinson *et al*., 2011). Given that certain biological traits appear to be sensitive to changes in habitat disturbance and that many human activities, and their associated impact pressures, act on the sea bed environment in a physical way (e.g. sediment abrasion by bottom fishing, smothering by sediment disposal, and sediment removal by dredging; Foden *et al*., 2011), the application of biological traits analysis could potentially offer a useful approach in assessing habitat sensitivity to human impacts (Hiddink *et al*., 2007).

The aim of this study is to provide a better understanding of the spatial extent of selected human activities and their impacts on seabed habitats using a biological traits-based sensitivity analysis. The scope of the present study extends spatially to cover the North Sea, English Channel, Irish Sea, and parts of the Celtic Sea (Figure 1). It uses the latest research findings to identify and quantify the most significant biological traits associated with different habitat types in their "natural" and unimpacted state, and assesses their sensitivity to four principle pressure types (abrasion, removal, smothering, and burial).

Methods

Pressure data types

Four human activity benthic pressure layers covering a significant area of the Northeast Atlantic region, utilising spatial data from multiple sources, are compiled for the present study. The pressure layers are; (i) surface sediment abrasion caused by bottom fishing activities (ICES, 2016), (ii) sediment removal by aggregate dredging activities, (iii) smothering caused by sediment disposal activities, and (iv) deposition of hard (concrete and steel) structures by renewable energy and oil and gas activities.

Sediment abrasion

Sea bed surface sediment abrasion caused by bottom fishing activities in the Northeast Atlantic has been generated by ICES (2016). Fishing vessel positional monitoring system (VMS) data was processed according to methods given by Lee *et al*., (2010), and combined with information on gear types generated by a European Union funded research project (Eigaard *et al*., 2016). The data cover a period between 2009–2015 and were used to determine average swept area ratios as the area of seabed impacted (km^2) each year in a given grid cell (e.g. 0.05 × 0.05-degree grid cells) using the approach of C-square grid (Rees, 2003). The footprint of impact associated with four bottom-contact gear types (e.g. beam trawlers, dredges, otter board trawlers, demersal seines) was assessed by Eigaard *et al*., (2016). In that study, gear information provided by the industry was used to determine the partial contributions from the key components of the four gear types: doors, sweeps, and groundgear for otter trawls, seine rope and ground gear for demersal seines, beam shoes, tickler chains, and ground gear for beam trawls and dredges. The individual gear footprints and vessel size-gear size relationships were then used to estimate the total combined swept-area per fishing hour.

Figure 1. Spatial extent of the present study highlighting place names which are referred to in the text.

This was then integrated with the VMS data to create a single surface abrasion pressure data layer. To enable direct comparison with other pressures the sediment abrasion pressure layer was first (log_2) transformed to remove any bias caused by anomalous high swept area values and then rescaled to values between 0 and 1.

Sediment removal (aggregate extraction)

Sediment removal was estimated by the extent of licensed marine aggregate (sand and gravel) extraction sites. Data were obtained from EMODnet (http://www.emodnet-humanactivities.eu) in the form of points indicating the central position of aggregate dredging sites. For the UK, licensed polygon areas were obtained from the Crown Estate (https://www.thecrownestate.co.uk/energy-minerals-and-infrastructure/downloads/maps-and-gis-data/.) To convert the EMODnet point data into estimated pressure polygon areas a 2.00 km radius buffer was placed around each point. This provided an approximate area for each non-UK dredging site across the study area, where the radius was determined by calculating average area of all the UK dredging sites (12.00 km^2). Only active dredging sites were considered.

Smothering (sediment disposal)

For sediment smothering, data on licensed sea disposal sites were obtained from EMODnet (http://www.emodnet-humanactivities.eu). These were a mix of point data and polygon areas. In order, to estimate the pressure footprint (Footprint is defined in the present study as the spatial extent of a pressure arising from a human activity.) of those sites represented only by point data, the average area of all the available polygon data was calculated (2.24 km^2). This was then used to calculate a radius (0.84 km^2) to buffer the point data to achieve the same average polygon area of 2.24 km^2. Only active disposal sites were considered.

Burial (placement of hard structures)

Activity data related to offshore wind farms, wave and tidal energy, and oil and gas activities were obtained from the Crown Estate UK (https://www.thecrownestate.co.uk/energy-minerals-and-infrastructure/downloads/maps-and-gis-data/) and EMODnet (http://www.emodnet-humanactivities.eu). Only operational sites were considered and given the point source nature of these activities their associated pressure "footprints" were assigned a value of 1. To determine the pressure footprint of each turbine the polygons were divided into a lattice based on the number of turbines within each wind farm licensed block. The nodes of the lattice were then used as the approximate position of each individual turbine. The number of turbines was obtained from the 4 C Offshore database (4C Offshore, 2017) and each estimated turbine location was then given a buffer of 15 m radius based on the methodology of Foden *et al.* (2011). No published estimates of wave or tidal energy devices pressure footprints were found, largely due to the contemporary nature of the technologies, but also because there are wide differences in the design of the technologies employed. To account for this, the present study applied a conservative buffer of 50 m radius around each development data point. In addition, both oil and gas well-heads, and production platforms were considered. Abandoned wells were not included, nor were platforms that have ceased operation and have been or are soon to be decommissioned. For these structures, a conservative 100 m buffer was placed

Table 1. Habitat Categories based on their EUNIS codes (EEA, 2017), and their assigned EUNIS habitat codes used to assess pressure specific broad-scale sensitivities in the present study.

Habitat category	EUNIS habitat codes
Deep coarse	A5.14—Circalittoral coarse sediment
	A5.15—Deep circalittoral coarse sediment
	A5.45—Deep circalittoral mixed sediments
Deep fine	A5.27—Deep circalittoral sand
	A5.35—Circalittoral sandy mud
	A5.36—Circalittoral fine mud
	A5.37—Deep circalittoral mud
Shallow coarse	A5.13—Infralittoral coarse sediment
	A5.44—Circalittoral mixed sediments
Shallow fine	A5.23—Infralittoral fine sand
	A5.24—Infralittoral muddy sand
	A5.25—Circalittoral fine sand
	A5.26—Circalittoral muddy sand

around each point following the approach adopted by Goodsir and Koch (2015).

Habitat mapping

Habitat spatial data was obtained from the European EMODnet seabed habitats project EUSeaMap (www.emodnet-seabedhabitats.eu) (Cameron and Askew, 2011). As the present approach pertains only to sedimentary habitats, all rocky and reef habitat types were excluded from the analysis. Sediment samples assigned to EUNIS level 4 habitat classes (EEA, 2017) were reclassified such that any sediment sample with a grain size composition having a mode >2 mm was classified as coarse, whereas all other sediment samples were by definition classified as fine. The coarse and fine sediment classes were further sub-divided according to depth, with deep-water habitats classified as occurring at depths between 50 and 1750 m, and shallow-water habitats occurring at depths < 50 m (MA, 2005). This resulted in four categorical habitat classes, each composed of several EUNIS habitat types (Table 1) that were subsequently used to assess pressure specific broad-scale habitat sensitivities and impacts.

Habitat attribute biological traits

Data on the dominant biological traits associated with the four categorical habitat classes defined in the present study (see above) were derived from data presented in Bolam *et al*., (2017). Bolam *et al*. (2017) utilised an extensive macrobenthic data set consisting of 722 separate macrobenthic samples representing 10 different EUNIS habitat classes from deep muds to shallow coarse sediments. Samples were excluded from areas licensed for aggregate extraction and dredging disposal activities, as well as areas subject to very low or no bottom fishing activity. The method employed for identifying samples from very low or no bottom fishing activity is described in Bolam *et al*., (2017). Accordingly, only unimpacted habitat traits in relation to their "natural" habitat attributes were described. These data were used to highlight the main traits associated with different habitat attributes (deep water, shallow water, course sediment, fine sediment) as used in the present study (Table 2). The broad-scale habitat categories as defined by this assessment (coarse deep, coarse shallow, fine deep and fine shallow sediments) are assumed not to vary in their physical or biological trait composition throughout their geographic range as mapped in Figure 3. Whilst this may seem like a large assumption, benthic community biological traits (as used in the present study) are observed to be much less variable across a range of physical habitat types compared to the variability observed in their species composition (Bolam *et al*., 2017). It is only when significant changes in habitat type occur (e.g. from predominately gravel to mud) that significant changes in biological traits composition are observed (Bolam *et al*., 2017).

Habitat sensitivity scores

The sensitivity of each habitat category (coarse deep, coarse shallow, fine deep and fine shallow) was then evaluated by a group of experts to evaluate the sensitivity (as high, moderate, or low sensitivities) of benthic habitat biological traits to the four pressure types under consideration (e.g. sediment abrasion, sediment removal, smothering and placement of hard structures). A total of five experts (four of which are authors of the present paper) formed an expert group. The group consisted of individuals who have published widely on the impacts of selected human activities on marine benthic ecosystems as part of their professional duties in providing licensing advice to statutory regulatory and management organisations in the UK. For example, Dr Kenny has conducted numerous studies on the effects of marine aggregate extraction on benthic habitats (Kenny and Rees, 1994 and Kenny and Rees, 1996). Dr Kenny has also contributed to research on sustainable fisheries and the assessment of impacts of bottom fishing on benthic ecosystems (Kenny *et al*., 2017; Van Denderen *et al*., 2016; Rijnsdorp *et al*., 2016). Dr Bolam leads research on the impacts of dredge material disposal on benthic habitats in UK estuarine, coastal and offshore areas, and has contributed to studies on the impacts of bottom fishing on benthic ecosystems (Bolam, 2011, 2012; Bolam *et al*., 2014, 2016). Dr Judd, since 2005, has been the UK Delegate for the OSPAR Commission expert group on Environmental Impacts of Human Activities (EIHA) and actively contributes to research on marine environmental impacts associated with the renewables sector and combined assessments of human activities and their management in marine ecosystems (Judd *et al*., 2015; Frid *et al*., 2012; Goodsir *et al*., 2015).

The expert group evaluated each biological trait associated with each habitat attribute (course, fine, deep, shallow), and assigned it a categorical value from 0 (least sensitive), 0.5 (moderately sensitive) to 1 (highly sensitive) in response to the different pressure categories, comparable to the approach adopted by Bolam *et al*. (2014). For example, biological traits such as large body size (> 500 mm), long-lived (>10 years) and surface living epifauna, were assessed to be highly sensitive to the effects of sediment abrasion caused by bottom fishing and sediment removal caused by dredging, whereas short-lived (<1 year) and small body size (11–20 mm) were assessed to be least sensitive to the same pressure types. Furthermore, the assessment of habitat sensitivity only considered the trait sensitivities in response to the initial disturbance event for each of the human activities.

We acknowledge that different experts may interpret the biological trait sensitives differently, however, such differences are unlikely to change the relative assessment of habitat sensitivities due to the large differences observed in the characteristic traits associated with the four principal habitat types assessed. This trait sensitivity scoring approach is, to a certain extent, analogous to that adopted by Bolam *et al*., (2014) regarding the Greater North Sea. The habitat attribute specific trait sensitivities were then

Table 2. Characteristic (numerically dominant) biological traits associated with the four principal seabed attribute types considered in the present assessment, modified from Bolam *et al.* (2017).

Trait category	Trait	Coarse (>2 mm)	Fine (<2 mm)	Deep (>50 m)	Shallow (<50 m)
Asexual benthic reproduction	Egg development	X			
Size >500 mm	Maximum size	X			
Longevity >10 years	Longevity	X			
Surface living (epifauna)	Sediment depth	X			
Deep infauna (>10 cm)	Sediment depth	X		X	
Pelagic broadcast spawning	Egg development		X		
Downward “conveyor” bioturbation	Bioturbation mode		X	X	
Size 21–100 mm	Maximum size		X		
Diffusive “errant” bioturbation	Bioturbation mode		X		X
Longevity 3–10 years	Longevity		X		
Shallow infauna (0–5 cm)	Sediment depth		X		
Pelagic larval development	Larval development		X		
Moderate depth infauna (6–10 cm)	Sediment depth		X		
Longevity 1–2 years	Longevity		X	X	
Upward “conveyor” bioturbation	Bioturbation mode			X	
Sessile	Mobility			X	
Size 201–500 mm	Maximum size			X	
Suspension feeding	Feeding mode			X	
Sexual benthic reproduction	Larval development			X	
Size 11–21 mm	Maximum size			X	
Burrowing “errant”	Mobility				X
Scavenger	Feeding mode				X
Predator	Feeding mode				X
Size 101–201 mm	Maximum size				X

averaged for each pressure category to generate pressure specific average sensitivity scores for each habitat category (coarse deep, coarse shallow, fine deep, and fine shallow) to generate habitat sensitivity scores between 0 and 1. This way pressure specific habitat sensitivity maps could be directly compared.

Estimating cumulative impact

Estimating the pressure specific impacts involved integrating the pressure and corresponding habitat sensitivity data layers (maps), e.g.

$$Pressure\ (0\text{–}1) * Sensitivity\ (0\text{–}1) = Impacts\ (0\text{–}1)$$

This was repeated for each pressure and corresponding habitat sensitivity layer before summing the pressure specific impact scores together to generate a single cumulative impact layer.

Results

Pressure mapping

Sediment surface abrasion caused by bottom fishing activity, the general location of marine aggregate extraction sites, the placement of hard structures (oil and gas, wind farms, tidal and wave energy structures) and sediment disposal sites are shown in Figure 2.

It is notable that surface sediment abrasion caused by bottom fishing activity extends across much of the study area (Figure 2a), but within this there are identifiable hot spots of sediment abrasion. Areas of high abrasion include the English Channel, the north-western Irish Sea along with much of Celtic sea, parts of the southern North Sea especially off the coasts of France, Belgium, Netherlands, Germany, and Denmark and in the Skagerrak. There were also notable absences of sediment abrasion in parts of the central western North Sea, and in areas to the west of Scotland and Ireland.

Placement of hard structures, sediment removal and smothering are all essentially point source pressures with relatively small spatial footprint compared to that of sediment abrasion (Figure 2a–d). However, it is notable that much of the placement of hard structures is in offshore areas, whereas sediment removal and smothering pressures are largely confined to coastal and inshore areas.

Habitat mapping

A map of the EUNIS habitats, re-classified into the habitat categories (see Table 1) for use in the present study, is shown in Figure 3.

Shallow coarse sediment (<50 m) was largely confined to coastal areas, particularly in the eastern parts of the southern North Sea, eastern English Channel, and eastern Irish Sea. Whereas significant areas of deep coarse sediment are typically found in the western part of the English Channel and off northern and western parts of Scotland. Shallow fine sediment (sand) was largely confined to the southern North Sea and coastal margins of the Celtic Sea and Irish Sea, whereas deep fine sediments (muds) tend to dominate the northern part of the North Sea and some areas to the west of Scotland and parts of the Celtic Sea. The North Sea is essentially divided into a northern deep water fine sediment habitat (mud) area and a southern shallow water fine sediment habitat (sand) area.

Habitat sensitivity scoring

Scoring of the habitat attribute specific traits against each of the pressure types is shown in Table 3, and Table 4 presents the pressure specific habitat sensitivities based on the average scores for each habitat attribute and pressure combination from Table 3.

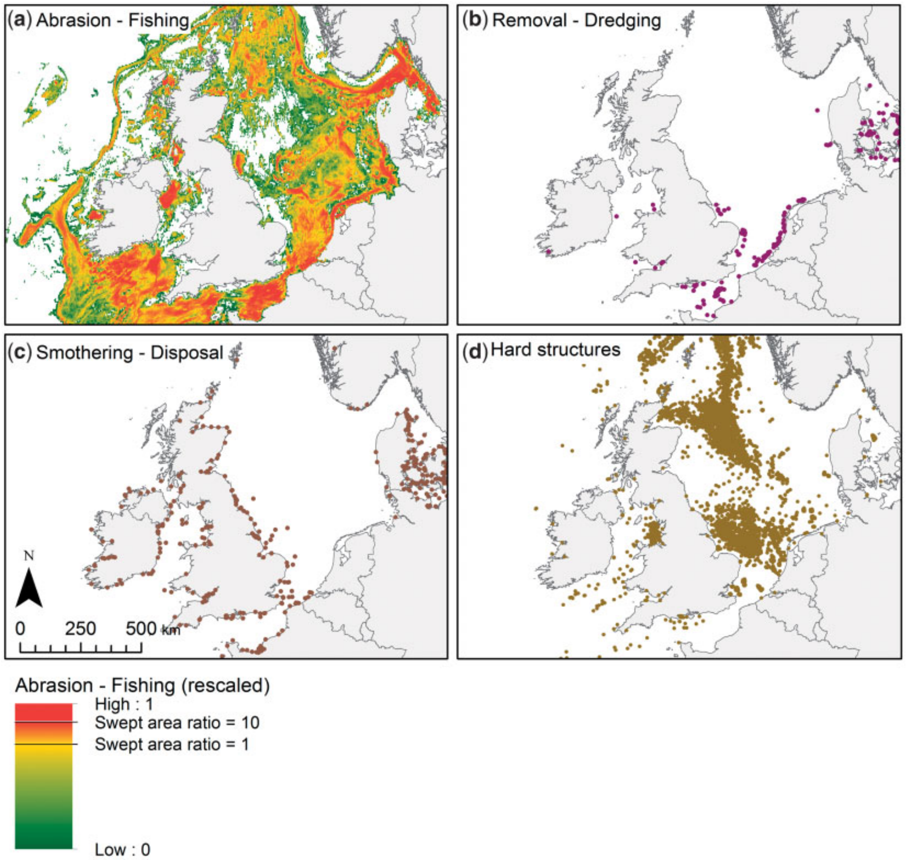

Figure 2. Footprints of (a) sediment surface abrasion (fishing), (b) sediment removal (aggregate dredging), (c) sediment smothering (sediment disposal), and (d) placement of hard structures (renewable energy, oil & gas; © Crown Copyright, 2017). Note that only map a) is a near "true-to-scale" footprint of the pressure, however, all areas depicted in the legend up to swept area ratio = 1, correspond to low fishing pressure (seabed impacted less than once per year). In contrast the area depicted in the legend above swept area ratio = 10, corresponds to high fishing pressure (seabed impacted more than once per year). The other pressures (b) to (d) have been scaled up to visualise their relative geographical extent and do not show a true representation of their "footprint."

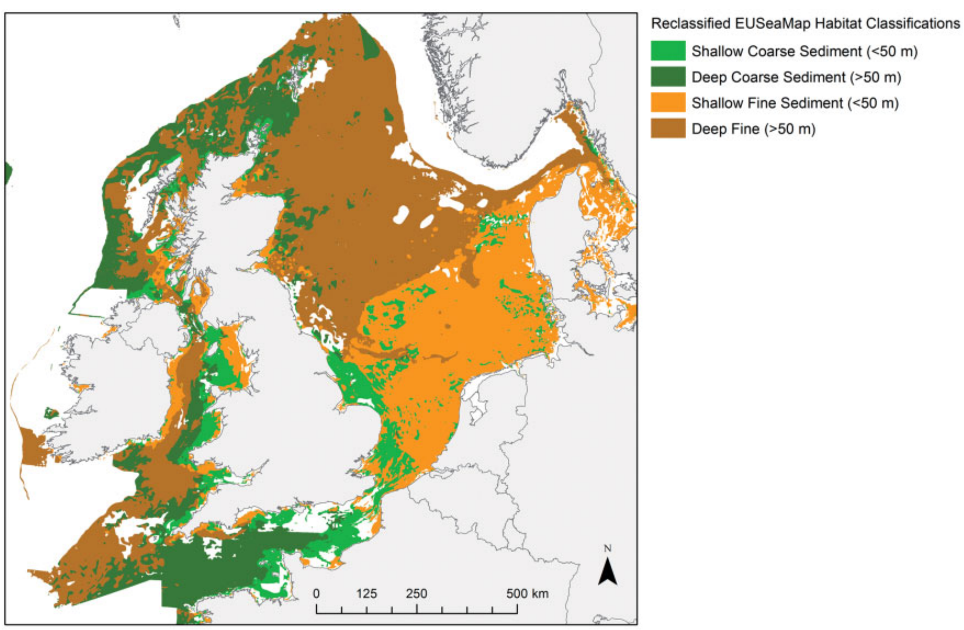

Figure 3. Reclassified EUNIS level four habitats according to predominantly coarse and fine sediment types and in relation to depth (shallow <50 m and deep >50 m). Shelf areas represented by white represent rocky or reef habitats and are not included in the present study.

Table 3. Sensitivity scores assigned to each of the characteristic habitat attribute traits, for each pressure types; note that the traits associated with the habitat category, e.g. deep coarse sediment is simply a combination of the characteristic traits associated with the deep and coarse habitat attributes.

Habitat attribute	Trait category (see Table 2)	Sediment surface abrasion	Sediment removal	Smothering	Hard structures
Coarse	Asexual benthic reproduction	0.5	0.5	0.5	0.5
	Size >500 mm	1	1	0.5	1
	Longevity > 10 years	1	1	1	0.5
	Longevity < 1 year	0	0	0	0
	Surface living epifauna	1	1	1	0
	Deep infauna (>10 cm)	0.5	1	0.5	1
	Average sensitivity score	0.67	0.75	0.58	0.50
Fine	Pelagic egg development	0	0	0	0
	Downward "conveyor" bioturbation	0.5	0.5	0.5	1
	Size 21–100 mm	0.5	1	0.5	0.5
	Diffusive "errant" bioturbation	0.5	0.5	.5	1
	Longevity 3–10 years	0.5	0.5	0.5	0.5
	Shallow infauna (0–5 cm)	1	1	0.5	1
	Pelagic larval development	0	0	0	0
	Moderate depth infauna (6–10 cm)	0.5	1	0.5	1
	Longevity 1–2 years	0	0	0	0
	Average sensitivity score	0.39	0.50	0.33	0.56
Deep	Downward "conveyor" bioturbation	0.5	0.5	0.5	1
	Upward "conveyor" bioturbation	0.5	0.5	0.5	1
	Sessile	1	1	1	0.5
	Size 201–500 mm	1	1	0.5	0.5
	Suspension feeding	0.5	1	1	0
	Sexual benthic reproduction	1	1	1	0.5
	Deep infauna (>10 cm)	0.5	1	0.5	1
	Size 11–20 mm	0	0.5	0.5	0.5
	Longevity 1–2 years	0	0	0	0
	Average sensitivity score	0.56	0.72	0.61	0.56
Shallow	Diffusive "errant" bioturbation	0.5	0.5	0.5	1
	Burrowing "errant"	0.5	1	0.5	1
	Scavenger	0.5	0.5	0.5	1
	Predator	.5	0.5	0.5	1
	Size 101–200 mm	0.5	1	0.5	0.5
	Average sensitivity score	0.50	0.70	0.50	0.90

Table 4. Average sensitivity scores determined for each habitat category in response to the four assessed pressure types.

Habitat category	Sediment surface abrasion	Sediment removal	Smothering	Hard structures
Coarse/Deep	0.61	0.74	0.60	0.53
Coarse/Shallow	0.58	0.73	0.54	0.70
Fine/Deep	0.47	0.61	0.47	0.56
Fine/Shallow	0.44	0.60	0.42	0.73

The result of the habitat sensitivity analysis reveals that the most sensitive habitat to sediment abrasion, sediment removal and smothering are all the same, e.g. deep-water coarse sediments (0.61, 0.74, and 0.60, respectively), this is followed by, in order of sensitivity; shallow-water coarse sediment (0.58, 0.73, and 0.54, respectively), deep-water fine sediment (0.47, 0.61, and 0.47, respectively) and finally shallow-water fine sediment (0.44, 0.60, and 0.42, respectively). However, the sensitivity scores associated with sediment removal (aggregate extraction) are considerably greater than those of sediment abrasion (fishing) and sediment smothering (disposal activities). In contrast, the most sensitive habitat in response to hard structure deposits (e.g. wind farms, oil and gas installations) was assessed to be shallow-water fine sediment (0.73) followed by, in order of sensitivity; shallow-water coarse sediment (0.7), deep-water fine sediment (0.56) and finally deep-water coarse sediment (0.53).

It is noteworthy, that in the case of hard structure pressures that both shallow-water habitats (e.g. coarse and fine sediment) emerge as being considerably more sensitive than their deep-water equivalents, a result which serves to highlight the importance of relative habitat stability (either natural or artificial) in assessing habitat sensitivity. For example, it is the introduction of a stable habitat (the hard structure) in an otherwise unstable mobile sedimentary environment that gives rise to an increased sensitivity score.

The assigned habitat category sensitivity scores (Table 4) in combination with the re-classified EUNIS habitat maps (Figure 3) allow maps of pressure specific habitat sensitivity to be produced (Figure 4). Such maps serve to highlight the potential impact

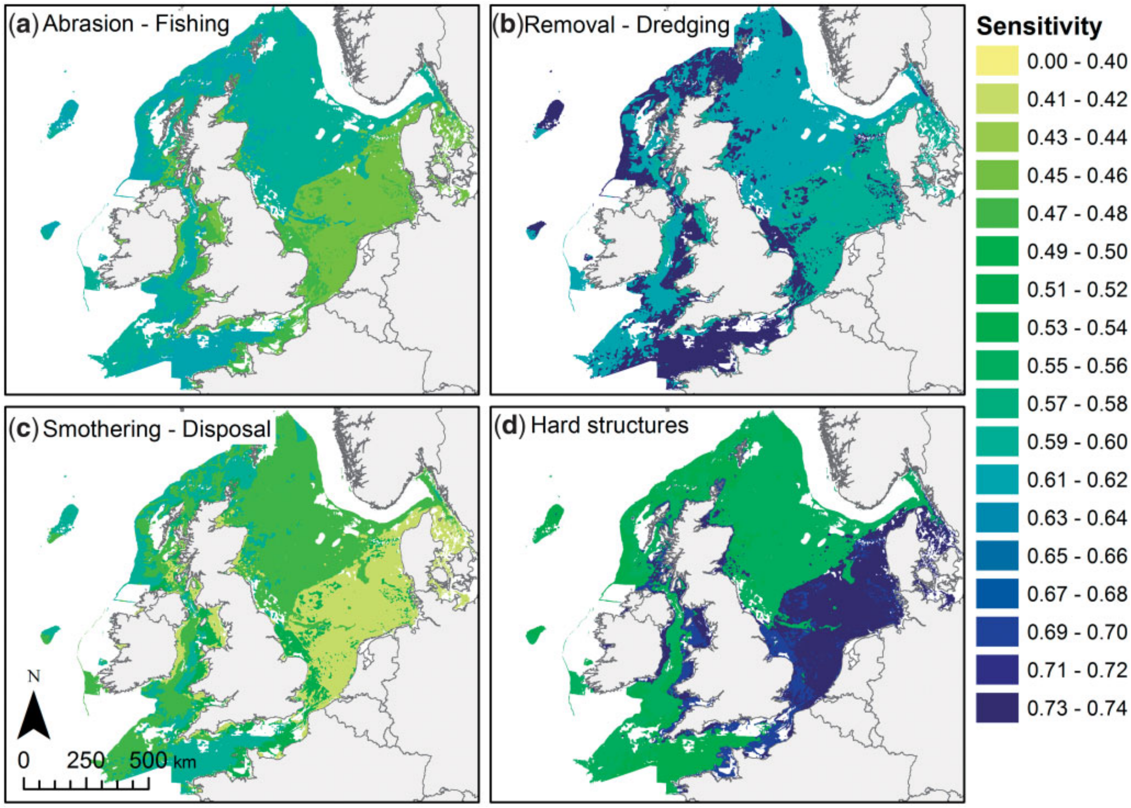

Figure 4. (a–d) Pressure specific habitat sensitivity maps highlighting the relative differences between habitat sensitivities and potential risk of impact in response to the considered pressure types. 0 = low sensitivity, 1 = high sensitivity.

associated with the various pressure types for each region. It is apparent that whilst sediment removal and hard structure placement elicit high habitat sensitivity scores, compared to that associated with sediment abrasion, the spatial footprints of these pressures are on a much smaller scale, being effectively point source activities. Clearly the magnitude of any impact will depend upon the spatial extent or footprint of the pressure, it's persistence (or frequency of disturbance), and the associated habitat sensitivity.

Impact mapping

Accordingly, maps of impact have been compiled by integrating the actual estimated pressure extent "footprint" and habitat sensitivity layers for each pressure type (Figure 5), which serves to highlight the large difference in the "true-to-scale" extent of each pressure type. At the scale of the mapped representation, the pressure associated with the large number of hard structures present in the North Sea is not visible and it is only the larger licensed sediment extraction and disposal sites that can be seen. Table 5 further highlights the difference in the extent of the impact footprints associated with each pressure type.

While the pressure categories of removal (dredging), smothering (disposal) and hard structures are calculated using precise coordinates for their footprint, abrasion from fishing activities, calculated as swept area ratio, has been averaged across a 0.05 × 0.05-degree grid cell. However, as swept area ratio is calculated as the area of abrasion based on vessel speed and gear width, a swept area ratio of < 1 means an area of seabed within the grid cell will essentially not be impacted by fishing abrasion. It is assumed, in the current assessment, that a swept area ratio >10 is sufficiently large to ensure that the entire grid cell has undergone disturbance at least once per year. It can be seen from Table 5 that approximately half of the study area is subject to a swept area ratio of between 0 and 1, whereas a further quarter of the study area is subject to a swept area ratio of between 1 and 10. However, one percent of the study area has a swept area ratio >10, which represents a disturbance frequency of at least once per year.

The four pressure impact maps were combined into a single "cumulative" benthic impact map by simply summing the pressure impact layer scores (Figure 6). The southern North Sea clearly reveals relatively low levels of impact compared to all other areas, especially the western English Channel, parts of the Irish Sea, Celtic Sea, and much of the Skagerrak. However, there are some areas of localised high impact in the southern North Sea, notably, off the Dutch and Belgian coasts and in the eastern English Channel, which are associated with aggregate extraction and disposal site activities.

Discussion

Broadscale assessments of benthic community responses to human activities are an important consideration when assessing the significance of impacts on the sustainability of marine ecosystem functions. Knowledge of the extent of different habitat types and their associated functions enables the risks of impacts caused by human activities to be fully quantified (Kostylev and Hannah, 2007), but more importantly it allows the significance of present-day impacts to be better understood and placed in the context of what society "values."

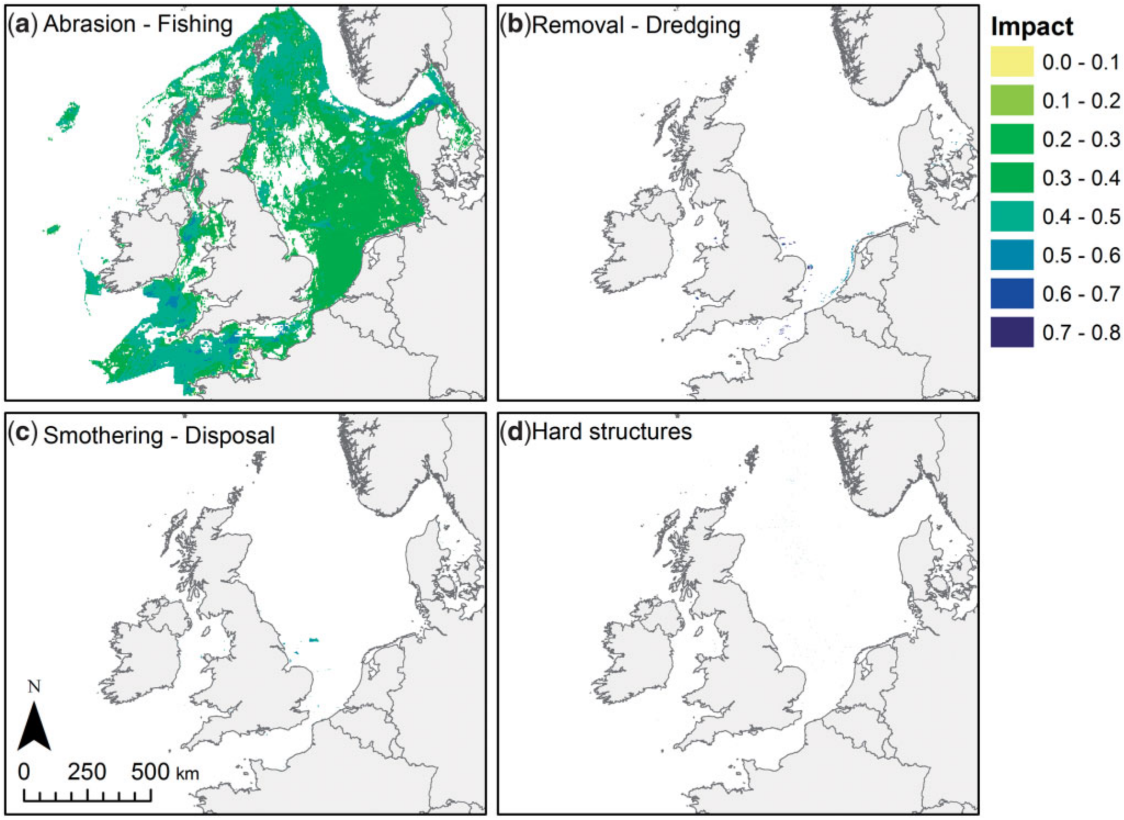

Figure 5. Impact maps for each pressure type showing "true-to-scale" footprints. 0 = least impacted, 1 = most impacted. Note at the scale of the maps the pressure footprints of dredging, disposal and hard structures are hardly visible.

Table 5. The spatial extent of each pressure footprint associated with each habitat category in km^2 as assessed in the present study.

	Shallow coarse (km^2)	Deep coarse (km^2)	Shallow fine (km^2)	Deep fine (km^2)	Total pressure area (km^2)	% of study area
Sediment removal	528	29	466	7	1030	0.13
Hard structures	12	7	36	104	160	0.02
Smothering	210	294	425	52	980	0.12
Sediment abrasion (low)	34 261	69 204	109 197	195 236	407 898	50.04
Sediment abrasion (moderate)	20 104	42 072	70 692	84 631	217 499	26.68
Sediment abrasion (high)	1692	1140	1772	3445	8048	0.99
Total area of habitat category	83 036	157 039	214 834	360 241	815 152	–

The main aim of this study was therefore to provide a better understanding of the spatial extent of selected human activity impact pressures and associated potential habitat sensitivities across large regions of the Northeast Atlantic European shelf resulting from the four main anthropogenic pressures currently imposed on seabed sediments (sediment abrasion, sediment removal, smothering, and placement of hard structures). We have utilised the results from Bolam *et al.* (2017), which describe the biological traits of macrofaunal assemblages associated with different unimpacted sedimentary habitats found in the NE Atlantic shelf region, in which sediment grain size and depth of water were the two most important environmental parameters explaining the variability of habitat specific biological traits. Indeed, it has long been known that sediment composition and depth of water are the main environmental parameters influencing the large-scale distribution of benthic species in the North Sea (e.g. Glémarec 1973; Duineveld *et al.*, 1991), often by directly affecting local finer scale gradients in temperature, tidal currents, wind induced waves and sediment resuspension (Rachor and Gerlach, 1978; Kröncke *et al.*, 1998) and more rarely to anoxia (Duineveld *et al.*, 1991, Kröncke *et al.*, 1998, Armonies *et al.*, 2001). As such, relating the different EUNIS habitat classes, as in the present study, to the four principal habitat categories was relatively straightforward. Each habitat category, essentially represented by a different combination of sediment grain size (coarse, fine) and depth (shallow, deep), was found to be dominated by different biological traits, summarised in Table 6.

Although the present analysis has estimated the spatial extent or "footprint" of the pressures and impacts associated with bottom fishing, dredging, disposal and selected construction

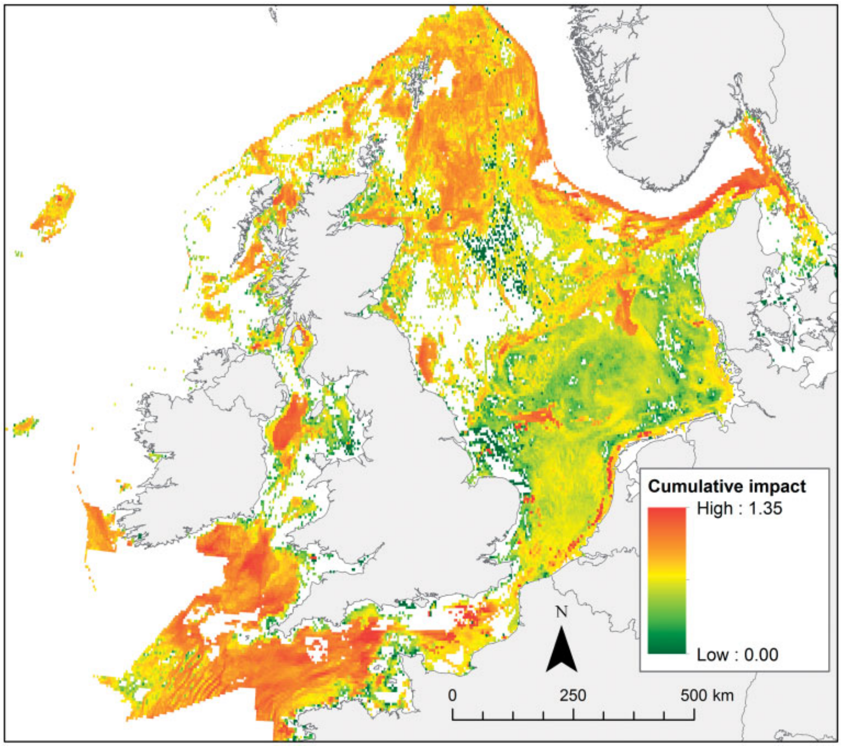

Figure 6. Cumulative impact map for sediment abrasion (bottom fishing activities), sediment removal (aggregate extraction), smothering (sediment disposal activities) and hard structure deposits (oil and gas, wind-farms, tidal, and wave generation).

Table 6. The dominant macrobenthic biological traits associated with each of the defined principal habitat categories assessed in the present study (after Bolam *et al.*, 2017).

Habitat category	Characteristic biological traits
Coarse/Deep	Longer living, larger individuals, sessile epifauna, benthic sexual reproduction
Coarse/Shallow	Longer living, larger individuals, but also the presence of mobile epifauna and smaller individuals
Fine/Deep	Larger individuals, sessile infauna, but also the presence of shorter living and smaller individuals
Fine/Shallow	Shorter living, smaller individuals, mobile infauna, but also the presence of scavenger and predator feeding types

activities, it has not explicitly addressed the frequency or temporal scale of the associated pressures and impacts, other than in relation to the sediment surface abrasion pressure which considered a 7-year period (2009–2015) of bottom fishing activity. Clearly, understanding how frequently the seabed is exposed to a given pressure is important, especially when trying to assess the resulting impacts on sea bed habitats and functions. The present study is not unique in recognising this limitation, indeed Korpinen and Andersen (2016) commented on the small number of cumulative impact studies which explicitly address the element of temporal disturbance. However, it is reasonable to assume that sediment dredging and disposal operations involve at least 1 activity event in a licensed area per year, and in some instances (Anon, 2015; Bolam *et al.*, 2016), many more times than this. Therefore, as a worse-case scenario, both dredging and disposal activities have been considered as representing almost continuous pressures in the present assessment. In contrast, the placement of hard structures onto the seabed represents a semi-permanent change to the habitat and therefore has a continuous pressure on the seabed, certainly beyond the initial impact associated with their installation.

Evaluating the consequences at the ecosystem-level of benthic habitat impacts arising from different human activities is difficult, because it largely depends on the "value" society attributes to the "goods" and "services" (MA, 2005) which specific habitats provide. At one level, the ecosystem impacts, can be estimated by determining the rate at which the benthos and its associated functions recover post-disturbance. Such recovery rates will depend on the extent of successful recruitment, settlement, and growth of the benthos, which (in part) is influenced by the availability of adequate nutrients and food, as well as the availability of suitable habitat. Most marine macrobenthic organisms reproduce, settle, and grow at specific times of the year (Henning and Kroncke, 2005). The timing of these events are typically determined by the onset of seawater thermal stratification caused by seasonal changes in marine climate and day length that influence the availability of food and nutrients (Brander *et al.*, 2016). In temperate regional seas, such as the North Sea, the onset of peak secondary benthic production typically follows the Spring (March–May) and Autumn (September–November) blooms in phytoplankton growth and production, therefore many benthic organisms typically follow seasonal and annual cycles of recruitment and growth (Henning and Kroncke, 2005). Indeed, sedimentary habitats which are shallow, tidally stressed, and which do not stratify during the summer generally exhibit higher total production estimates than those in contrasting habitats (Bolam *et al.*, 2009). Accordingly, it may be expected that such habitats would recover more rapidly post-impact than habitats which are in deeper water, and seasonally stratified (Bolam *et al.*, 2014). Therefore, the most significant impacts are most likely to be associated with those activities and pressures which have relatively large spatial footprints, a high frequency of occurrence, and occur within habitats that have high relative sensitivity or low levels of secondary production. In this respect, it is noteworthy that the result of the combined impact assessment presented (Figure 6) is, for a large part of the area assessed, the same as the fisheries impact result (Figure 4a).

Management implications

The results of this study reveal the spatial trends in the relative sea bed impacts resulting from different human activities, based up on the sensitivity of the habitat to a given human activity and pressure type.

Some of the more substantial changes assessed in benthic habitat function evaluated in the present study are potentially associated with the placement of hard structures in shallow mobile sedimentary habitats, which result in a shift in habitat dominated by small, short-lived infaunal species (associated with fine sediment habitat), to a habitat dominated by larger, longer-lived, sessile epibenthic suspension feeders (associated with hard, rock-like, habitat created by the placement of hard structures). However, the ecological significance of the shift in dominant biological traits is difficult to assess, as despite the overall impact footprint being relatively small, the potential functional changes associated with a significant change in the biological traits may be substantial and persistent (Bergström *et al.*, 2013). In contrast, the impacts of bottom fishing, dredging and disposal activities were all assessed to be potentially most severe when executed in deep, sedimentary habitats.

Implicitly, aggregate extraction, energy extraction and fishing activities all occur in areas where the resource is sufficiently abundant as to make its exploitation economically viable. However, these activities may or may not be spatially coincident with the habitats upon which their impacts could be minimized. For example, the present study suggests that offshore wind farms may have a lower impact on seabed function if they were placed on hard seabed bottoms in deep waters. However, this would inevitably lead to increased costs of installation (Urick, 1983) and may also lead to additional pressures, e.g. increased propagation of noise (James and Costa Ros, 2015). While decisions regarding the locations of licenced boundaries for disposal of dredged material are ultimately governed by a need to minimise impacts on various stakeholders (protected areas, other users), the sites are, theoretically, not operationally restricted to any specific area. However, there are economic and ecological costs associated with transportation of the material to more distant areas where the disposal may have less of an impact on the marine ecosystem, e.g. by avoiding areas of coarse sediments, particularly those in deep waters.

However, of all the pressure types considered, it is arguably sediment abrasion arising from bottom fishing activities, which presents he greatest potentially gives rise to the most extensive benthic habitat impacts, and this is especially true for deep water habitats located to the west of the English Channel and parts of the Celtic Sea. Our results support those of other trait-based assessments where the benthic impacts of trawling have been shown to be greatest when occurring in coarse sediment habitats (Rijnsdorp et al., 2016; Van Denderen et al., 2016). Therefore, it may be argued that bottom fishing activities at levels of effort which result in seabed impacts at a frequency of at least once a year are comparable to the frequency (or persistence) of impact associated with dredging, disposal and selected construction activities. Measured in this way, the spatial extent of fishing activities (as determined by the swept area ratio of >10), is only about four times greater than the total area impacted by a combination of dredging disposal, marine aggregate extraction and construction activities (Table 5). However, the potential risk of impact posed by bottom fishing activities is much higher than that associated with other licensed activities given its much larger footprint. For example, unlike other human activities and pressures considered in this study, fishing is not managed or licensed to occur within specific areas, rather it is managed to avoid certain areas on account of avoiding impacts to biodiversity or important spawning grounds. Fishers are essentially able to go where they please, which increases the risk of bottom fishing impacts occurring in sensitive habitats not currently protected (Hiddink *et al.*, 2007).

The present study therefore offers further evidence in support of the need to adopt fishery management policies which identify "core" fishing grounds that minimise the adverse ecological impacts of fishing. In addition, the findings may help support decision making and implementing marine policy, especially regarding the allocation of monitoring and assessment resources needed to generate the most cost-effective outcomes for the management of multiple human activities.

Limitations

As with other types of cumulative impact assessment (Korpinen and Andersen, 2016), the present study has its limitations and associated uncertainties. For example, it does not include the functional responses of the larger, more mobile epifaunal invertebrates (e.g. crabs, bottom-living fish) that generally live on the seabed sediments. The response or sensitivity of this, generally more mobile, component of the seabed is likely to differ from that of the less-mobile infaunal assemblages, and their effect on seabed function. In addition, we have made no attempt to relate changes in any specific trait category to a specific functional property of the seabed; trait sensitivity is used here as a direct proxy for functional sensitivity. Although recent approaches have improved our understanding of which traits are sensitive to different impact pressures (Bolam *et al.*, 2016; Beauchard *et al.*, 2017), our understanding of which traits are important in regulating certain important benthic ecosystem functions, such as nutrient and carbon recycling remains largely unresolved. Finally, only those traits which have been shown to display significant proportional differences between different habitats (Bolam *et al.*, 2017) were included in the present assessment. The anthropogenic pressures considered in this study are also likely to alter the assemblage composition of other functional traits; these could not be included into our analyses.

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